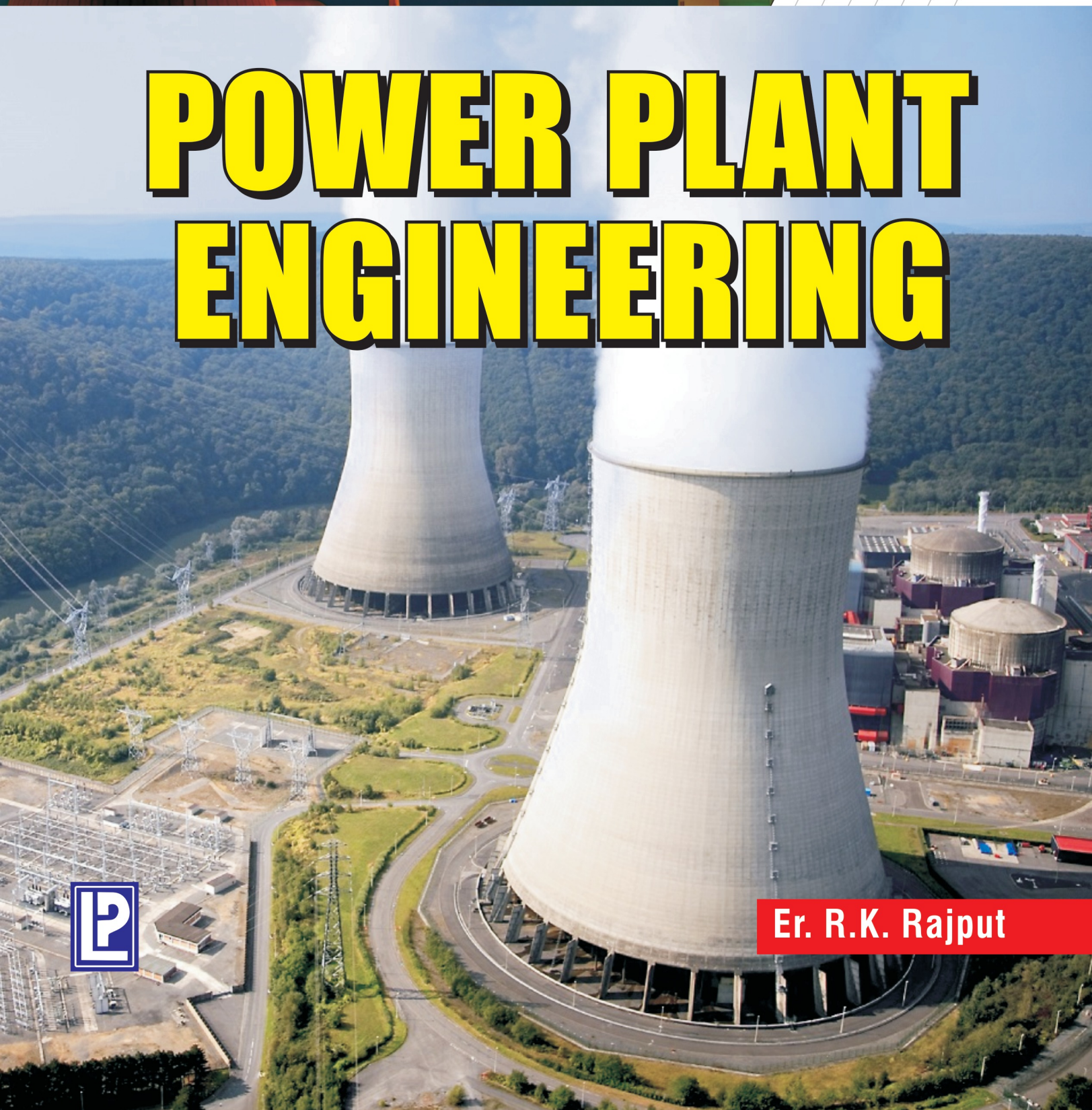
Fifth Edition

A TEXTBOOK OF

POWER PLANT ENGINEERING



Er. R.K. Rajput

A TEXTBOOK OF
POWER PLANT ENGINEERING

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A TEXTBOOK OF

POWER PLANT ENGINEERING

IN

SI UNITS

For

Engineering Students of Various Disciplines and Competitive Examinations (GATE, UPSC, etc.)

By

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Preface to The Fifth Edition

I am pleased to present the ***Fifth Edition*** of this book. The warm reception which the previous editions and reprints have enjoyed all over India and abroad has been a matter of great satisfaction to me.

Beside revising the whole book a **new chapter "14"** has been added which assimilates the following ***contents***:

Chapter 14: 'GATE' and 'UPSC' Examinations' Questions (Latest-selected) with Answers/ Solutions.

A. Conventional Questions with Answers/Solutions.

B. Multiple-choice Questions with Answers and "*Explanations*".

Any constructive suggestions for further improvement of the book will be thankfully acknowledged and incorporated in the next edition.

Er. R.K. Rajput
(Author)

Preface to The First Edition

On the subject of "*Power Plant Engineering*" several books are available in the market but they either lack in proper subject treatment or the solved examples are inadequate in number. The purpose of writing this book is to bridge these gaps and to present such a book to the students which should be easy to understand and should assimilate comprehensive treatment of the subject matter in simple, lucid and direct language.

The book comprises of 13 Chapters and an Objective Type Questions Bank. Each chapter contains adequate text supported by simple and self explanatory figures, large number of worked examples both in SI and MKS units, highlights, theoretical questions and several unsolved examples.

Chapters—Brief Contents

1. **Introductory.** This chapter gives the introduction of the various sources of the energy, Principal types of the Power Plants and Combustion of Fuels.
2. **Power Plants Cycles.** This chapter deals with the various cycles used in Power Plants, viz., Rankine Cycle, Regenerative Cycle, Binary Vapour Cycle, Otto Cycle, Diesel Cycle, Duel Combustion Cycle, Gas Turbine Cycles.
3. **Steam Power Plant.** Under this chapter, following aspects of Steam Power Plant have been discussed: Layout of a Modern Steam Power Plant, Fuel Handling, Combustion Equipment for Steam Boilers, Ash Handling, Dust Collection, Chimney Draught, Boiler Accessories, Steam Nozzles, Steam Turbines, Cooling Towers, Cooling Ponds etc.
4. **Diesel Engine Power Plant.** This chapter deals with I.C. Engines used in such a Plant and essential components of Diesel Power Plants. It also deals with Combustion Phenomenon in I.C. Engines along with its related topics and layout of a Diesel Engine Power Plant etc.
5. **Gas Turbine Power Plant.** This chapter deals with general aspects of Gas Turbine used in such a Plant along with the description of Gas Power Cycle used in such turbines. It also deals with topics such as Operation of Gas Turbines, Gas Turbines Power Plant Layout etc.
6. **Hydro-Electric Power Plant.** Under this chapter the following topics are dealth with : Elements of Hydro-Electric Power Plant, Hydro-Electric Turbines, Plant Layout, Hydro-Electric Plant Controls, Hydrology etc.

7. **Nuclear Power Plant.** This chapter deals with the General Aspects of Nuclear Engineering, Nuclear Power Systems, Nuclear Reactors and their Description, Nuclear Energy etc.
8. **Combined Operation of Different Power Plants.** This chapter deals with : Advantages of Combined Operation of Plants, Load Division between Power Stations, Hydro-Electric Plant in Combination with Steam Plant, Pump Storage Plant in Combination with Steam or Nuclear Power Plants, Co-ordination of Hydro-Electric and Gas Turbine Stations, Co-ordination of different types of Power Plants.
9. **Economics of Power Generation.** This chapter deals with topics such as Principle of Power Plant Design, Location of Power Plant, Layout of Power Plant Building, Cost Analysis, Selection of Type of Generation, Selection of Power Plant Equipment, Economics in Plant Selection, Economic Load Sharing etc.
10. **Non-Conventional Power Generation.** This chapter deals with the Wind Power Plant, Tidal Power Plant, Solar Power Plant, Geothermal Power Plant, Direct Energy Conversion Systems.
11. **Plant Instrumentation.** This chapter deals with the various instruments used in a Power Plant such as Pressure Gauges, Thermometers, Liquid Gauges, Flow Meters, p-H Measuring Instruments, Speed Measuring Instruments etc.
12. **Major Electrical Equipment used in Power Plant.** In this chapter following electrical equipment have been discussed : Generating Equipment, Transformers, Switch Gear, Protection of Electrical Systems.
13. **Pollution and its Control.** It deals with : Pollution from Thermal Plants, pollution from Nuclear Power Plants, and pollution from Hydro-electric Power Plants.

Objective Type Questions Bank

The bank assimilates 600 Objective Type Questions.

The book will prove to be of great help to the students preparing for engineering degree, A.M.I.E. (India), diploma and other competitive examinations.

The author's grateful thanks are due to Smt. Ramesh Rajput (wife) for extending full co-operation during the preparation of the manuscript.

The author's thanks are also due to Mr. Rakesh Syal for drawing neat diagrams for this book.

In the end the author wishes to express his gratitudes to M/s Laxmi Publications for taking extra pains in printing the book at a rapid pace and very systematically.

Although every care has been taken to make the book free of error both in text as well as in solved examples, yet the author shall feel obliged if any error present is brought to his notice. Constructive criticism of the book will be warmly received.

Er. R.K. Rajput
(Author)

Introduction to SI Units and Conversion Factors

A. INTRODUCTION TO SI UNITS

SI, the international system of units are divided into three classes:

1. Base units 2. Derived units 3. Supplementary units.

From the scientific point of view division of SI units into these classes is to a certain extent arbitrary, because it is not essential to the physics of the subject. Nevertheless the General Conference, considering the advantages of a single, practical, world-wide system for international relations, for teaching and for scientific work, decided to base the international system on a choice of six well-defined units given in Table 1 below:

Table 1. SI Base Units

Quantity	*Name*	*Symbol*
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
luminous intensity	candela	cd
amount of substance	mole	mol

The second class of SI units contains derived units, *i.e.,* units which can be formed by combining base units according to the algebraic relations linking the corresponding quantities. Several of these algebraic expressions in terms of base units can be replaced by special names and symbols can themselves be used to form other derived units.

Derived units may, therefore, be classified under three headings. Some of them are given in Tables 2, 3 and 4.

Table 2. Examples of SI Derived Units Expressed in Terms of Base Units

Quantity	*SI Units*	
	Name	*Symbol*
area	square metre	m^2
volume	cubic metre	m^3
speed, velocity	metre per second	m/s
acceleration	metre per second squared	m/s^2
wave number	1 per metre	m^{-1}
density, mass density	kilogram per cubic metre	kg/m^3
concentration (of amount of substance)	mole per cubic metre	mol/m^3
activity (radioactive)	1 per second	s^{-1}
specific volume	cubic metre per kilogram	m^3/kg
luminance	candela per square metre	cd/m^2

Table 3. SI Derived Units with Special Names

Quantity	*SI Units*			
	Name	*Symbol*	*Expression in terms of other units*	*Expression in terms of SI base units*
frequency	hertz	Hz	–	s^{-1}
force	newton	N	–	$m.kg.s^{-2}$
pressure	pascal	Pa	N/m^2	$m^{-1}.kg.s^{-2}$
energy, work, quantity of heat power	joule	J	N.m	$m^2.kg.s^{-2}$
radiant flux quantity of electricity	watt	W	J/s	$m^2.kg.s^{-3}$
electric charge	coulomb	C	A.s	s.A
electric tension, electric potential	volt	V	W/A	$m^2.kg.s^{-3}.A^{-1}$
capacitance	farad	F	C/V	$m^{-2}.kg^{-1}.s^4$
electric resistance	ohm	Ω	V/A	$m^2.kg.s^{-3}.A^{-2}$
conductance	siemens	S	A/V	$m^{-2}.kg^{-1}.s^3.A^2$
magnetic flux	weber	Wb	V.S.	$m^2.kg.s^{-2}.A^{-1}$
magnetic flux density	tesla	T	Wb/m^2	$kg.s^{-2}.A^{-1}$
inductance	henry	H	Wb/A	$m^2.kg.s^{-2}.A^{-2}$
luminous flux	lumen	lm	–	cd.sr
illuminance	lux	lx	–	m^{-2}.cd.sr

Table 4. Examples of SI Derived Units Expressed by Means of Special Names

Quantity	*SI Units*		
	Name	*Symbol*	*Expression in terms of SI base units*
dynamic viscosity	pascal second	Pa-s	$m^{-1}.kg.s^{-1}$
moment of force	metre newton	N.m	$m^2.kg.s^{-2}$
surface tension	newton per metre	N/m	$kg.s^{-2}$
heat flux density, irradiance	watt per square metre	W/m^2	$kg.s^{-2}$
heat capacity, entropy	joule per kelvin	J/K	$m^2.kg.s^{-2}.K^{-1}$
specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg.K)	$m^2.s^{-2}.K^{-1}$
specific energy	joule per kilogram	J/kg	$m^2.s^{-2}$
thermal conductivity	watt per metre kelvin	W/(m.K)	$m.kg.s^{-3}.K^{-1}$
energy density	joule per cubic metre	J/m^3	$m^{-1}.kg.s^{-2}$
electric field strength	volt per metre	V/m	$m.kg.s^{-3}.A^{-1}$
electric charge density	coulomb per cubic metre	C/m^3	$m^{-3}.s.A$
electric flux density	coulomb per square metre	C/m^2	$m^{-2}.s.A$
permittivity	farad per metre	F/m	$m^{-3}.kg^{-1}.s^4.A^4$
current density	ampere per square metre	A/m^2	–
magnetic field strength	ampere per metre	A/m	–
permeability	henry per metre	H/m	$m.kg.s^{-2}.A^{-2}$
molar energy	joule per mole	J/mol	$m^2.kg.s^{-2}mol^{-1}$
molar heat capacity	joule per mole kelvin	J/(mol.K)	$m^2.kg.s^{-2}.K^{-1}.mol^{-1}$

The SI units assigned to third class called "Supplementary units" may be regarded either as base units or as derived units. Refer to Table 5 and Table 6.

Table 5. SI Supplementary Units

Quantity	*SI Units*	
	Name	*Symbol*
plane angle	radian	rad
solid angle	steradian	sr

Table 6. Examples of SI Derived Units Formed by Using Supplementary Units

Quantity	*SI Units*	
	Name	*Symbol*
angular velocity	radian per second	rad/s
angular acceleration	radian per second squared	rad/s^2
radiant intensity	watt per steradian	W/sr
radiance	watt per square metre steradian	$W\text{-}m^{-2}.sr^{-1}$

Table 7. SI Prefixes

Factor	*Prefix*	*Symbol*	*Factor*	*Prefix*	*Symbol*
10^{12}	tera	T	10^{-1}	deci	d
10^{9}	giga	G	10^{-2}	centi	c
10^{6}	mega	M	10^{-3}	milli	m
10^{3}	kilo	k	10^{-6}	micro	μ
10^{2}	hecto	h	10^{-9}	nano	n
10^{1}	deca	da	10^{-12}	pico	p
			10^{-15}	fasnto	f
			10^{-18}	atto	a

B. CONVERSION FACTORS

1. Force:

1 newton = $kg\text{-}m/sec^2$ = 0.012 kgf

1 kgf = 9.81 N

2. Pressure:

1 bar = 750.06 mm Hg = 0.9869 atm = 10^5 N/m^2 = 10^3 $kg/m\text{-}sec^2$

1 N/m^2 = 1 pascal = 10^{-5} bar = 10^{-2} $kg/m\text{-}sec^2$

1 atm = 760 mm Hg = 1.03 kgf/cm^2 = 1.01325 bar

= 1.01325×10^5 N/m^2

3. Work, Energy or Heat:

1 joule = 1 newton metre = 1 watt-sec

= 2.7778×10^{-7} kWh = 0.239 cal

= 0.239×10^{-3} kcal

1 cal = 4.184 joule = 1.1622×10^{-6} kWh

1 kcal = 4.184×10^3 joule = 427 kgf-m

= 1.1622×10^{-3} kWh

1 kWh = 8.6042×10^5 cal = 860.42 kcal = 3.6×10^6 joule

$$1 \text{ kgf-m} = \left(\frac{1}{427}\right) \text{ kcal} = 9.81 \text{ joules}$$

4. Power:

1 watt = 1 joule/sec = 0.860 kcal/h
1 h.p. = 75 m kgf/sec = 0.1757 kcal/sec = 735.3 watt
1 kW = 1000 watts = 860 kcal/h

5. Specific heat:

1 kcal/kg-K = 4.184 kJ/kg-K

6. Thermal conductivity:

1 watt/m-K = 0.8598 kcal/h-m-°C
1 kcal/h-m-°C = 1.16123 watt/m-K = 1.16123 joules/s-m-K.

7. Heat transfer co-efficient:

1 watt/m^2-K = 0.86 kcal/m^2-h-°C
1 kcal/m^2-h-°C = 1.163 watt/m^2-K.

C. IMPORTANT ENGINEERING CONSTANTS AND EXPRESSIONS

Engineering constants and expressions	*M.K.S. system*	*SI Units*
1. Value of g_0	9.81 kg-m/kgf-sec^2	1 kg-m/N-sec^2
2. Universal gas constant	848 kgf-m/kg mole-K	848 × 9.81 = 8314 J/kg-mole-K ($\because$ 1 kgf-m = 9.81 joules)
3. Gas constant (R)	29.27 kgf-m/kg-K for air	$\frac{8314}{29}$ = 287 joules/kg-K for air
4. Specific heats (for air)	c_v = 0.17 kcal/kg-K	c_v = 0.17 × 4.184 = 0.71128 kJ/kg-K
	c_p = 0.24 kcal/kg-K	c_p = 0.24 × 4.184 = 1 kJ/kg-K
5. Flow through nozzle-exit velocity (C_2)	$91.5\sqrt{U}$, where U is in kcal	$44.7\sqrt{U}$, where U is in kJ
6. Refrigeration 1 ton	= 50 kcal/min	= 210 kJ/min
7. **Heat transfer** The Stefan Boltzmann Law is given by:	$Q = \sigma T^4$ kcal/m^2-h when $\sigma = 4.9 \times 10^{-8}$ kcal/h-m^2-K^4	$Q = \sigma T^4$ watts/m^2-h when $\sigma = 5.67 \times 10^{-8}$ W/m^2-K^4

Compiled by
Smt. **RAMESH RAJPUT**

1 Introduction

1.1. Energy and power. 1.2. Sources of energy—Fuels—Energy stored in water—Nuclear energy—Wind power—Solar energy—Tidal power—Geothermal energy—Thermoelectric power. **1.3. Principal types of power plants. 1.4. Combustion of fuels**—Combustion chemistry—How to convert volumetric analysis to weight analysis ?—How to convert weight analysis to volumetric analysis ?—Weight of air required for complete combustion of fuel—Excess air—Weight of carbon in flue gases—Weight of flue gas per kg of fuel burnt.—*Worked Examples—Highlights—Theoretical Questions—Unsolved Examples.*

1.1. ENERGY AND POWER

Energy. The historical as well as present-day civilization of mankind are closely interwoven with energy, and there is little reason to doubt but that in the future our existence will be ever more dependent upon this thing called **energy.** *Energy* probably was the original stuff or creation. Energy appears in many forms, but has one thing in common—*energy is possessed of the ability to produce a dynamic, vital effect*. Energy is associated with physical substance, but is not a substance itself. It shows itself by excited, animated state assumed by material which receives energy. The examples which can be quoted in respect of energy are almost endless in number. In this era energy is being produced in enormous quantities. As more and more of it is produced per person, the comforts, conveniences, and pleasures of life are even enhanced.

Energy exists in various forms *e.g., mechanical, thermal, electrical* etc. One form of energy can be converted into other by the use of suitable arrangements. Out of all these forms of energy, *electrical energy* is *preferred* due to the following *advantages* : 1. *Can be easily transported from one place to another*. 2. *Losses in transport are minimum.* 3. *Can be easily subdivided.* 4. *Economical in use.* 5. *Easily converted into other forms of energy.* 6. *Easily controlled and regulated to suit requirements.*

Power. Any physical unit of energy when divided by a unit of time automatically becomes a *unit of power*. However, it is in connection with the mechanical and electrical forms of energy that the term "*power*" is generally used. The rate of production or consumption of heat energy and, to a certain extent, of radiation energy is not ordinarily thought of as power. *Power is primarily associated with mechanical work and electrical energy*. Therefore, *power* can be defined as the *rate of flow of energy* and can state that a *power plant* is a *unit built for production and delivery of a flow of mechanical and electrical energy*. In common usage, a machine or assemblage of equipment that produces and delivers a flow of mechanical or electrical energy is a *power plant*. Hence, an internal combustion engine is a power plant, a water wheel is a power plant, etc. However, what we generally mean by the term is that assemblage of equipment, permanently located on some chosen site which receives raw energy in the form of a substance capable of being operated on in such a way as to produce electrical energy for delivery from the power plant.

With the advancement in technology the power consumption is rising steadily. This necessitates that in addition to the existing sources of power such as coal, water, petroleum etc. other sources of energy should be searched out and new and more efficient ways of producing energy should be devised. Nuclear energy has enlarged the world's power resources. The energy released by *1 kg of uranium is equivalent to energy obtained by 4500 tonnes of high grade coal*.

1.2. SOURCES OF ENERGY

The various sources of energy are :

1. Fuels
   - Solids—Coal, coke anthracite etc.
   - Liquids—Petroleum and its derivates
   - Gases—Natural gas, blast furnace gas etc.

2. Energy stored in water
3. Nuclear energy
4. Wind power
5. Solar energy
6. Tidal power
7. Geothermal energy
8. Thermoelectric power.

1.2.1. Fuels

Fuels may be *chemical* or *nuclear*. Here we shall consider chemical fuels only.

A chemical fuel is a substance which releases heat energy on combustion. The principal combustible elements of each fuel are *carbon* and *hydrogen*. Though *sulphur* is a combustible element too but its presence in the fuel is considered to be *undesirable.*

Classification of fuels :

Fuels can be *classified* according to whether

1. They *occur in nature* called *primary fuels* or are *prepared* called *secondary fuels*.

2. They are *in solid, liquid* or *gaseous state*. The detailed classification of fuels can be given in a summary form as below :

Type of fuel	*Natural (Primary)*	*Prepared (Secondary)*
Solid	Wood Peat Lignite coal	Coke Charcoal Briquettes
Liquid	Petroleum	Gasoline Kerosene Fuel oil Alcohol Benzol Shale oil
Gaseous	Natural gas	Petroleum gas Producer gas Coal gas Coke-oven gas Blast furnace gas Carburetted gas Sewer gas

1.2.1.1. Solid fuels

Coal. Its main constituents are carbon, hydrogen, oxygen, nitrogen, sulphur, moisture and ash. Coal passes through different stages during its formation from vegetation. These stages are enumerated and discussed below :

Plant debris-Peat-Lignite-Brown coal-Sub-bituminous coal-Bituminous coal-Semi-bituminous coal-Semi-anthracite coal-Anthracite coal-graphite.

Peat. It is the first stage in the formation of coal from wood. It contains huge amount of moisture and therefore it is dried for about 1 to 2 months before it is put to use. It is used as a domestic fuel in Europe and for power generation in Russia. In India it does not come in the categories of good fuels.

Lignites and brown coals. These are intermediate stages between peat and coal. They have a woody or often a clay like appearance associated with high moisture, high ash and low heat contents. Lignites are usually amorphous in character and impose transport difficulties as they break easily. They burn with a smoky flame. Some of this type are suitable for local use only.

Bituminous coal. It burns with long yellow and smoky flames and has high percentages of volatile matter. The average calorific value of bituminous coal is about 31350 kJ/kg. It may be of two types, namely *caking* or *non-caking*.

Semi-bituminous coal. It is softer than the anthracite. It burns with a very small amount of smoke. It contains 15 to 20 per cent volatile matter and has a tendency to break into small sizes during storage or transportation.

Semi-anthracite. It has less fixed carbon and less lustre as compared to true anthracite and gives out longer and more luminous flames when burnt.

Anthracite. It is very hard coal and has a shining black lustre. It ignites slowly unless the furnace temperature is high. It is non-caking and has high percentage of fixed carbon. It burns either with very short blue flames or without flames. The calorific value of this fuel is high to the tune of 35500 kJ/kg and as such is very suitable for steam generation.

Wood charcoal. It is obtained by destructive distillation of wood. During the process the volatile matter and water are expelled. The physical properties of the residue (charcoal) however depends upon the rate of heating and temperature.

Coke. It consists of carbon, mineral matter with about 2% sulphur and small quantities of hydrogen, nitrogen and phosphorus. It is solid residue left after the destructive distillation of certain kinds of coals. It is smokeless and clear fuel and can be produced by several processes. It is mainly used in blast furnace to produce heat and at the same time to reduce the iron ore.

Briquettes. These are prepared from fine coal or coke by compressing the material under high pressure.

Analysis of coal. The following two types of analysis is done on the coal :

1. Proximate analysis
2. Ultimate analysis.

1. **Proximate analysis.** In this analysis, *individual elements are not determined ; only the percentage of moisture, volatile matters, fixed carbon and ash are determined.*

Example. Moisture = 4.5%, volatile matter = 5.5%, fixed carbon = 20.5%.

This type of analysis is easily done and is for *commercial purposes* only.

2. **Ultimate analysis.** In the ultimate analysis, the percentage of various elements are determined.

Example. Carbon = 90%, hydrogen = 2%, oxygen = 4%, nitrogen = 1%, sulphur = 15% and ash = 1.5%.

This type of analysis is useful for *combustion calculations.*

Properties of Coal. *Important properties of coal* are given below :

1. Energy content or heating value
2. Sulphur content
3. Burning characteristics
4. Grindability
5. Weatherability
6. Ash softening temperature.

A *good coal* should have :

(*i*) low ash content and high calorific value

(*ii*) small percentage of sulphur (less than 1%)

(*iii*) good burning characteristics (*i.e.,* should burn freely without agitation) so that combustion will be complete

(*iv*) high grindability index (in case of ball mill grinding)

(*v*) high weatherability.

Ranking of Coal. ASME and ASTM have accepted a specification based on the fixed carbon and heating value of the mineral matter free analysis.

—Higher ranking is done on the basis of fixed carbon percentage (*dry basis*).

—Lower ranking is done on the heating value on the *moist basis*.

Example. 62% C and a calorific value of 5000 kcal/kg is ranked as (62–500) rank.

Rank is an inherent property of the fuel depending upon its relative progression in the classification process.

Grading of Coal. Grading is done on the following basis :

(*i*) Size (*ii*) Heating value

(*iii*) Ash content

(*iv*) Ash softening temperature

(*v*) Sulphur content.

Example. A grade written as 5–10 cm, 500-A8-F24-S1.6 indicate the coal as having :

—a size of 5–10 cm,

—heating value of 5000 kcal/kg,

—8 to 10% ash,

—ash softening temperature of 2400–2590°F, and

—a sulphur content of 1.4 to 1.6%.

A rank and grade of a coal gives a complete report of the material. Thus the following rank and grade of the coal described above :

(62–500), 5–10 cm, 500-A8-F24-S1.6.

1.2.1.2. Liquid fuels

The chief source of liquid fuels is petroleum which is obtained from wells under the earth's crust. These fuels have proved *more advantageous in comparison to solid fuels* in the following respects.

Advantages :

1. Require less space for storage.
2. Higher calorific value.
3. Easy control of consumption.
4. Staff economy.
5. Absence of danger from spontaneous combustion.
6. Easy handling and transportation.
7. Cleanliness.
8. No ash problem.
9. Non-deterioration of the oil in storage.

Petroleum. There are different opinions regarding the origin of petroleum. However, now it is accepted that petroleum has originated probably from organic matter like fish and plant life etc., by bacterial action or by their distillation under pressure and heat. It consists of a mixture of gases, liquids and solid hydrocarbons with small amounts of nitrogen and sulphur compounds. In India the main sources of petroleum are Assam and Gujarat.

Heavy fuel oil or crude oil is imported and then refined at different refineries. The refining of crude oil supplies the most important product called *petrol*. Petrol can also be made by polymerization of refinery gases.

Other liquid fuels are kerosene, fuels oils, colloidal fuels and alcohol.

The following table gives *composition* of some common liquid fuels used in terms of the elements in *weight percentage.*

Fuel	*Carbon*	*Hydrogen*	*Sulphur*	*Ash*
Petrol	85.5	14.4	0.1	–
Benzene	91.7	8.0	0.3	–
Kerosene	86.3	13.6	0.1	–
Diesel oil	86.3	12.8	0.9	–
Light fuel oil	86.2	12.4	1.4	–
Heavy fuel oil	88.3	9.5	1.2	1.0

Important Properties of Liquid Fuels

(1) Specific gravity (2) Flash point

(3) Fire point (4) Volatility

(5) Pour point (6) Viscosity
(7) Carbon residue (8) Octane number
(9) Cetane number (10) Corrosive property
(11) Ash content (12) Gum content
(13) Heating value (14) Sulphur content.

The requisite properties vary from device to device which uses the fuel to generate power. For example, *higher the octane number, higher can be the compression ratio and the thermal efficiency will be higher.* Similarly, *the cetane number of a diesel oil should be as high as possible.*

In general the liquid fuels should have :

(*i*) low ash content (*ii*) high heating value
(*iii*) low gum content (*iv*) less corrosive tendency
(*v*) low sulphur content (*vi*) low pour point.

Viscosity and other properties vary from purpose to purpose to which the fuel is employed.

1.2.1.3. Gaseous fuels

Natural gas. The main constituents of natural gas are methane (CH_4) and ethane (C_2H_6). It has calorific value nearly 21000 kJ/m^3. Natural gas is used alternately or simultaneously with oil for internal combustion engines.

Coal gas. Mainly consists of hydrogen, carbon monoxide and hydro-carbons. It is prepared by carbonization of coal. It finds its use in boilers and sometimes used for commercial purposes.

Coke-oven gas. It is obtained during the production of coke by heating the bituminous coal. The volatile content of coal is driven off by heating and major portion of this gas is utilised in heating the ovens. This gas must be thoroughly filtered before using in gas engines.

Blast furnace gas. It is obtained from smelting operation in which air is forced through layers of coke and iron ore, the example being that of pig iron manufacture where this gas is produced as by product and contains about 20% carbon monoxide (CO). After filtering it may be blended with richer gas or used in gas engines directly. The heating value of this gas is very low.

Producer gas. It results from the partial oxidation of coal, coke or peat when they are burnt with an insufficient quantity of air. It is produced in specially designed retorts. It has low heating value and in general is suitable for large installations. It is also used in steel industry for firing open hearth furnaces.

Water or Illuminating gas. It is produced by blowing steam into white hot coke or coal. The decomposition of steam takes place liberating free hydrogen and oxygen in the steam combines with carbon to form carbon monoxide according to the reaction :

$$C + H_2O \longrightarrow CO + H_2$$

The gas composition varies as the hydrogen content if the coal is used.

Sewer gas. It is obtained from sewage disposal vats in which fermentation and decay occur. It consists of mainly marsh gas (CH_4) and is collected at large disposal plants. It works as a fuel for gas engines which is turn drive the plant pumps and agitators.

Gageous fuels are becoming popular because of following *advantages* they possess :

Advantages :

1. Better control of combustion.
2. Much less excess air is needed for complete combustion.
3. Economy in fuel and more efficiency of furnace operation.
4. Easy maintenance of oxidizing or reducing atmosphere.
5. Cleanliness.
6. No problem of storage if the supply is available from public supply line.
7. The distribution of gaseous fuels even over a wide area is easy through the instrumentality of pipe lines and as such handling of the fuel is altogether eliminated. Gaseous fuels give economy of heat and produce higher temperatures as they can be preheated in regenerative furnaces and thus heat from hot flue gases can be recovered.

Important Properties of Gaseous Fuels

1. Heating value or calorific value
2. Viscosity
3. Specific gravity
4. Density
5. Diffusibility.

Typical composition of some gaseous fuels is given below :

Fuel	H_2	CO	CH_4	C_2H_4	C_2H_6	C_4H_8	O_2	CO_2	N_2
Natural gas	–	1	93	–	3	–	–	–	3
Coal gas	53.6	9.0	25	–	–	3	0.4	3	6
Blast furnace gas	2	27	–	–	–	–	–	11	–

1.2.1.4. Calorific or Heating values of fuels

The calorific value of the fuel is defined as the energy liberated by the complete oxidation of a unit mass or volume of a fuel. It is expressed in kJ/kg for solid and liquid fuels and kJ/m^3 for gases.

Fuels which contain hydrogen have two calorific values, the *higher* and the *lower*. The '*lower calorific value*' is the heat liberated per kg of fuel after deducting the heat necessary to vaporise the steam, formed from hydrogen. The '*higher or gross calorific value*' *of the fuel is one*

indicated by a constant-volume calorimeter in which the steam is condensed and the heat of vapour is recovered.

The lower or net calorific value is obtained by subtracting latent heat of water vapour from gross calorific value. In other words, the relation between lower calorific value (L.C.V.) and higher calorific value (H.C.V.) can be expressed in the following way :

$$\text{L.C.V.} = (\text{H.C.V.} - 2465\ m_w) \qquad ...(1.1)$$

where m_w is the mass of water vapour produced by combustion of 1 kg of fuel and 2465 kJ/kg is the latent heat corresponding to standard temperature (saturation) of 15°C.

In MKS units:
L.C.V. = (H.C.V. – 588.76 m_w)
where m_w is the mass of water vapour produced by combustion of 1 kg of fuel and 588.76 is the latent heat value in kcal as read from steam tables for 1 kg of water vapour.

Dulong's Formula (Solid/liquid fuels). Dulong suggested a formula for the calculation of the calorific value of the solid or liquid fuels from their chemical composition which is as given below :

Gross calorific value

$$\text{or H.C.V.} = \frac{1}{100}\left[33800 + 144000\left(\text{H} - \frac{\text{O}}{8}\right) + 9270\ \text{S}\right] \text{kJ/kg} \qquad ...(1.2)$$

In MKS units:

$$\text{H.C.V.} = \frac{1}{100}\left[8080\ \text{C} + 34500\left(\text{H} - \frac{\text{O}}{8}\right) + 2240\ \text{S kcal / kg}\right]$$

where C, H, O and S are carbon, hydrogen, oxygen and sulphur in percentages respectively in 100 kg of fuel. In the above formula, the oxygen is assumed to be in combination with hydrogen and only extra surplus hydrogen supplies the necessary heat.

1.2.2. Energy Stored in Water

The energy contained in flowing streams of water is a form of mechanical energy. It may exist as the kinetic energy of a moving stream or as potential energy of water at some elevation with respect to a lower datum level, an example of which would be the water held behind a dam. *Hydraulic plants* are slowly increasing in number, although the number of new plants of this type built is quite small compared with those which exploit heat energy. As a usual thing, the most desirable hydroelectric sites are the first to be utilized, consequently, as more hydroelectric plants are built, the owners must pay increasingly higher development costs.

From the stand point of capitalistic economics, it is often hard to justify the development of hydroelectric power in comparison with steam power, but from the stand point of the conservation of a fixed natural resource, namely, its mineral fuels, it is obvious that every effort should be made to harness the water power of the country, since if unharnessed it goes to waste, whereas fuel, if unmined, remains intact and undiminished in value in the ground.

Water power is quite cheap where water is available in abundance. Although *capital cost of hydroelectric power plants is higher as compared to other types of power plants yet their operating costs are quite low.*

1.2.3. Nuclear Energy

One of the outstanding facts about nuclear power is the *large amount of energy that can be released from a small mass of active material.* Complete fission of one kg of uranium contains the energy equivalent of 4500 tonnes of coal or 2000 tonnes of oil. The *nuclear power is not only available in abundance but it is cheaper than the power generated by conventional sources.*

The following factors go in favour of nuclear energy :

(*i*) Practically independent of geographical factors.

(*ii*) No combustion products.

(*iii*) Clean source of power which does not contribute to air pollution.

(*iv*) Fuel transportation networks and large storage facilities not required.

The economic advantage of nuclear power can be realised only if one can ensure a guaranteed base load of about 75%. The number of electro-chemical processes (fertiliser plants), desalination of water and use of electricity for pumping water from tube wells assure a constant base load. Therefore, such type of power requirements must be developed before the adoption of nuclear power in the country.

1.2.4. Wind Power

The man has been served by the power from winds for many centuries but the total amount of energy generated in this manner is small. The expense of installation and variability of operation have tended to limit the use of the windmill to intermittent services where *its variable output has no serious disadvantage.* The principal services of this nature are the *pumping of water into storage tanks and the charging of storage batteries.*

Windmill power equipment may be classified as follows :

1. *The multi-bladed turbine wheel.* This is the foremost type in use and its efficiency is about 10 per cent of the kinetic energy of the wind passing through it.

2. *The high-speed propeller type.*

3. The rotor.

The propeller and rotor types are *suitable for the generation of electrical energy,* as both of them possess the ability to start in very low winds. The *Propeller type is more*

likely to be used in small units such as the driving of small battery charging generators, whereas the *rotor,* which is rarely seen, is more practical *for large installations,* even of several hundred kilowatts' capacity.

In India, the wind velocity along coastline has a range 10–16 kmph and a survey of wind power has revealed that wind power is capable of exploitation for pumping water from deep wells or for generating small amounts of electric energy.

Modern windmills are capable of working on velocities as low as 3–7 kmph while *maximum efficiency is attained at 10–12 kmph.*

A normal working life of 20 to 25 years is estimated for windmills.

The great advantage of this source of energy is that *no operator is needed and no maintenance and repairs are necessary for long intervals.*

Characteristics of wind power/energy. Some characteristics of wind energy are given below :

1. No fuel provision and transport are required in wind energy systems.
2. It is a renewable source of energy.
3. Wind power systems are non-polluting.
4. Wind power systems, up to a few kW, are less costly, but on a large scale, costs can be competitive with conventional electricity. Lower costs can be achieved by mass production.

Problems associated with "wind energy":

1. Wind energy systems are noisy in operation.
2. Large areas are needed to install *wind farms* for electrical power generators.
3. Wind energy available is dilute and fluctuating in nature. Because of dilute form, conversion machines have to be necessarily large.
4. Wind energy needs storage means because of its irregularity.

1.2.5. Solar Energy

A lot of work to utilise solar energy for generation of steam has been done in some countries, particularly the U.S.S.R. and it is likely that this could be developed on commercial scale.

A serious fault of this source of energy is, of course, that it is effective only during the day, so that if a continuous output is needed, some large reservoir of energy, such as a storage battery or a heat accumulator tank, must be drawn upon at night. Also, the output is handicapped if there is cloudy weather. Nevertheless, there are some locations in the world where strong solar radiation is received very regularly, and where the sources of mineral fuel are either scanty or entirely lacking. Such locations offer more interest to the solar power plant builder than the more favoured regions of earth.

For developing solar energy two ways have been explored *viz*., the glass lens and the reflector. These devices concentrate the solar rays to a focal point which is characterised by a high degree of heat which can be utilised to boil water and generate steam. The reflector is the better of the two methods due to the convenience with which it can be manufactured in different shapes and sizes. If an arrangement is provided to turn the reflector with the sun, so that the rays can constantly concentrate at the focal point, a continuous supply of heat is made available during the hours of the day. However, a great deal of practical research is still necessary before the solar energy can be commercially exploited at a cheaper rate.

Conditions for utilisation of solar energy, in India, are favourable since for nearly six months of the year sunshine is uninterrupted during the day, while in the other six months cloudy weather and rain provide conditions suitable for water power. Thus, a coordination of solar energy with water power can provide a workable plan for most places in India.

1.2.6. Tidal Power

The rise and fall of tides offers a means for storing water at the rise and discharging the same at fall. Of course the head of water available under such cases is very low but with increased catchment area considerable amounts of power can be generated at a negligible cost.

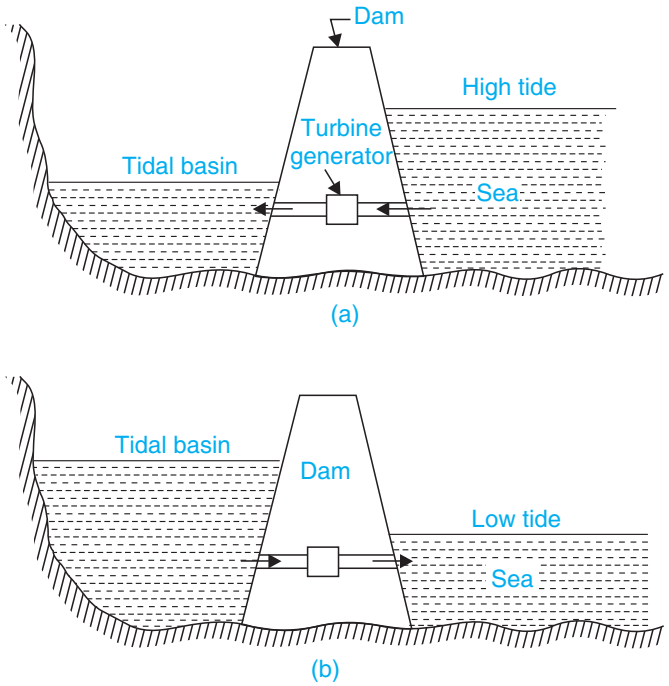


Fig. 1.1. Generation of power by tides.

The use of tides for electric power generation is practical in a few favourably situated sites where the geography of an inlet of bay favours the construction of a large

scale hydroelectric plant. To harness the tides, a dam would be built across the mouth of the bay in which large gates and low head hydraulic turbines would be installed. At the time of high tide the gates are opened and after storing water in the tidal basin the gates are closed. After the tide has received, there is a working hydraulic head between the basin water and open sea/ocean and the water is allowed to flow back to the sea through water turbines installed in the dam. With this type of arrangement, the generation of electric power is *not continuous*. However by using reversible water turbine the turbine can be run continuously as shown in Fig. 1.1.

1.2.7. Geothermal Energy

In many places on the earth natural steam escapes from surface vents. Such natural steam wells suggest the possibility of tapping terrestrial heat (or geothermal energy) in this form and using it for the development of power. Unfortunately, the locations where the steam-producing substrata seem to be fairly close to the surface are far removed from centres of civilization where the power could be usefully employed. Nevertheless, there are probably many places where, although no natural steam vent or hot springs are showing, deep drillings might tap a source of underground steam. The cost of such explorations and the great likelihood of an unsuccessful conclusion are not very conductive to exploitation of this source of energy.

There are *two* ways of electric power production from geothermal energy :

(*i*) Heat energy is transferred to a working fluid which operates the power cycle. This may be particularly useful at places of fresh volcanic activity where the molten interior mass of earth vents to the surface through fissures and substantially high temperatures, such as between 450 to 550°C can be found. By embedding coil of pipes and sending water through them steam can be raised.

(*ii*) The hot geothermal water and/or steam is used to operate the turbines directly. From the well-head the steam is transmitted by pipe lines up to 1 m in diameter over distances up to about 3 km to the power station. Water separators are usually employed to separate moisture and solid particles from steam.

Presently, only steam coming out of the ground is used to generate electricity, the hot water is discarded, because it contains as much as 30% dissolved salts and minerals, and these cause serious rust damage to the turbine. The water, however, contains more than $\frac{1}{3}$rd of the available thermal energy.

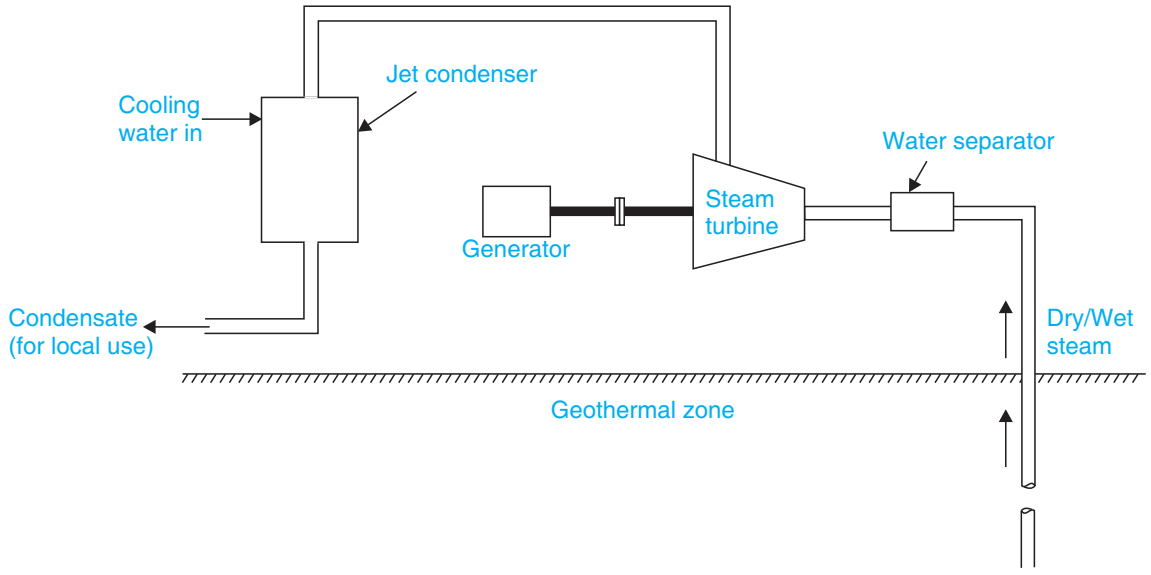


Fig. 1.2. Geothermal power plant.

1.2.8. Thermoelectric Power

According to *Seebeck effect*, when the two ends of a loop of two dissimilar metals are held at different temperatures, an electromotive force is developed and the current flows in loop. This method, by selection of suitable materials, can also be used for power generation. This method involves *low initial cost* and *negligible operating cost.*

1.3. PRINCIPAL TYPES OF POWER PLANTS

The principal types of power plants dealt in this book are :

1. Steam plants using coal, oil or nuclear fission.
2. Internal combustion engine plants.
3. Gas turbine plants.
4. Hydroelectric plants.

Steam plants using Coal, Oil or Nuclear Fission. The steam plants in which coal or oil is used comprise the *steam generating equipment* and the *prime movers*. In the boilers/steam generators steam is produced and then utilised to drive the *turbines/engines* which are *coupled to generators to get electricity*. The furnace may employ grate burning of *solid fuel, pulverised fuel* in burners or furnace oil in oil burners. Besides, the plant may contain several *heat saving devices* such as water heaters, economisers, air pre-heater etc. which effect an improvement in the overall efficiency of all boiler plants. The equipment for firing of fuel into the furnaces and also that for handling of fuel and ash are other important aspects of plant study besides such auxiliary equipment as needed for condensing exhaust steam, water treatment, water cooling, dust removal, draft control etc.

In nuclear stations heat is produced in a reactor which replaces the conventional boiler.

Internal Combustion Engine Plants. In these plants spark ignition (S.I.) or compression ignition (C.I.) engines are used as prime movers to drive electric generators. The *C.I. engines using diesel fuel are most commonly used* whereas the use of *S.I. engines are restricted to drive small portable electric generators.*

The diesel engine power plant may, besides the engine proper, include fuel handling, oil cooling, water cooling, starting and supercharging equipment.

Gas Turbine Plant. A gas turbine plant, working on a modified gas cycle, would contain besides the gas turbine, the *starting device, auxiliary lubrication, fuel control system, oil cooler, combustor, reheater, regenerator* etc. *A combination gas turbine plant employs an auxiliary steam plant obtaining its heat from gas turbine exhaust*. Such a combination plant has advantage of both gas and steam plants and some commercial plants are working on this system.

Hydroelectric Plants. This type of plant makes use of energy of water stored at an elevation and allowed to drop to a lower level. The electric generator is driven by a water turbine through which the water from the pond is made to work.

A hydroelectric plant comprises the *turbines, governing gear, coolant circulators* etc.

The *operation* of such a plant is usually *much simpler* than that of a steam, diesel or gas powered plant.

1.4. COMBUSTION OF FUELS

1.4.1. Combustion Chemistry

Under this heading we shall consider various important reactions concerning different elements which go to form the fuels and gases. Primarily there will be necessity to have some knowledge about the symbols and molecular weight of some important elements, compounds and gases. Table 1.1 given below satisfies the requirement.

Table 1.1

	Molecule		*Atom*	
	Symbol	*Molecule weight*	*Symbol*	*Molecular weight*
Hydrogen	H_2	2	H	1
Oxygen	O_2	32	O	16
Nitrogen	N_2	28	N	14
Carbon	C	12	C	12
Sulphur	S	32	S	32
Water	H_2O	18	–	–
Carbon monoxide	CO	28	–	–
Carbon dioxide	CO_2	44	–	–
Sulphur dioxide	SO_2	64	–	–
Marsh gas (Methane)	CH_4	16	–	–
Ethylene	C_2H_4	28	–	–
Ethane	C_2H_6	30	–	–

1. Carbon (complete combustion)

The complete combustion of carbon may be expressed by

$$C + O_2 = CO_2 \qquad ...(1.3)$$

or 1 kg (carbon) + $\frac{8}{3}$ kg (oxygen) = $\frac{11}{3}$ kg (carbon dioxide) ...(1.4)

Equation (1.3) indicates that one molecule of carbon combines with one molecule of oxygen to give one molecule of carbon dioxide.

Equation (1.4) indicates that 1 kg of carbon needs 8/3 kg of oxygen for its complete combustion and produces 11/3 kg of carbon dioxide.

2. Carbon (incomplete combustion)

Carbon combines with oxygen to form carbon monoxide (and not carbon dioxide as in the first case) according to the equation :

$$2C + O_2 = 2CO$$

$$2 \text{ mol} + 1 \text{ mol} = 2 \text{ mol}$$

or $$1 \text{ mol} + 1/2 \text{ mol} = 1 \text{ mol} \qquad ...(1.5)$$

$$24 + 32 = 56$$

or 1 kg (carbon) + 4/3 kg (oxygen)

= 7/3 kg (carbon monoxide) ...(1.6)

Equation (1.5) indicates that 1 molecule of carbon combines with $\frac{1}{2}$ molecule of oxygen to produce 1 molecule of carbon monoxide.

Equation (1.6) represents that 1 kg of carbon requires 4/3 kg of oxygen to produce 7/3 kg of carbon monoxide.

3. Carbon monoxide

It combines with oxygen to produce carbon dioxide.

$$2CO + O_2 = 2CO_2$$
$$2 \text{ vol} + 1 \text{ vol} = 2 \text{ vol}$$
$$1 \text{ vol} + \tfrac{1}{2} \text{ vol} = 1 \text{ vol} \quad ...(1.7)$$
$$56 + 32 = 88$$

or 1 kg (carbon monoxide) + 4/7 kg (oxygen)
= 11/7 kg (carbon monoxide) ...(1.8)

Equation (1.7) shows that one volume of carbon monoxide combines with half volume of oxygen and produce one volume of carbon monoxide gas.

Equation (1.8) indicates that 1 kg of carbon monoxide reacts with 4/7 kg of oxygen to give 11/7 kg of carbon dioxide.

4. Sulphur

Sulphur burns in the presence of oxygen to produce sulphur dioxide

$$S + O_2 = SO_2$$
$$1 \text{ mol} + 1 \text{ mol} = 1 \text{ mol} \quad ...(1.9)$$
$$32 + 32 = 64$$

or 1 kg (sulphur) + 1 kg (oxygen)
= 2 kg (sulphur dioxide) ...(1.10)

5. Hydrogen

Hydrogen burns with oxygen to give water as the product

$$2H_2 + O_2 = 2H_2O$$
$$1 \text{ vol} + \tfrac{1}{2} \text{ vol} = 1 \text{ vol} \quad ...(1.11)$$
$$4 + 32 = 36$$

1 kg (hydrogen) + 8 kg (oxygen) = 9 kg (water) ...(1.12)

6. Methane (Marsh gas)

When methane burns in the presence of oxygen the combustion products are carbon dioxide and water vapours,

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$
$$1 \text{ vol} + 2 \text{ vol} = 1 \text{ vol} + 2 \text{ vol} \quad ...(1.13)$$
$$16 + 64 = 44 + 36$$

or 1 kg (methane) + 4 kg (oxygen)
= 11/4 kg (carbon dioxide) + 9/4 kg (water) ...(1.14)

7. Ethylene

On combustion with oxygen it also gives carbon dioxide and water vapour as the products

$$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$$
$$1 \text{ vol} + 3 \text{ vol} = 2 \text{ vol} + 2 \text{ vol} \quad ...(1.15)$$
$$28 + 96 = 88 + 36$$

or 1 kg (ethylene) + 24/7 kg (oxygen)
= 22/7 kg (carbon dioxide) + 9/7 kg (water) ...(1.16)

1.4.2. How to Convert Volumetric Analysis to Weight Analysis ?

The conversion of volumetric analysis to weight analysis involves the following *steps* :

1. Multiply the volume of each constituent by its molecular weight.

2. Add all these weights and then divide each weight by the total of all and express it as percentage.

1.4.3. How to Convert Weight Analysis to Volumetric Analysis ?

1. Divide the weight of each constituent by its molecular weight.

2. Add up these volumes and divide each volume by the total of all and express it as a percentage.

1.4.4. Weight of Air Required for Complete Combustion of Fuel

The exact amount of oxygen required, *theoretically*, for complete combustion of one kg of fuel can be determined from the analysis of the fuel as follows :

Firstly, the amount of oxygen required for each of the constituents of the fuel is calculated separately with the help of chemical equations.

Then these requirements are added and the total amount of oxygen required is obtained.

(If some oxygen is already present in the fuel then it must be *deducted* from the calculated amount of oxygen required for the combustion of the constituents).

The oxygen for the combustion of fuel has to be obtained from atmospheric air, which consists of oxygen, nitrogen, a small amount of carbon dioxide and small traces of rare gases like neon, argon etc. But for all engineering calculations, composition of air is taken as follows :

By weight..... $\begin{cases} \text{Nitrogen} = 77\% \\ \text{Oxygen} = 23\% \end{cases}$

By volume ..... $\begin{cases} \text{Nitrogen} = 79\% \\ \text{Oxygen} = 21\% \end{cases}$

Thus the amount of oxygen required for the combustion of certain fuel is known, the amount of air necessary for the combustion of 1 kg of fuel can be determined.

"The theoretical or stoichiometric quantity of air is that quantity which is required for complete combustion of 1 kg of fuel without any oxygen appearing in the products of combustion."

1.4.5. Excess Air

For combustion of fuel we need air. As per theoretical basis there is a minimum amount of air which is required by the fuel to burn completely, *but always, air in excess is used*

because whole of air supplied for combustion purposes does not come in contact with the fuel completely and as such a portion of fuel may be left unburnt. But if a large quantity of excess air is used it exercises *a cooling effect on combustion process which however can be avoided by preheating the air. The weight of excess air supplied can be determined from the weight of oxygen which is left unused.*

The amount of excess air supplied varies with the type of fuel and the firing conditions. It may approach a value of 100% but modern practice is to use 25% to 50% excess air.

1.4.6. Weight of Carbon in Flue Gases

The weight of carbon contained in one kg of flue or exhaust gas can be calculated from the amounts of CO_2 and CO contained in it.

In eqn. (1.4) it was shown that 1 kg of carbon produces 11/3 kg of CO_2 when completely burnt. Hence 1 kg of CO_2 will contain 3/11 kg of carbon.

In eqn. (1.6) it can be seen that 1 kg of carbon produces 7/3 kg of CO, hence 1 kg CO contains 3/7 kg of carbon.

Therefore, weight of carbon per kg of fuel

$$= \left(\frac{3}{11}CO_2 + \frac{3}{7}CO\right)$$

where CO_2 and CO are the quantities of carbon dioxide and carbon monoxide present in 1 kg of flue or exhaust gas.

1.4.7. Weight of Flue Gas per kg of Fuel Burnt

Due to supply of air, the weight of flue gas or exhaust gas is always more than that of fuel burnt. The actual weight of dry flue gases can be obtained by comparing the weight of carbon present in the flue gases with the weight of carbon in the fuel, since there is no loss of carbon during the combustion process. As the analysis of the exhaust gases is volumetric, so *this must first be reduced to weight analysis.*

Also, *total weight of carbon in one kg of flue gas is*

$$= \left(\frac{3}{11}CO_2 + \frac{3}{7}CO\right)$$

$\therefore$ *The weight of flue gas / kg of fuel burnt*

$$= \frac{\text{Weight of carbon in one kg of fuel}}{\text{Weight of carbon in one kg of flue gas}}.$$

WORKED EXAMPLES

Example 1.1. *The percentage composition of sample of liquid fuel by weight is, C = 84.8 per cent, and H_2 = 15.2 per cent. Calculate (i) the weight of air needed for the combustion of 1 kg of fuel ; (ii) the volumetric composition of the products of combustion if 15 per cent excess air is supplied.*

Solution.

Element, wt (kg)	*O_2 used (kg)*	*Dry products (kg)*
C = 0.848	$0.848 \times \frac{8}{3} = 2.261$	$\frac{0.848 \times 11}{3}$
H_2 = 0.152	$0.152 \times 8 = 1.216$	= 3.109 (CO_2)
	Total O_2 = 3.477	

(i) Minimum weight of air needed for combustion:

$$= \frac{3.477 \times 100}{23} = \mathbf{15.11\ kg.}\quad \textbf{(Ans.)}$$

Excess air supplied

$$= \frac{15.11 \times 15}{100} = 2.266 \text{ kg}$$

Wt. of oxygen in excess air

$$= \frac{2.266 \times 23}{100} = 0.521 \text{ kg}$$

Total air supplied for combustion

= Minimum air + Excess air

= 15.11 + 2.266 = 17.376 kg

$\therefore$ Wt. of nitrogen (N_2) in flue gases

$$= \frac{17.376 \times 77}{100} = 13.38 \text{ kg.}$$

(ii) To get *volumetric composition of the products of combustion* let us use tabular method:

Name of gas	*Weight (x)*	*Molecular weight (y)*	*Proportional volume* $(z) = \frac{(x)}{(y)}$	*Percentage volume* $= \frac{(z)}{\Sigma(z)} \times 100$
CO_2	3.109	44	0.0707	12.51 per cent **(Ans.)**
O_2	0.521	32	0.0163	2.89 per cent **(Ans.)**
N_2	13.38	28	0.4780	84.60 per cent **(Ans.)**
			Σz = 0.5650	

Example 1.2. *The percentage composition of a sample of coal is C = 90 ; H_2 = 3.5 ; O_2 = 3.0 ; N_2 = 1.0 ; S = 0.5 ; the remainder being ash. Estimate the minimum weight of air required for the combustion of 1 kg of this fuel and the composition of the dry products of combustion, by volume, if 50 per cent excess air is supplied.*

Solution.

Element, wt (kg)	*O_2 reqd. (kg)*	*Dry products (kg)*
C = 0.9	$0.9 \times \frac{8}{3} = 2.400$	$0.9 \times \frac{11}{3} = 3.30\ (CO_2)$
H_2 = 0.335	0.035 × 8 = 0.280	...
O_2 = 0.03	...	...
N_2 = 0.01	...	0.01 (N_2)
S = 0.005	$0.005 \times \frac{1}{1} = 0.005$	$0.005 \times \frac{2}{1} = 0.01\ (SO_2)$
	Total O_2 = 2.685	

Weight of O_2 to be supplied
= Wt. of O_2 reqd. – Wt. of O_2 already present in the fuel
= 2.685 – 0.03 = **2.655 kg.** **(Ans.)**

Minimum weight of air required for combustion

$$= 2.655 \times \frac{100}{23} = \mathbf{11.54\ kg.}\ \textbf{(Ans.)}$$

As 50 per cent excess air is supplied, the total wt. of air supplied

= 11.53 × 1.5 = 17.30 kg

Wt. of nitrogen (N_2) present in the air

$$= \frac{17.30 \times 77}{100} = 13.32\ \text{kg}$$

Wt. of N_2 already in the fuel = 0.01 kg

Total wt. of N_2 = 13.32 + 0.01 = 13.33 kg

Wt. of free oxygen (O_2) due to excess air

$$= \frac{(11.54 \times 0.5) \times 23}{100} = 1.327\ \text{kg}$$

The percentage composition of dry flue gases can be found out as given below :

Name of gas	*Weight (x)*	*Molecular weight (y)*	*Proportional volume* $(z) = \frac{(x)}{(y)}$	*Percentage volume* $= \frac{(z)}{\Sigma(z)} \times 100$
CO_2	3.30	44	0.0750	**12.65 per cent**
N_2	13.33	28	0.4761	**80.30 per cent**
O_2	1.326	32	0.0414	**6.98 per cent**
SO_2	0.01	64	0.000156	**0.0002 per cent**
			Σz = 0.592656	**(Ans.)**

Example 1.3. *Percentage volumetric analysis of a sample of flue gases of a coal fired boiler gave CO_2 = 10.4 ; CO = 0.2 ; O_2 = 7.8 and N_2 = 81.6 (by difference). Gravemetric percentage analysis of coal was C = 78, H_2 = 6, O_2 = 3 and incombustible = 13. Estimate :*

(i) Weight of dry flue gases per kg of fuel.

(ii) Weight of excess air per kg of fuel.

Solution.

Element, wt. (kg)	*O_2 reqd. (kg)*	*Dry products (kg)*
C = 0.78	$0.78 \times \frac{8}{3} = 2.08$	$0.78 \times \frac{11}{3} = 2.86\ (CO_2)$
H_2 = 0.06	0.06 × 8 = 0.48	
O_2 = 0.03	Total O_2 = 2.56	

Minimum wt. of air needed for combustion

$$= (2.56 - 0.03) \times \frac{100}{23} = 11\ \text{kg.}$$

(i) Weight of dry flue gases per kg of fuel :

To determine the wt. of flue gases per kg of fuel let us use tabular method to convert volumetric analysis to analysis by weight.

Name of gas	*Vol. per m^3 of flue gas (x)*	*Molecular weight weight (y)*	*Relative weight* $z = x \times y$	*Weight per kg of flue gas* $= \frac{z}{\Sigma z}$
CO_2	0.104	44	4.576	0.1525
CO	0.002	28	0.056	0.0019
N_2	0.816	28	22.848	0.7616
O_2	0.078	32	2.496	0.0832
			Σz = 29.976 (say 30)	

Amount of carbon present per kg of gases
= Amount of carbon in 0.1525 kg of CO_2
+ Amount of carbon present in 0.0019 kg of CO

$$= \frac{3}{11} \times 0.1525 + \frac{3}{7} \times 0.0019 = 0.0416 + 0.0008$$

= 0.0424 kg.

Also carbon in the fuel = 0.78 kg.

∴ *Weight of dry flue gas per kg of fuel*

$$= \frac{\text{Weight of carbon in 1 kg of fuel}}{\text{Weight of carbon in 1 kg of flue gas}}$$

$$= \frac{0.78}{0.0424} = \mathbf{18.4\ kg.} \quad \textbf{(Ans.)}$$

(*ii*) *Weight of excess air per kg of fuel :*

Weight of excess oxygen per kg of flue gas

$$= 0.0832 - \frac{4}{7} \times 0.0019$$

$$\left[\begin{array}{c} 2CO + O_2 = 2CO_2 \\ 56 + 32 = 88 \\ 1\,kg + \frac{4}{7}\,kg = \frac{11}{7}\,kg \end{array}\right]$$

= 0.0832 – 0.0011

(allowing for unburnt carbon monoxide)

= 0.0821 kg

Weight of excess O_2 per kg of fuel

= 18.4 × 0.0821 = 1.51 kg

Weight of excess air per kg of fuel

$$= \frac{1.51 \times 100}{23} = \mathbf{6.56\ kg.} \quad \textbf{(Ans.)}$$

Example 1.4. *A petrol sample was found to have 86 per cent carbon and 14 per cent hydrogen by weight. When used in an engine the air supply is 90 per cent of that theoretically required for complete combustion. Assuming that all the hydrogen is burnt and that the carbon burns to carbon monoxide and carbon dioxide so that there is no free carbon left, calculate the percentage analysis of dry exhaust gases by volume.*

Solution.

Element, wt. (kg)	*O_2 needed (kg)*
C = 0.86	0.86 × 8/3 = 2.29
H_2 = 0.14	0.14 × 8 = 1.12
	Total O_2 needed = 3.41

Minimum quantity of air for complete combustion

$$= \frac{3.41 \times 100}{23} = 14.83 \text{ kg/kg of fuel.}$$

Amount of less air supplied

$$= \frac{14.83 \times 10}{100} = 1.483 \text{ kg/kg of fuel.}$$

Amount of air saved by burning carbon to carbon monoxide instead of carbon dioxide

$$= \text{Oxygen saved} \times \frac{100}{23}$$

$$= \left[\frac{8}{3}(CO_2) - \frac{4}{3}(CO)\right] \times \frac{100}{23}$$

= 5.8 kg/kg of carbon.

Hence $\frac{1.483}{5.8}$ = 0.256 kg of carbon burns to carbon monoxide and as such 0.86 – 0.256 = 0.604 kg of carbon burns to carbon dioxide.

∴ Carbon dioxide (CO_2) formed

= 0.604 × 11/3 = 2.215 kg

Carbon monoxide (CO) formed

= 0.256 × 7/3 = 0.597 kg

Nitrogen in the air supplied

= 14.83 × 77/100 × 0.9 = 10.3 kg.

Volumetric analysis of dry exhaust gases

Dry products	*Weight (kg) (x)*	*Molecular weight (y)*	*Proportional volume* $(z) = \frac{(x)}{(y)}$	*Percentage volume* $= \frac{(z)}{(\Sigma z)} \times 100$
CO_2	2.215	44	$\frac{2.215}{44} = 0.050$	$\frac{0.050}{0.439} \times 100 = \mathbf{11.39\%}$
CO	0.597	28	$\frac{0.597}{28} = 0.201$	$\frac{0.021}{0.441} \times 100 = \mathbf{4.78\%}$
N_2	10.3	28	$\frac{10.3}{28} = 0.368$	$\frac{0.368}{0.441} \times 1 = \mathbf{83.82\%}$
			$\Sigma z = 0.439$	**Ans.**

Example 1.5. *A boiler in a power station was fired with coal having an ultimate composition of C = 84%, H_2 = 4.5%, O_2 = 4.0% and the rest non-combustibles and calorific value of 33900 kJ/kg. The coal was burnt with 85% excess air and the mean temperature of the flue gases leaving the boiler was found to be 315.5°C when the ambient temperature in the boiler bouse was 32.22°C. Assuming air to be consisting of 23% by weight of O_2 and 77% by weight of N_2 and specific heat of flue gases as 1.005 kJ/kg K, determine :*

(i) kg air actually supplied per kg coal burnt.

(ii) kg flue gases per kg fuel burnt.

(iii) The percentage of the energy of the coal that is carried away by flue gases per kg of coal burnt.

Solution.

Element, wt. (kg)	*O_2 required (kg)*	*Wt. of products (kg)*
C = 0.84	$0.84 \times \frac{8}{3} = 2.24$	$0.84 \times \frac{11}{3} = 3.08\ (CO_2)$
H_2 = 0.045	$0.045 \times 8 = 0.36$	
	Total O_2 = 2.60	

Weight of O_2 already present in the fuel
= 0.04

Weight of O_2 needed for combustion
= 2.60 – 0.04 = 2.56 kg

Air required for combustion
= 2.56 × 100/23 = 11.13 kg.

(i) Actual quantity of air supplied:
= 1.85 × 11.13 = **20.6 kg.** **(Ans.)**

Weight of N_2 in the air required for combustion
= 11.13 × 0.77 = 8.57 kg.

Weight of N_2 in excess air
= 11.13 × 0.77 × 0.85 = 7.285 kg

∴ Total N_2 = 8.57 + 7.285 = 15.85 kg

O_2 in excess air = 11.13 × 0.85 × 0.23 = 2.18 kg.

(ii) Total wt. of flue gases:
= Wt. of CO_2 + Wt. of N_2 + Wt. of O_2 in excess air
= 3.08 + 15.85 + 2.18
= **21.11 kg.** **(Ans.)**

Heat taken away by flue gases
= Weight of flue gases × specific heat × rise of temperature
= 21.11 × 1.005 × (315.5 – 32.22)
= 6010 kJ

(iii) Percentage energy of coal taken away by flue gases per kg:

$$= \frac{6010}{33900} \times 100 = \mathbf{17.73\%}.$$ **(Ans.)**

Example 1.6. *The following is the ultimate analysis of a sample of petrol by weight :*

Carbon = 85% ; Hydrogen = 15%.

Calculate the ratio of air to petrol consumption by weight if the volumetric analysis of the dry exhaust gas is :

CO_2 = 11.5% ; CO = 1.2%, O_2 = 0.9% ; N_2 = 86%.

Also find percentage excess air.

Solution.

Name of gases	*Volume per m^3 of flue gas (x)*	*Molecular weight (y)*	*Relative weight $z = x \times y$*	*Weight per kg of flue gas = $\frac{z}{\Sigma z}$*
CO_2	0.115	44	5.06	0.1700
CO	0.012	28	0.336	0.0113
O_2	0.009	32	0.288	0.0096
N_2	0.86	28	24.08	0.8091
			Σz = 29.76	

∴ Weight of carbon per kg of flue gas
= Weight of carbon in 0.17 kg of CO_2 + weight of carbon in 0.0113 kg of CO

$$= \frac{3}{11} \times 0.17 + \frac{3}{7} \times 0.0113 = 0.0512 \text{ kg}$$

∴ Weight of dry flue gas per kg of fuel

$$= \frac{0.85}{0.0512} = 16.6 \text{ kg}$$

Vapour of combustion = 9 × 0.15 = 1.35 kg

Total weight of gas = 16.6 + 1.35
= 17.95 kg per kg of fuel.

∴ Air supplied = (17.95 – 1)
= 16.95 kg/kg of fuel

∴ *Ratio of air to petrol* = **16.95 : 1.** **(Ans.)**

Stoichiometric air

$$= \left[\left(0.85 \times \frac{8}{3}\right) + (0.15 \times 8)\right] \times \frac{100}{23}$$

= 15.07 kg per kg of fuel

$\therefore$ Excess air $= 16.95 - 15.07 = 1.88$ kg

$\therefore$ *Percentage excess air* $= \dfrac{1.88}{15.07} \times 100$

$= \mathbf{12.47\%}$. **(Ans.)**

Example 1.7. *A sample of fuel has the following percentage composition :*

Carbon = 86%, Hydrogen = 8%.

Sulphur = 3%, Oxygen = 2%, Ash = 1%.

For an air-fuel ratio of 12 : 1, calculate :

(i) Mixture strength as a percentage rich or weak.

(ii) Volumetric analysis of the dry products of combustion.

Solution.

Element, wt. (kg)	*O_2 reqd. (kg)*
C = 0.86	$0.86 \times \frac{8}{3} = 2.29$
H_2 = 0.08	$0.08 \times 8 = 0.64$
S = 0.03	$0.03 \times \frac{1}{1} = 0.03$
O_2 = 0.02	
	Total $O_2 = \underline{2.96}$

Weight of oxygen to be supplied per kg of fuel

$= 2.96 - 0.02 = 2.94$ kg

Weight of minimum air required for complete combustion

$= \dfrac{2.94 \times 100}{23} = 12.78$ kg

Hence "*correct*" fuel air ratio $= \dfrac{1}{12.78} : 1.$

But actual ratio is $\dfrac{1}{12} : 1.$

(i) $\therefore$ *Mixture strength* $= \dfrac{12.78}{12} \times 100$

$= 106.5\%$.

This shows that mixture is **6.5% rich.** **(Ans.)**

Deficient amount of air $= 12.78 - 12 = 0.78$ kg

Amount of air saved by burning 1 kg of C to CO instead of CO_2

$= \text{Oxygen saved} \times \dfrac{100}{23}$

$= \left[\dfrac{8}{3}(CO_2) - \dfrac{4}{3}(CO)\right] \times \dfrac{100}{23} = 5.8$ kg

Hence $\dfrac{0.78}{5.8} = 0.134$ kg of carbon burns to CO and as such $0.86 - 0.134 = 0.726$ kg of carbon burns to CO_2.

$\therefore$ CO formed $= 0.134 \times \dfrac{7}{3} = 0.313$ kg

CO_2 formed $= 0.726 \times \dfrac{11}{3} = 2.662$ kg

N_2 supplied $= 12 \times 0.77 = 9.24$ kg

SO_2 formed $= 0.03 \times 2 = 0.06$ kg.

(ii) The percentage composition of dry flue gases is given as below :

Dry products	*Weight (kg) x*	*Molecular weight y*	*Proportional volume* $z = \frac{x}{y}$	*Percentage volume* $= \frac{z}{\Sigma z} \times 100$
CO	0.313	28	0.0112	**2.78 per cent. (Ans.)**
CO_2	2.662	44	0.0605	**15.03 per cent. (Ans.)**
N_2	9.24	28	0.3300	**81.97 per cent. (Ans.)**
SO_2	0.06	64	0.0009	**0.22 per cent. (Ans.)**
			$\Sigma z = 0.4026$	

Example 1.8. *Find an expression for the weight of air supplied per kg of fuel when carbon content of the fuel and the volumetric analysis of the flue gas is known.*

Show that carbon burnt to CO per kg of fuel is $\dfrac{(CO)(C)}{CO + CO_2}$ *where CO and CO_2 represent percentage of carbon monoxide and carbon dioxide in dry flue gas by volume and C represents percentage by weight of carbon that is actually burnt.*

Solution. Let C = Percentage of carbon, by weight, in the fuel burnt,

CO_2 = Percentage by volume of carbon dioxide in the dry flue gas,

CO = Percentage by volume of carbon monoxide in the dry flue gas, and

N_2 = Percentage by volume of nitrogen in the dry flue gas.

Consider 100 m^3 of the gas.

The actual weight of CO_2

$= CO_2 \times a \times b \times 44$ in 100 m^3 of gas.

The actual weight of CO

$= CO \times a \times b \times 28$ in 100 m^3 of gas.

The actual weight of N_2

$= N_2 \times a \times b \times 28$ in 100 m^3 of gas.

The molecular weight of CO

$= 28$.

The molecular weight of N_2

$= 28$.

Total mass of carbon per 100 m^3 of flue gas

$$= [a \times b \times 44 \times CO_2] \times \frac{12}{44} + [a \times b \times 28 \times CO] \times \frac{12}{28}$$

The reactions producing CO_2 and CO are

$$C + O_2 = CO_2$$
$$12 + 32 = 44$$

$\therefore$ C per kg of $CO_2 = \frac{12}{44}$

Also, $2C + O_2 = 2CO$

$24 + 32 = 56$

$\therefore$ C per kg of $CO = \frac{12}{28}$

All the carbon available in carbon dioxide and carbon monoxide comes from carbon present in the fuel. Also it can be safely assumed that all nitrogen comes from air (this analysis being not applicable to the fuels containing nitrogen).

Total carbon in the flue gas = $a \times b \times 12(CO_2 + CO)$ per kg of carbon in the flue gas

$$= \frac{a \times b \times 28 \times N_2}{a \times b \times 12(CO + CO_2)} \quad ...(i)$$

For every kg of fuel supplied for combustion $\frac{C}{100}$ kg of carbon pass out of the flue, whence the weight of N_2 per kg of fuel is

$$\frac{28N_2}{12\,(CO + CO_2)} \times \frac{C}{100} \text{ kg.}$$

If all this nitrogen has come from the atmosphere, then air supplied per kg of fuel

$$= \frac{28 \times N_2 \times C \times 100}{12(CO + CO_2) \times 100 \times 77}$$

(since air contains 77% nitrogen by weight)

$\therefore$ *Air per kg of fuel*

$$= \frac{N_2 \times C}{\frac{100 \times 77 \times 12}{28 \times 100}(CO + CO_2)}$$

$$= \frac{\mathbf{N_2 \times C}}{\mathbf{33(CO + CO_2)}}. \quad \textbf{(Ans.)}$$

It has been shown above that the total carbon of the flue gas is given by $a \times b \times 12\ (CO_2 + CO)$ and that in CO by $a \times b \times 12$ CO, whence the proportion of carbon burnt to CO is given by

$$\frac{a \times b \times 12 \times CO}{a \times b \times 12(CO + CO_2)} = \frac{CO}{CO + CO_2}$$

and if C is the proportion of carbon actually burnt per kg of fuel, then *carbon burnt to CO per kg of fuel*

$$= \frac{\mathbf{(CO)(C)}}{\mathbf{CO + CO_2}}. \quad \textbf{(Ans.)}$$

Example 1.9. *The following results were obtained in a trial on a boiler fitted with economiser :*

	CO_2	CO	O_2	N_2
Analysis of gas entering the economiser	8.3	0	11.4	80.3
Analysis of gas leaving the economiser	7.9	0	11.5	80.6

(i) Determine the air leakage into the economiser if the carbon content of the fuel is 80%.

(ii) Determine the reduction in temperature of the gas due to air leakage if atmospheric temperature is 20°C and flue gas temperature is 410°C. Ash collected from ash pan is 15% by weight of the fuel fired.

Take : c_p for air = 1.005 kJ/kg K and c_p for flue gas = 1.05 kJ/kg K.

Solution. (*i*) Air supplied $= \frac{N_2 \times C}{33(CO_2 + CO)}$

Air supplied on the basis of conditions at entry to the economiser

$$= \frac{80.3 \times 80}{33(8.3 + 0)} = 23.45 \text{ kg}$$

Air supplied on the basis of conditions at exit

$$= \frac{80.6 \times 80}{33(7.9 + 0)} = 24.73 \text{ kg}$$

$\therefore$ *Air leakage* $= 24.73 - 23.45$

$= \mathbf{1.28}$ **kg of air per kg of fuel.** **(Ans.)**

(*ii*) For each kg of fuel burnt, the ash collected is 15% *i.e.,* 0.15 kg.

$\therefore$ Weight of fuel passing up the chimney

$= 1 - 0.15 = 0.85$ kg.

$\therefore$ Total weight of products

= Weight of air supplied per kg of fuel + Weight of fuel passing through chimney per kg of fuel

$= 23.45 + 0.85 = 24.3$ kg.

Heat in flue gases per kg of coal

= Weight of flue gases × specific heat × temperature rise above 0°C

$= 24.3 \times 1.05 \times (410 - 0) = 10461$ kJ

Heat in leakage air

= Weight of leakage air × specific heat × temperature rise of air above 0°C

$= 1.28 \times 1.005 \times (20 - 0) = 25.73$ kJ

We can still consider, in the mixture, the gas and the air as separate and having their own specific heats, but sharing a common temperature t.

For heat balance :

$$(1.005 \times 1.28 + 24.3 \times 1.05)\, t = 10461 + 25.73$$
$$26.8t = 10486.73$$
$$\therefore \quad t = 391.3°C.$$

$\therefore$ *Fall in temperature as a result of the air leakage into the economiser*

$= 410 - 391.3 =$ **18.7°C.** **(Ans.)**

Example 1.10. *The ultimate analysis of a sample of coal gave the following analysis by weight C = 65%, H_2 = 6%, S = 1.5%, O_2 = 18%. Find the calorific value of this coal by using Dulong's formula.*

Solution. Dulong's formula

$$\text{H.C.V.} = \frac{1}{100}\left[33800\,\text{C} + 144000\left(\text{H} - \frac{0}{8}\right) + 9270\,\text{S}\right] \text{kJ}$$

$$= \frac{1}{100}\left[33800 \times 65 + 144000\left(6 - \frac{18}{8}\right) + 9270 \times 1.5\right]$$

$$= \frac{1}{100}\,[2197000 + 540000 + 13905]$$

$$= \frac{1}{100}\,(2750905) = 27509 \text{ kJ/kg.}$$

Also the combustion of 1 kg of coal produces $0.06 \times 9 = 0.54$ kg of steam.

$$\text{L.C.V.} = (\text{H.C.V.} - 2465\, m_w)$$
$$= (27509 - 2465 \times 0.54)$$
$$= (27509 - 1331) =$$ **26178 kJ/kg.** **(Ans.)**

Example 1.11. *Find the gross thermal efficiency of boiler in which the quantity of steam raised per hour was 2250 kg and the coal consumption was 225 kg per hour.*

From the analysis by weight the dried fuel was found to contain 87% carbon and 4% hydrogen. The feed water temperature was 61°C, the boiler gauge pressure 5 bar, and dryness of steam 0.95. The calorific value of carbon is 33700 kJ/kg and that of hydrogen, 144600 kJ/kg.

Solution. Boiler gauge pressure = 5 bar

$\therefore$ Boiler absolute pressure $= 5 + 1 = 6$ bar

Dryness fraction of steam, $x = 0.95$

Feed water temperature $= 61°C$

Quantity of steam produced $= 2250$ kg/h

Coal consumption $= 225$ kg/h

From steam tables, corresponding to 6 bar

$h_f = 670.4$ kJ/kg

$h_{fg} = 2085$ kJ/kg

Heat of 1 kg of the steam,

$$H = h_f + x h_{fg} = 670.4 + 0.95 \times 2085$$
$$= 670.4 + 1980.75$$
$$= 2651.15 \text{ kJ/kg}$$

Heat supplied to steam per kg

= 2651.15 – heat contained in 1 kg of feed water

$= 2651.15 - 1 \times 4.18 \times (61 - 0)$

$= 2396.2$ kJ/kg

Total heat supplied to steam per hour

$= 2396.2 \times 2250$ kJ

Calorific value of coal

$= 33700\,\text{C} + 144600\,\text{H}$

$= 33700 \times 0.87 + 144600 \times 0.04$

$= 29319 + 5784 = 35103$ kJ/kg

Total heat input

$= 35103 \times 225$ kJ

$$\therefore \quad \eta_{boiler} = \frac{2396.2 \times 2250}{35103 \times 225} =$$ **68.26%.** **(Ans.)**

Example 1.12. *A boiler generates 360 kg of steam per hour at a pressure of 8 bar absolute. The dryness fraction of the steam may be taken 0.95. Coal used has the following composition per kg :*

Carbon	*= 0.70*
Hydrogen	*= 0.05*
Oxygen	*= 0.10*
Sulphur	*= 0.02*
Ash	*= 0.13*

If the hourly rate of burning is 60 kg and the feed water temperature is 25°C, calculate the boiler efficiency.

Solution. From steam tables, corresponding to 8 bar pressure,

$h_f = 720.9$ kJ/kg

$h_{fg} = 2046.5$ kJ/kg

Quantity of heat supplied per kg of steam

$= (h_f + x h_{fg}) - 1 \times 4.18 \times (25 - 0)$

$= 720.9 + 0.95 \times 2046.5 - 4.18 \times 25$

$= 720.9 + 1944.2 - 104.5$

$= 2560.6$ kJ/kg

Heat supplied per hour

$= 2560.6 \times 360$ kJ

Calorific value of coal

$= 33800\,\text{C} + 144000\,(\text{H} - 0/8) + 9270\,\text{S}$

$$= 33800 \times 0.7 + 144000\left(0.50 - \frac{0.1}{8}\right) + 9270 \times 0.02$$

$= 23660 + 5400 + 185.4 = 29245.4$

Total heat input

$= 60 \times 29245.4$ kJ

$$\therefore \quad \eta_{boiler} = \frac{2560.6 \times 360}{60 \times 29245.4} \times 100$$
$$=$$ **52.53%.** **(Ans.)**

Example 1.13. *A water gas at 21°C and 1.033 bar is burned with dry air supplied at 21°C and 1.033 bar. The fuel gas composition is CO_2 = 6%, N_2 = 5.5%, H_2 = 48%, O_2 = 0.5%, CH_4 = 2%, CO = 38%. The orsat analysis of the flue gas showed CO_2 = 15.5%, O_2 = 4.76% and CO = 0.2%. Find the percentage of excess air supplied for combustion and the volume of the flue gas at 232°C and 1.03 bar formed per m^3 of the fuel.*

Solution. Let x mole be changing from CO to CO_2.

Reactants mole / mole of fuel	*Reaction*	*O_2 required*	*Products*			
			CO_2	*CO*	*O_2*	*N_2*
$CO_2 = 0.06$		–	0.06			
$N_2 = 0.055$		–				0.055
$H_2 = 0.48$	$H_2 + \frac{1}{2}O_2 = H_2O$	0.24				
$O_2 = 0.005$		– 0.005				With O_2 =
$CH_4 = 0.02$	$CH_4 + 2O_2 = CO_2$					$O_2 \times \frac{0.79}{0.21}$
	$+ 2H_2O$	0.04	0.02			
$CO = 0.38$	$CO + \frac{1}{2}O_2 = CO_2$	$x/2$	x	$0.38–x$		
	Total	$0.275 + x/2$	$0.08 + x$	$0.38 - x$	$O_2 - 0.275 - x/2$	$3.762\ O_2 + 0.055$

Let oxygen supplied be O_2 mol.

$\therefore$ Oxygen in exhaust = $(O_2 - 0.275 - x/2)$ mol.

But flue gas analysis is :

$CO_2 = 0.155$, CO = 0.002, $O_2 = 0.0476$.

Comparing the values from table and flue gas analysis, we have:

$$\frac{\frac{1}{0.08 + x}}{\frac{1}{0.38 - x}} = \frac{\frac{1}{0.155}}{\frac{1}{0.002}}$$

$\therefore \quad x = 0.374$

Similarly, $$\frac{\frac{1}{0.08 + x}}{\frac{1}{O_2 - 0.275 - x/2}} = \frac{\frac{1}{0.155}}{\frac{1}{0.0476}}$$

$\therefore \quad O_2 = 0.6014$

Products per mole of fuel, $CO_2 = 0.454$,

CO = 0.006, $O_2 = 0.1394$, $N_2 = 2.3174$

Total products 2.9168 mol per mol of fuel.

Unburnt CO = $0.38 - x = 0.38 - 0.374 = 0.006$ mol

O_2 required to burn unburnt CO to CO_2 = 0.03 mol

$\therefore$ Excess oxygen in exhaust

$= 0.1394 - 0.003 = 0.1364$

Theoretical oxygen needed

$$= 0.275 + \frac{0.374}{2} = 0.462$$

Excess air = Excess oxygen

$$= \frac{0.1364}{0.462} = \mathbf{0.2952\ or\ 29.52\%.}\ \textbf{(Ans.)}$$

The products are at 21°C and 76 cm of Hg, changing this volume to 232°C and 1.03 bar

$$= \frac{1.033 \times 2.9168}{(21 + 273)} = \frac{1.03 \times V}{(232 + 273)}$$

$\therefore$ **Volume, V = 5.025 mol.** **(Ans.)**

HIGHLIGHTS

1. Energy appears in many forms, but has one thing in common—energy is possessed of the ability to produce a dynamic, vital effect.
2. Sources of energy are :
   (*i*) Fuels (*ii*) Energy stored in water
   (*iii*) Nuclear energy (*iv*) Wind power
   (*v*) Solar energy (*vi*) Tidal power
   (*vii*) Geothermal energy (*viii*) Thermoelectric power.
3. A chemical fuel is a substance which releases heat energy on combustion. The principal element of each fuel are carbon and hydrogen. Though sulphur is a combustible element too but its presence in the fuel is considered to be undesirable.
4. The principal types of power plants are :
   (*i*) Steam plants using coal, oil or nuclear fission
   (*ii*) Internal combustion engine plants

(*iii*) Gas turbine plants
(*iv*) Hydro-electric plants.

5. The weight of excess air supplied can be determined from the weight of oxygen which is left unused.

6. The weight of carbon per kg of fuel = $\frac{3}{11}$ CO_2 + $\frac{3}{7}$ CO where CO_2 and CO are the quantities of carbon dioxide and carbon monoxide present in 1 kg of flue or exhaust gas.

The weight of flue gas/kg of fuel burnt

$$= \frac{\text{Weight of carbon in one kg of fuel}}{\text{Weight of carbon in one kg of flue gas}}.$$

THEORETICAL QUESTIONS

1. Enumerate sources of energy.
2. What is a chemical fuel ? How does it differ from a nuclear fuel ?
3. How are chemical fuels classified ?
4. Explain briefly the following solid fuels :
   Lignites and brown coals, bituminous coal and coke.
5. List the advantages of liquid fuels.
6. Describe the following gaseous fuels :
   Coal gas, Coke-oven gas, Blast furnace gas and Producer gas.
7. What are the advantages of gaseous fuels ?
8. State the factors which go in favour of nuclear energy.
9. Write short notes on :
   Tidal power, wind power and thermoelectric power.
10. Name the principal types of power plants.
11. Why do we feel the necessity of using excess air for burning fuels ?
12. How can the following be calculated ?
    (*i*) Weight of carbon in flue gases.
    (*ii*) Weight of flue gas per kg of fuel burnt.

UNSOLVED EXAMPLES

1. A fuel has the following composition by weight : Carbon = 86% ; hydrogen = 11.75% and oxygen = 2.25%. Calculate the theoretical air supply per kg of fuel, and the weight of products of combustion per kg of fuel.
   [**Ans.** 13.98 kg ; 4.21 kg]

2. The volumetric analysis of a fuel gas is : CO_2 = 14% ; CO = 1% ; O_2 = 5% and N_2 = 80%. Calculate the fuel gas composition by weight.
   [**Ans.** 20.24% ; 0.93% ; 5.25% ; 73.58%]

3. The ultimate analysis of a dry coal burnt in a boiler gauge C = 84% ; H_2 = 9% and incombustibles 7% by weight. Determine the weight of dry flue gases per kg of coal burnt, if volumetric combustion of the flue gas is : CO_2 = 8.75%, CO = 2.25% ; O_2 = 8% and N_2 = 81%. [**Ans.** 18.92 kg]

4. During a trial in a boiler, the dry flue gas analysis by volume was obtained as CO_2 = 13%, CO = 0.3%, O_2 = 6%, N_2 = 80.7%. The coal analysis by weight was reported as C = 62.4%, H_2 = 4.2%, O_2 = 4.5%, moisture = 15% and ash = 13.9%. Estimate :
   (*a*) Theoretical air required to burn 1 kg of coal.
   (*b*) Weight of air actually supplied per kg of coal, and
   (*c*) The amount of excess air supplied per kg of coal burnt.
   [**Ans.** (*a*) 8.5 kg ; (*b*) 11.5 kg ; (*c*) 3 kg]

5. A steam boiler uses pulverised coal in the furnace. The ultimate analysis of coal (by weight) as received is : C = 78% ; H_2 = 3% ; O_2 = 3% ; ash = 10% and moisture = 5%. Excess air supplied is 30%. Calculate the weight of air to be supplied and weight of gaseous product formed per kg of coal burnt.
   [**Ans.** 13 kg ; CO_2 = 2.86 kg ; H_2 = 0.27 kg ; excess O_2 = 0.69 kg and N_2 = 9.81 kg per kg of coal]

6. The percentage composition by mass of a crude oil is given as follows : C = 90%, H_2 = 3.3%, O_2 = 3%, N_2 = 0.8% ; S = 0.9% and remaining incombustible. If 50% excess air is supplied, find the percentages of dry exhaust gases found by volume.
   [**Ans.** CO_2 = 12.7% ; SO_2 = 0.05% ; O_2 = 7%, N_2 = 80.25%]

7. In a boiler trial, the analysis of the coal used is as follows : C = 20%, H_2 = 4.5%, O_2 = 7.5%, remainder-incombustible matter.
   The dry flue gas has the following composition by volume : CO_2 = 8.5%, CO = 1.2%, N_2 = 80.3%, O_2 = 10% determine :
   (*i*) Minimum weight of air required per kg of coal.
   (*ii*) Percentage excess air. [**Ans.** (*i*) 3.56 kg, (*ii*) 63.2%]

8. The ultimate analysis of a sample of petrol by weight is : Carbon = 0.835 ; hydrogen = 0.165. Calculate the ratio of air to petrol consumption by weight, if the volumetric analysis of the dry exhaust gas is : Carbon dioxide = 12.1 ; carbon monoxide = 1.1 ; oxygen = 0.8 ; nitrogen = 85.4%. Also find the percentage excess air.
   [**Ans.** 16.265 : 1 ; 5.6%]

9. The percentage composition of a sample of fuel was found to be C = 85%, H_2 = 9%, S = 3%, O_2 = 1.5%, Ash = 1.5%. For an air-fuel ratio of 12 : 1, calculate (*i*) the mixture strength as a percentage rich or weak, (*ii*) the volumetric analysis of the dry products of combustion.
   [**Ans.** 8.83% rich ; CO_2 = 12.16%, CO = 2.54%, N_2 = 84.83%, SO_2 = 0.47%]

10. The ultimate analysis of fuel used in a boiler is given as follows : C = 87%, H_2 = 4%, O_2 = 3.5% and the remainder is ash. The volume of CO_2 in the exhaust gases noted by CO_2 recorder is 12.5%.
    Find the percentage excess air supplied per kg of fuel.
    [**Ans.** 51.95%]

11. The ultimate analysis of coal used in a boiler is given as follows :

$C = 82\%$, $H_2 = 5.4\%$, $O_2 = 7\%$, $N_2 = 0.5\%$, $S = 0.6\%$, moisture = 1% and the remainder is ash.

The volumetric analysis of the exhaust gases determined by Orsat apparatus is given as follows :

$CO_2 = 9.6\%$, $CO = 1.2\%$, $O_2 = 7.8\%$ and $N_2 = 81.4\%$.

From fundamental determine the percentage of excess air supplied to the furnace of the boiler. [**Ans.** 57%]

12. The percentage composition of a sample of crude oil was found by analysis to be :

$C = 90\%$, $H_2 = 3.3\%$, $O_2 = 3\%$, $N_2 = 0.8\%$, $S = 0.9\%$,

Ash = 2%

If 50% excess air is supplied, find the percentage composition of the dry flue gases by volume.

[**Ans.** $CO_2 = 12.69\%$, $SO_2 = 0.05\%$, $O_2 = 7\%$, $N_2 = 80.26\%$]

13. The volumetric analysis of exhaust gases of an oil engine is : $CO_2 = 15\%$, $CO = 2.2\%$, $O_2 = 1.6\%$, Nitrogen = 81.2%. Convert this analysis into analysis by weight.

[**Ans.** $CO_2 = 21.6\%$, $CO = 2.2\%$, $O_2 = 1.7\%$, $N_2 = 74.5\%$]

14. The dry exhaust gas from an oil engine had the following percentage composition by volume :

$CO_2 = 8.85\%$, $CO = 1.2\%$, $O_2 = 6.8\%$, $N_2 = 83.15\%$.

The fuel had the percentage composition by weight as follows : $C = 84\%$, $H_2 = 14\%$, $O_2 = 2\%$.

Determine the weight of air supplied per kg of fuel burnt.

[**Ans.** 21.08 kg]

15. In a boiler trial, the fuel used has the following analysis by weight : $C = 85\%$, $H_2 = 4\%$ and ash = 11%. If the flue gas analysis gave $CO_2 = 12\%$, $O_2 = 8\%$ and nitrogen = 80% by volume, find per kg of dry fuel :

(*i*) Weight of necessary air.

(*ii*) Weight of excess air. [**Ans.** (*i*) 11.25 kg, (*ii*) 6.57 kg]

Power Plant Cycles

2

2.1. Introduction. 2.2. Classification of power plant cycles. 2.3. Carnot cycle. 2.4. Rankine cycle. 2.5. Modified rankine cycle. 2.6. Reheat cycle. 2.7. Regenerative cycle. 2.8. Binary vapour cycle. 2.9. Otto cycle. 2.10. Diesel cycle. 2.11. Dual combustion cycle 2.12. Gas turbine cycles—*Highlights—Theoretical Questions—Unsolved Examples.*

2.1. INTRODUCTION

A *thermal power station* works on the *basic principle that heat liberated by burning fuel is converted into mechanical work by means of a suitable working fluid. The mechanical work is converted into electric energy by the help of generators*.

A working fluid goes through a repetitive cyclic change and this cyclic change involving heat and work is known as the *thermodynamic cycle.* Thus a *thermodynamic cycle is a series of operations, involving a heat source, a heat receiver, a machine or utilizer between the source and the receiver and a working substance.*

In a *steam power station*, heat is released by burning fuel, this heat is taken up by water which works as the working fuel. Water is converted into steam as it receives heat in a boiler. The steam then expands in a turbine producing mechanical work which is then converted into electrical energy through a generator. The exhaust steam from the turbine is then condensed in a condenser and condensate thereafter pumped to the boiler where it again receives heat and the cycle is repeated.

2.2. CLASSIFICATION OF POWER PLANT CYCLES

Thermal power plants, in general, may work on vapour cycles or gas power cycles.

Vapour power cycles—Classification :

1. Rankine cycle
2. Reheat cycle
3. Regenerative cycle
4. Binary vapour cycle.

Gas power cycles—Classification :

1. Otto cycle
2. Diesel cycle
3. Dual combustion cycle
4. Gas turbine cycles
   (*i*) Open cycle (*ii*) Closed cycle.

2.3. CARNOT CYCLE

Fig. 2.1 shows a Carnot cycle on T-s and p-V diagrams. It consists of (*i*) two constant pressure operations (4–1) and (2–3) and (*ii*) two frictionless adiabatics (1–2) and (3–4). These operations are discussed below :

1. **Operation (4–1).** 1 kg of boiling water at temperature T_1 is heated to form wet steam of dryness fraction x_1. Thus heat is absorbed at constant temperature T_1 and pressure p_1 during this operation.

2. **Operation (1–2).** During this operation steam is expanded isentropically to temperature T_2 and pressure p_2. The point '2' represents the condition of steam after expansion.

3. **Operation (2–3).** During this operation heat is rejected at constant pressure p_2 and temperature T_2. As the steam is exhausted it becomes wetter and cooled from 2 to 3.

4. **Operation (3–4).** In this operation the wet steam at '3' is compressed isentropically till the steam regains its original state of temperature T_1 and pressure p_1. Thus cycle is completed.

Refer to T-s diagram :

Heat supplied at constant temperature T_1 [operation (4–1)] = Area 4–1-b-a = $T_1 (s_1 - s_4)$ or $T_1 (s_2 - s_3)$.

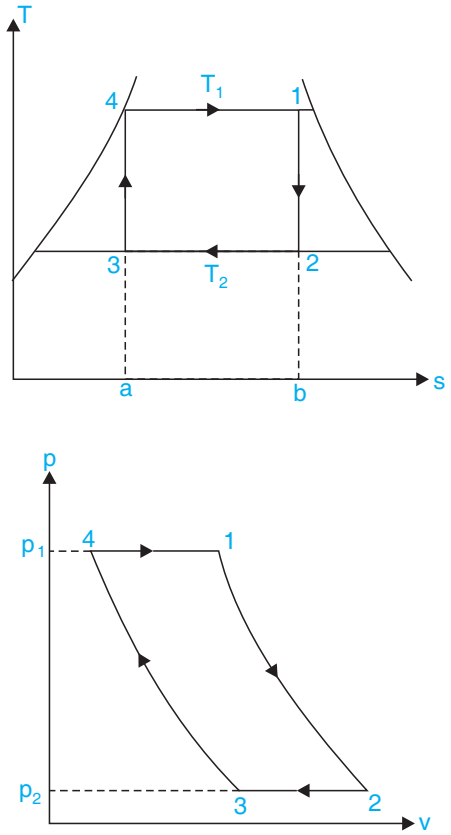


Fig. 2.1. Carnot cycle on T-s and p-v diagrams.

Heat rejected at constant temperature T_2 (operation 2–3) = Area 2–3-a-b = $T_2\,(s_2 - s_3)$.

Since there is no exchange of heat during isentropic operations (1–2) and (3–4), therefore,

Net work done = Heat supplied – heat rejected

$$= T_1\,(s_2 - s_3) - T_2\,(s_2 - s_3)$$

$$= (T_1 - T_2)\,(s_2 - s_3).$$

$$\text{Carnot cycle } \eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{(T_1 - T_2)\,(s_2 - s_3)}{T_1\,(s_2 - s_3)} = \frac{T_1 - T_2}{T_1} \quad \ldots(2.1)$$

Limitations of Carnot cycle:

Though Carnot cycle is simple (thermodynamically) and has the highest thermal efficiency for given values of T_1 and T_2, yet it is extremely difficult to operate in practice because of the following *reasons* :

1. It is difficult to compress a wet vapour isentropically to the saturated state as required by the process 3–4.

2. It is difficult to control the quality of the condensate coming out of the condenser so that the state '3' is exactly obtained.

3. The efficiency of the Carnot cycle is greatly affected by the temperature T_1 at which heat is transferred to the working fluid. Since the critical temperature for steam is only 374°C, therefore, if the cycle is to be operated in the *wet region*, the maximum possible temperature is severely limited.

4. The cycle is still more difficult to operate in practice with superheated steam due to the necessity of supplying the superheat at constant temperature instead of constant pressure (as it is customary).

In a practical cycle, limits of pressure and volume are far more easily realised than limits of temperature so that at present no practical engine operates on the Carnot cycle, although all modern cycles aspire to achieve it.

2.4. RANKINE CYCLE

Rankine cycle *is the theoretical cycle on which the steam turbine (or engine) works.*

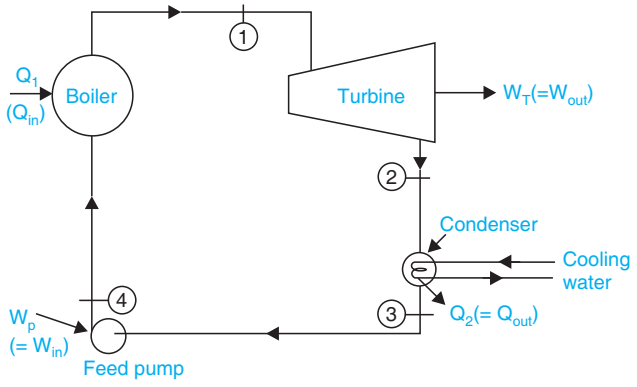
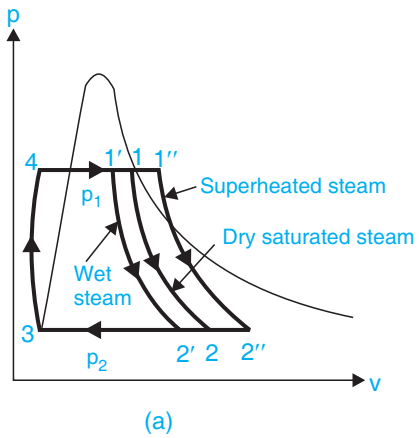


Fig. 2.2. Rankine cycle.



(a)

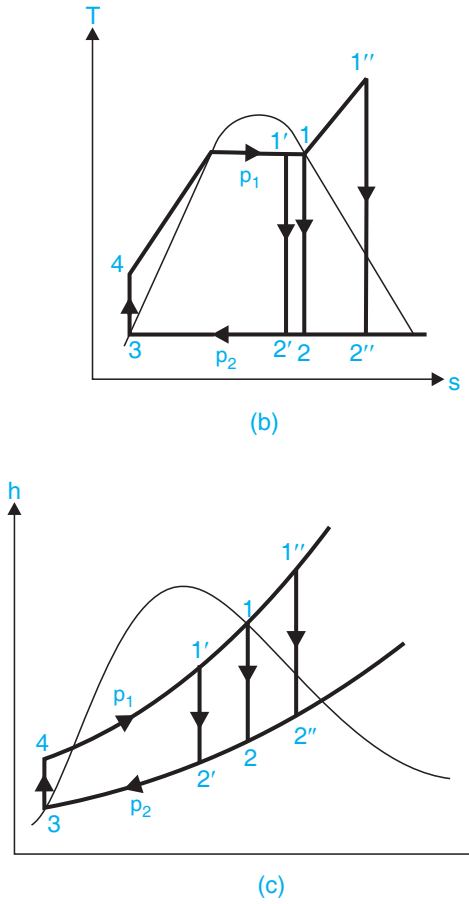


Fig. 2.3. (*a*) *p-v* diagram ; (*b*) *T-s* diagram ; (*c*) *h-s* diagram for Rankine cycle.

The Rankine cycle is shown in Fig. 2.2. It consists of the following *processes* :

Process 1–2 : Reversible adiabatic expansion in the turbine (or steam engine).

Process 2–3 : Constant-pressure transfer of heat in the condenser.

Process 3–4 : Reversible adiabatic pumping process in the feed pump.

Process 4–1 : Constant-pressure transfer of heat in the boiler.

Fig. 2.3 shows the Rankine cycle on *p-v*, *T-s* and *h-s* diagrams (when the saturated steam enters the turbine, the steam can be wet or superheated also).

Consider 1 kg of fluid :

Applying *steady flow energy equation* (S.F.E.E.) to boiler, turbine, condenser and pump, we have :

(*i*) **For boiler** (as control volume), we get:

$$h_{f_4} + Q_1 = h_1$$

$$\therefore \quad Q_1 = h_1 - h_{f_4} \qquad ...(2.2)$$

(*ii*) **For turbine** (as control volume), we get:

$h_1 = W_T + h_2$, where W_T = turbine work

$$\therefore \quad W_T = h_1 - h_2 \qquad ...(2.3)$$

(*iii*) **For condenser**, we get:

$$h_2 = Q_2 + h_{f_3}$$

$$\therefore \quad Q_2 = h_2 - h_{f_3} \qquad ...(2.4)$$

(*iv*) **For the feed pump**, we get:

$$h_{f_3} + W_P = h_{f_4}, \quad \text{where, } W_P = \text{Pump work}$$

$$\therefore \quad W_P = h_{f_4} - h_{f_3}$$

Now, efficiency of Rankine cycle is given by:

$$\eta_{\text{Rankine}} = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_P}{Q_1}$$

$$= \frac{(h_1 - h_2) - (h_{f_4} - h_{f_3})}{(h_1 - h_{f_4})} \qquad ...(2.5)$$

The feed pump handles liquid water which is incompressible which means with the increase in pressure its density or specific volume undergoes a little change. Using general property relation for reversible adiabatic compression, we get:

$$Tds = dh - vdp$$

$$\because \quad ds = 0$$

$$\therefore \quad dh = vdp$$

or $$\Delta h = v\,\Delta p$$

(since change in specific volume is negligible)

or $$h_{f_4} - h_{f_3} = v_3 (p_1 - p_2)$$

When p is in bar and v is in m^3/kg, we have:

$$h_{f_4} - h_{f_3} = v_3 (p_1 - p_2) \times 10^5 \text{ J/kg}$$

The feed pump term $(h_{f_4} - h_{f_3})$ being a small quantity in comparison with turbine work, W_T is usually neglected, *especially when the boiler pressures are low*.

Then, $$\eta_{\text{Rankine}} = \frac{h_1 - h_2}{h_1 - h_{f_4}} \qquad ...[2.5\ (a)]$$

Comparison between Rankine cycle and Carnot cycle :

The following points are worth noting :

(*i*) Between the same temperature limits Rankine cycle provides a higher specific work output than a Carnot cycle, consequently Rankine cycle *requires a smaller steam flow rate resulting in smaller size plant for a given power output*. However, Rankine cycle calls for higher *rates of heat transfer in boiler and condenser*.

(*ii*) Since in Rankine cycle only part of the heat is supplied isothermally at constant higher temperature T_1, therefore, its *efficiency is lower* than that of Carnot cycle. The efficiency of the Rankine cycle will approach that of the Carnot cycle more nearly if the *superheat temperature rise is reduced*.

(*iii*) The advantage of using pump to feed liquid to the boiler instead to compressing a wet vapour is obvious that the *work for compression is very large compared to the pump*.

Fig. 2.4 shows the plots between efficiency and specific steam consumption against boiler pressure for Carnot and ideal Rankine cycles.

Effect of operating conditions on Rankine cycle efficiency :

The Rankine cycle efficiency can be *improved* by :

(*i*) Increasing the average temperature at which heat is supplied.

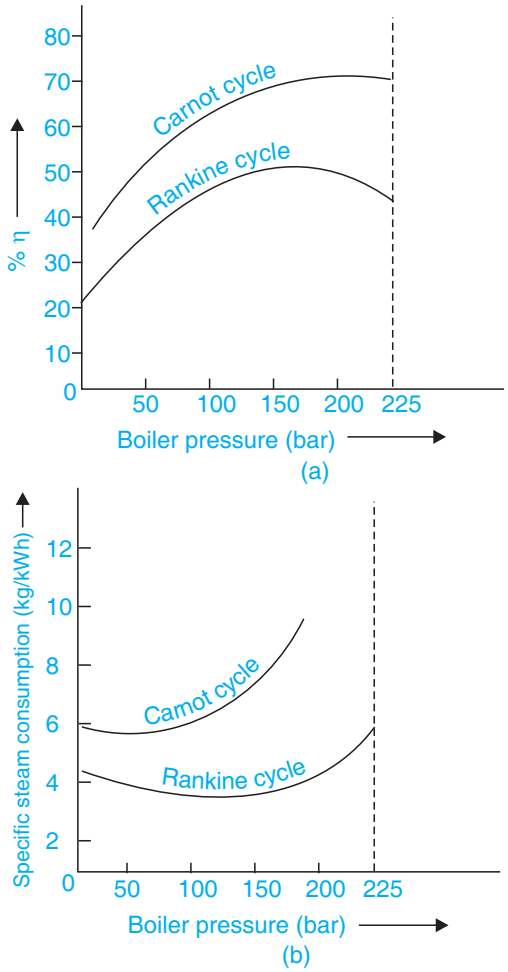


Fig. 2.4

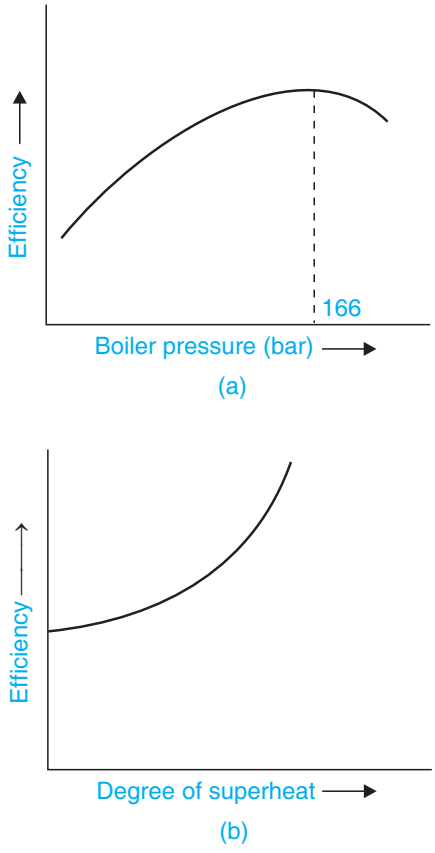
(*ii*) Decreasing/reducing the temperature at which heat is rejected.

This can be achieved by making suitable changes in the conditions of steam generation or condensation, as discussed below :

1. **Increasing boiler pressure.** It has been observed that by increasing the boiler pressure (other factors remaining the same) the cycle tends to rise and reaches a maximum value at a boiler pressure of about 166 bar [Fig. 2.5 (*a*)].

2. **Superheating.** All other factors remaining the same, if the steam is superheated before allowing it to expand the *Rankine cycle efficiency may be increased* [Fig. 2.5 (*b*)]. The use of superheated steam also *ensures longer turbine blade life* because of the absence of erosion from high velocity water particles that are suspended in wet vapour.

3. **Reducing condenser pressure.** The thermal efficiency of the cycle can be amply improved by reducing the condenser pressure [Fig. 2.5 (*c*)] (hence by reducing the temperature at which heat is rejected), especially in high vacuums. But the increase in efficiency is obtained at the *increased cost of condensation apparatus*.



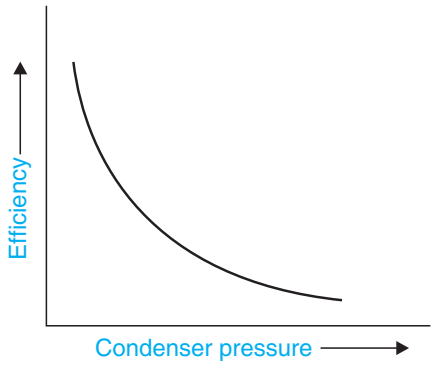


Fig. 2.5. Effect of operating conditions on the thermal efficiency of the Rankine cycle.

The thermal efficiency of the Rankine cycle is also *improved* by the following methods :

(*i*) *By regenerative feed heating.*

(*ii*) *By reheating of steam.*

(*iii*) *By water extraction.*

(*iv*) *By using binary-vapour.*

☞**Example 2.1.** *The following data refer to a simple steam power plant :*

S. No.	*Location*	*Pressure*	*Quality/temp.*	*Velocity*
1.	*Inlet to turbine*	*6 MPa (= 60 bar)*	*380°C*	–
2.	*Exit from turbine inlet to condenser*	*10 kPa (= 0.1 bar)*	*0.9*	*200 m/s*
3.	*Exit from condenser and inlet to pump*	*9 kPa (= 0.09 bar)*	*Saturated liquid*	–
4.	*Exit from pump and inlet to boiler*	*7 MPa (= 70 bar)*	–	–
5.	*Exit from boiler*	*6.5 MPa (= 65 bar)*	*400°C*	–
	Rate of steam flow = 10000 kg/h.			

Calculate :

(*i*) *Power output of the turbine.*

(*ii*) *Heat transfer per hour in the boiler and condenser separately.*

(*iii*) *Mass of cooling water circulated per hour in the condenser. Choose the inlet temperature of cooling water 20°C and 30°C at exit from the condenser.*

(*iv*) *Diameter of the pipe connecting turbine with condenser.*

Solution. Refer to Fig. 2.6.

(*i*) **Power output of the turbine, P :**

At 60 bar, 380°C : From steam tables,

$$h_1 = 3043.0 \text{ (at } 350°C) + \frac{3177.2 - 3043.0}{(400 - 350)} \times 30 \text{ ... By interpolation}$$

$$= 3123.5 \text{ kJ/kg}$$

At 0.1 bar :

h_{f_2} = 191.8 kJ/kg,

h_{fg_2} = 2392.8 kJ/kg (from steam tables)

and x_2 = 0.9 (given)

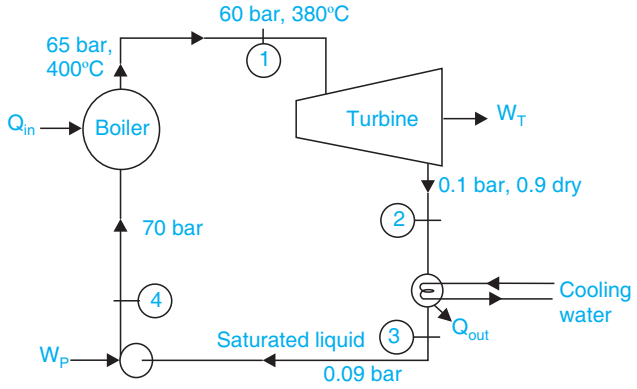


Fig. 2.6

$$\therefore \quad h_2 = h_{f_2} + x_2 \, h_{fg_2}$$

$$= 191.8 + 0.9 \times 2392.8$$

$$= 2345.3 \text{ kJ/kg}$$

Power output of the turbine = $m_s (h_1 - h_2)$ kW,

[where m_s = Rate of steam flow in kg/s and h_1, h_2 = Enthalpy of steam in kJ/kg]

$$= \frac{10000}{3600} (3123.5 - 2345.3)$$

= 2162 kW

Hence, power output of the turbine

= 2162 kW. (Ans.)

(*ii*) **Heat transfer per hour in the boiler and condenser :**

At 70 bar : h_{f_4} = 1267.4 kJ/kg

At 65 bar, 400°C :

$$h_a = \frac{3177.2\,(60 \text{ bar}) + 3158.1\,(70 \text{ bar})}{2}$$

= 3167.6 kJ/kg .....(By interpolation)

∴ Heat transfer per hour in the boiler,

$$Q_1 = 10000\,(h_a - h_{f_4}) \text{ kJ/h}$$

$$= 10000\,(3167.6 - 1267.4)$$

$$= \mathbf{1.9 \times 10^7 \text{ kJ/h.}} \quad \textbf{(Ans.)}$$

At 0.09 bar : h_{f_3} = 183.3 kJ/kg

Heat transfer per hour in the condenser,

$$Q_2 = 10000\,(h_2 - h_{f_3})$$

$$= 10000\,(2345.3 - 183.3)$$

$$= \mathbf{2.16 \times 10^7 \text{ kJ/h.}} \quad \textbf{(Ans.)}$$

(*iii*) **Mass of cooling water circulated per hour in the condenser, m_w :**

Heat lost by steam = Heat gained by the cooling water

$$Q_2 = m_w \times c_{pw}\,(t_2 - t_1)$$

$$2.16 \times 10^7 = m_w \times 4.18\,(30 - 20)$$

$$\therefore \quad \mathbf{m_w} = \frac{2.16 \times 10^7}{4.18\,(30 - 20)}$$

$$= \mathbf{1.116 \times 10^7 \text{ kg/h.}} \quad \textbf{(Ans.)}$$

(*iv*) **Diameter of the pipe connecting turbine with condenser, d :**

$$\frac{\pi}{4}\,d^2 \times C = m_s\,x_2\,v_{g_2} \qquad ...(i)$$

Here, d = Diameter of the pipe (m),

C = Velocity of steam = 200 m/s (given),

m_s = Mass of steam in kg/s,

x_2 = Dryness fraction at '2', and

v_{g_2} = Specific volume at pressure 0.1 bar (= 14.67 m^3/kg).

Substituting the various values in eqn. (*i*), we get:

$$\frac{\pi}{4}\,d^2 \times 200 = \frac{10000}{3600} \times 0.9 \times 14.67$$

$$d = \left(\frac{10000 \times 0.9 \times 14.67 \times 4}{3600 \times \pi \times 200}\right)^{1/2}$$

= 0.483 m or 483 mm.

Hence, diameter of the pipe = **483 mm.** **(Ans.)**

Example 2.2. *A steam turbine receives steam at 15 bar and 350°C and exhausts to the condenser at 0.06 bar. Determine the thermal efficiency of the ideal Rankine cycle operating between these two limits.*

Solution. Pressure of steam at the entry to the steam turbine,

p_1 = 15 bar, 350°C

Condenser pressure, p_2 = 0.06 bar

Rankine efficiency :

From steam tables,

At 15 bar, 350°C : h = 3147.5 kJ/kg,

s = 7.102 kJ/kg K

At 0.06 bar : h_f = 151.5 kJ/kg,

h_{fg} = 2415.9 kJ/kg

s_f = 0.521 kJ/kg K,

s_{fg} = 7.809 kJ/kg K

Since the steam in the turbine expands isentropically,

$$s_1 = s_2 = s_{f_2} + x_2 s_{fg_2}$$

$$7.102 = 0.521 + x_2 \times 7.809$$

$$\therefore \quad x_2 = \frac{7.102 - 0.521}{7.809} = 0.843$$

h_1 = 3147.5 kJ/kg,

$$h_2 = h_{f_2} + x_2 h_{fg_2}$$

$$= 151.5 + 0.843 \times 2415.9$$

$$= 2188.1 \text{ kJ/kg}$$

$$\therefore \quad \eta_{\text{Rankine}} = \frac{h_1 - h_2}{h_1 - h_{f_2}} \text{ (neglecting pump work)}$$

$$= \frac{3147.5 - 2188.1}{3147.5 - 151.5}$$

$$= \mathbf{0.32 \quad or \quad 32\%.} \quad \textbf{(Ans.)}$$

Example 2.3. *In a steam turbine steam at 20 bar, 360°C is expanded to 0.08 bar. It then enters a condenser, where it is condensed to saturated liquid water. The pump feeds back the water into the boiler. Assume ideal processes, find per kg of steam the net work and the cycle efficiency.*

Solution. Boiler pressure, p_1 = 20 bar (360°C)

Condenser pressure, p_2 = 0.08 bar

From steam tables,

At 20 bar (p_1), 360°C : h_1 = 3159.3 kJ/kg

s_1 = 6.9917 kJ/kg K

At 0.08 bar (p_2) : $h_3 = h_{f(p_2)}$

= 173.88 kJ/kg,

$s_3 = s_{f(p_2)}$

= 0.5926 kJ/kg K

$h_{fg(p_2)}$ = 2403.1 kJ/kg,

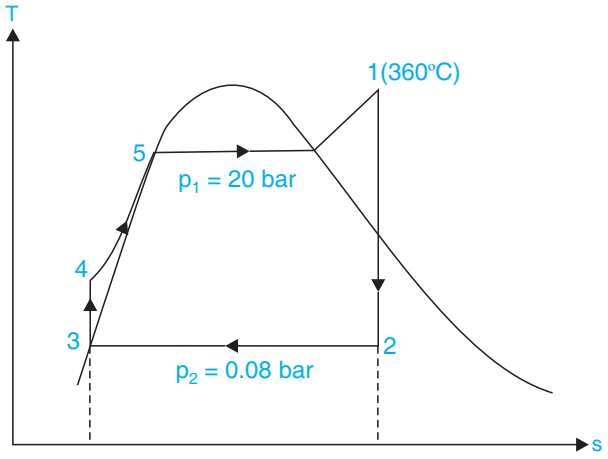


Fig. 2.7

$$s_{g(p_2)} = 8.2287 \text{ kJ/kg K}$$

$$v_{f(p_2)} = 0.001008 \text{ m}^3/\text{kg}$$

$$\therefore \quad s_{fg(p_2)} = 7.6361 \text{ kJ/kg K}$$

Now, $s_1 = s_2$

$$6.9917 = s_{f(p_2)} + x_2 \, s_{fg(p_2)}$$

$$= 0.5926 + x_2 \times 7.6361$$

$$\therefore \quad x_2 = \frac{6.9917 - 0.5926}{7.6361} = 0.838$$

$$\therefore \quad h_2 = h_{f(p_2)} + x_2 \, h_{fg(p_2)}$$

$$= 173.88 + 0.838 \times 2403.1$$

$$= 2187.68 \text{ kJ/kg.}$$

Net work, W_{net} :

$$W_{net} = W_{turbine} - W_{pump} \qquad ...(i)$$

$$W_{pump} = h_{f_4} - h_{f(p_2)} \; (= h_{f_3})$$

$$= v_{f(p_2)} \; (p_1 - p_2)$$

$$= 0.00108 \text{ (m}^3/\text{kg)} \times (20 - 0.08) \times 100 \text{ kN/m}^2$$

$$= 2.008 \text{ kJ/kg}$$

[and $h_{f_4} = 2.008 + h_{f(p_2)} = 2.008 + 173.88$

$= 175.89$ kJ/kg]

$$W_{turbine} = h_1 - h_2 = 3153.9 - 2187.68$$

$$= 971.62 \text{ kJ/kg}$$

$$\therefore \quad W_{net} = 971.62 - 2.008$$

$$= \mathbf{969.61 \text{ kJ/kg.}} \quad \textbf{(Ans.)}$$

$$Q_1 = h_1 - h_{f_4} = 3159.3 - 175.89$$

$$= 2983.41 \text{ kJ/kg}$$

$$\therefore \quad \eta_{cycle} = \frac{W_{net}}{Q_1} = \frac{969.61}{2983.41}$$

$$= \mathbf{0.325 \quad or \quad 32.5\%.} \quad \textbf{(Ans.)}$$

Example 2.4. *A simple Rankine cycle works between pressures 28 bar and 0.06 bar, the initial condition of steam being dry saturated. Calculate the cycle efficiency, work ratio and specific steam consumption.*

Solution.

From steam tables,

At 28 bar : $h_1 = 2802$ kJ/kg,

$s_1 = 6.2104$ kJ/kg K

At 0.06 bar : $h_{f_2} = h_{f_3} = 151.5$ kJ/kg,

$h_{fg_2} = 2415.9$ kJ/kg,

$s_{f_2} = 0.521$ kJ/kg K,

$s_{fg_2} = 7.809$ kJ/kg K

$v_f = 0.001 \text{ m}^3/\text{kg}$

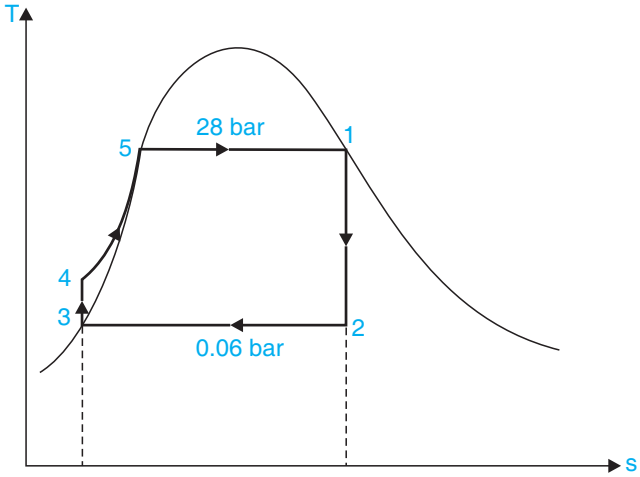


Fig. 2.8

Considering turbine *process 1–2*, we have :

$$s_1 = s_2$$

$$6.2104 = s_{f_2} + x_2 \, s_{fg_2}$$

$$= 0.521 + x_2 \times 7.809$$

$$\therefore \quad x_2 = \frac{6.2104 - 0.521}{7.809} = 0.728$$

$$\therefore \quad h_2 = h_{f_2} + x_2 \, h_{fg_2}$$

$$= 151.5 + 0.728 \times 2415.9$$

$$= 1910.27 \text{ kJ/kg}$$

$\therefore$ Turbine work,

$$W_{turbine} = h_1 - h_2 = 2802 - 1910.27$$

$$= 891.73 \text{ kJ/kg}$$

Pump work,

$$W_{pump} = h_{f_4} - h_{f_3} = v_f (p_1 - p_2)$$

$$= \frac{0.001\,(28 - 0.06) \times 10^5}{1000}$$

$$= 2.79 \text{ kJ/kg}$$

$$[\because \quad h_{f_4} = h_{f_3} + 2.79 = 151.5 + 2.79 = 154.29 \text{ kJ/kg}]$$

$\therefore$ Net work,

$$W_{net} = W_{turbine} - W_{pump}$$

$$= 891.73 - 2.79 = 888.94 \text{ kJ/kg}$$

Cycle efficiency

$$= \frac{W_{net}}{Q_1} = \frac{888.94}{h_1 - h_{f_4}}$$

$$= \frac{888.94}{2802 - 154.29}$$

$$= \mathbf{0.3357 \text{ or } 33.57\%.} \quad \textbf{(Ans.)}$$

Work ratio $= \dfrac{W_{net}}{W_{turbine}} = \dfrac{888.94}{891.73}$

$$= \mathbf{0.997.} \quad \textbf{(Ans.)}$$

Specific steam consumption

$$= \frac{3600}{W_{net}} = \frac{3600}{888.94}$$

$$= \mathbf{4.049 \text{ kg/kWh.}} \quad \textbf{(Ans.)}$$

☞**Example 2.5.** *In a Rankine cycle, the steam at inlet to turbine is saturated at a pressure of 35 bar and the exhaust pressure is 0.2 bar. Determine :*

(i) The pump work (ii) The turbine work

(iii) The Rankine efficiency

(iv) The condenser heat flow

(v) The dryness at the end of expansion.

Assume flow rate of 9.5 kg/s.

Solution. Pressure and condition of steam, at inlet to the turbine,

$$p_1 = 35 \text{ bar}, x = 1$$

Exhaust pressure,

$$p_2 = 0.2 \text{ bar}$$

Flow rate, $\dot{m} = 9.5$ kg/s

From steam tables :

At 35 bar : $h_1 = h_{g_1} = 2802$ kJ/kg,

$s_{g_1} = 6.1228$ kJ/kg K

At 0.26 bar : $h_f = 251.5$ kJ/kg,

$h_{fg} = 2358.4$ kJ/kg,

$v_f = 0.001017$ m^3/kg,

$s_f = 0.8321$ kJ/kg K,

$s_{fg} = 7.0773$ kJ/kg K.

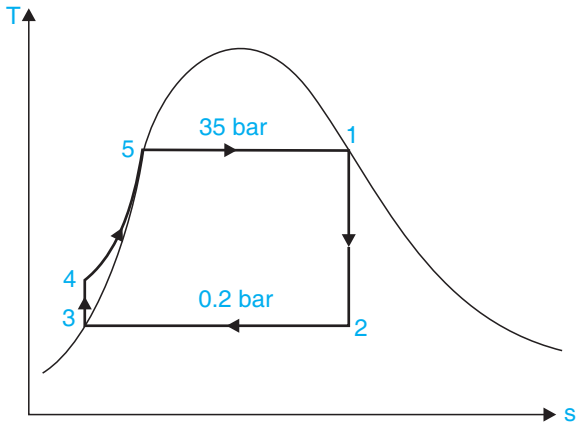


Fig. 2.9

(i) **The pump work :**

Pump work $= (p_4 - p_3)\, v_f$

$= (35 - 0.2) \times 10^5 \times 0.001017$ J

or 3.54 kJ/kg

$$\left[\text{Also } h_{f_4} - h_{f_3} = \text{Pump work} = 3.54 \text{ kJ/kg}, \quad \therefore \quad h_{f_4} = 251.5 + 3.54 = 255.04 \text{ kJ/kg}\right]$$

Now power required to drive the pump

$= 9.5 \times 3.54$ kJ/s or **33.63 kW.** **(Ans.)**

(ii) **The turbine work :**

$$s_1 = s_2 = s_{f_2} + x_2 \times s_{fg_2}$$

$$6.1228 = 0.8321 + x_2 \times 7.0773$$

$$\therefore \quad x_2 = \frac{6.1228 - 0.8321}{7.0773} = 0.747$$

$$\therefore \quad h_2 = h_{f_2} + x_2\, h_{fg_2}$$

$$= 251.5 + 0.747 \times 2358.4$$

$$= 2013 \text{ kJ/kg}$$

$\therefore$ *Turbine work* $= \dot{m}\ (h_1 - h_2)$

$= 9.5\ (2302 - 2013)$

$= \mathbf{7495.5 \text{ kW.}}$ **(Ans.)**

It may be noted that pump work (33.63 kW) is very small as compared to the turbine work (7495.5 kW).

(iii) **The Rankine efficiency :**

$$\eta_{Rankine} = \frac{h_1 - h_2}{h_1 - h_{f_2}} = \frac{2802 - 2013}{2802 - 251.5}$$

$$= \frac{789}{2550.5} = \mathbf{0.3093} \text{ or } \mathbf{30.93\%.} \quad \textbf{(Ans.)}$$

(*iv*) **The condenser heat flow :**

The condenser heat flow

$$= \dot{m}\ (h_2 - h_{f_3}) = 9.5\ (2013 - 251.5)$$

$$= \mathbf{16734.25\ kW.}\quad \textbf{(Ans.)}$$

(*v*) **The dryness at the end of expansion :**

The dryness at the end of expansion,

$$x_2 = \mathbf{0.747}\quad \text{or}\quad \mathbf{74.7\%.}\quad \textbf{(Ans.)}$$

2.5. MODIFIED RANKINE CYCLE

Figs. 2.10 and 2.11 show the modified Rankine cycle on *p-v* and *T-s* diagrams respectively. It will be noted that *p-v* diagram is very narrow at the toe *i.e.,* point '*n*' and the work obtained near toe is very small. In fact this work is too inadequate to overcome friction (due to reciprocating parts) even. Therefore, the adiabatic is terminated at '*s*' ; the pressure drop decreases suddenly whilst the volume remains constant. This operation is represented by the line *sq*. By this doing the stroke length is reduced; in other words the cylinder dimensions reduce but at the expense of small loss of work (area '*sqn*') which, however, is negligibly small.

The work done during the modified Rankine cycle can be calculated in the following way :

Let p_1, v_1, u_1 and h_1 correspond to initial condition of steam at '*m*'.

p_2, v_2, u_2 and h_2 correspond to condition of steam at '*s*'.

p_3, h_3 correspond to condition of steam at '*n*'.

Work done during the cycle/kg of steam

= area '*lmsqk*'

= area '*olmg*' + area '*gmsj*' – area '*okqj*'

$= p_1v_1 + (u_1 - u_2) - p_3v_2$

Heat supplied

$= h_1 - h_{f_3}$

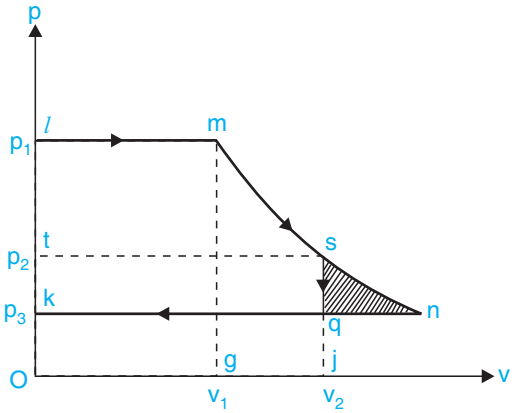


Fig. 2.10. *p-v* diagram of Modified Rankine cycle.

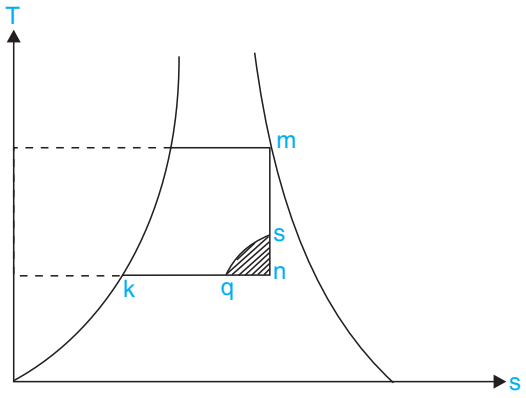


Fig. 2.11. *T-s* diagram of Modified Rankine cycle.

∴ The modified Rankine efficiency

$$= \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{p_1v_1 + (u_1 - u_2) - p_3v_2}{h_1 - h_{f_3}} \qquad ...(2.6)$$

Alternative method for finding modified Rankine efficiency :

Work done during the cycle/kg of steam

= area '*lmsqk*'

= area '*lmst*' + area '*tsqk*'

$= (h_1 - h_2) + (p_2 - p_3)\ v_2$

Heat supplied

$= h_1 - h_{f_3}$

Modified Rankine efficiency

$$= \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{(h_1 - h_2) + (p_2 - p_3)\ v_2}{h_1 - h_{f_3}} \qquad ...(2.7)$$

Note. Modified Rankine cycle is used for reciprocating steam engines because stroke length and hence cylinder size is reduced with the sacrifice of practically a quite negligible amount of work done.

Example 2.6. *Steam at a pressure of 15 bar and 300°C is delivered to the throttle of an engine. The steam expands to 2 bar when release occurs. The steam exhaust takes place at 1.1 bar. A performance test gave the result of the specific steam consumption of 12.8 kg/kWh and a mechanical efficiency of 80%. Determine :*

(*i*) *Ideal work or the modified Rankine engine work per kg.*

(*ii*) *Efficiency of the modified Rankine engine or ideal thermal efficiency.*

(*iii*) *The indicated and brake work per kg.*

(*iv*) *The brake thermal efficiency.*

(*v*) *The relative efficiency on the basis of indicated work and brake work.*

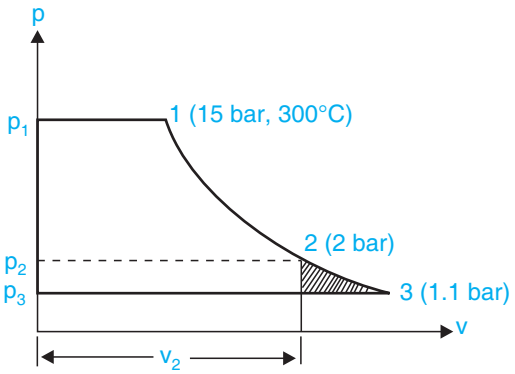
Solution. Fig. 2.12 shows the *p-v* and *T-s* diagrams for modified Rankine cycle.

From steam tables :

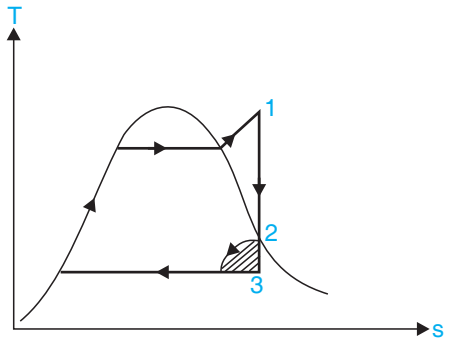
1. ***At 15 bar, 300°C :*** $h_1 = 3037.6$ kJ/kg,
$v_1 = 0.169$ m^3/kg,
$s = 6.918$ kJ/kg K.

2. ***At 2 bar :*** $t_s = 120.2°C$,
$h_f = 504.7$ kJ/kg,
$h_{fg} = 2201.6$ kJ/kg,
$s_f = 1.5301$ kJ/kg K,
$s_{fg} = 5.5967$ kJ/kg K,
$v_f = 0.00106$ m^3/kg,
$v_g = 0.885$ m^3/kg.

3. ***At 1.1 bar :*** $t_s = 102.3°C$,
$h_f = 428.8$ kJ/kg,
$h_{fg} = 2250.8$ kJ/kg,
$s_f = 1.333$ kJ/kg K,
$s_{fg} = 5.9947$ kJ/kg K,
$v_f = 0.001$ m^3/kg,
$v_g = 1.549$ m^3/kg.



(a)



(b)

Fig. 2.12

During isentropic expansion 1–2, we have:

$$s_1 = s_2$$

$$6.918 = s_{f_2} + x_2\, s_{fg_2}$$

$$= 1.5301 + x_2 \times 5.5967$$

$$\therefore \quad x_2 = \frac{6.918 - 1.5301}{5.5967} = 0.96.$$

Then $$h_2 = h_{f_2} + x_2 h_{fg_2} = 504.7 + 0.96 \times 2201.6$$

$$= 2618.2 \text{ kJ/kg}$$

$$v_2 = x_2\, v_{g_2} + (1 - x_2)\, v_{f_2}$$

$$= 0.96 \times 0.885 + (1 - 0.96) \times 0.00106$$

$$= 0.849 \text{ m}^3\text{/kg}.$$

(*i*) Ideal work :

Ideal work or modified Rankine engine work/kg,

$$W = (h_1 - h_2) + (p_2 - p_3)\, v_2$$

$$= (3037.6 - 2618.2) + (2 - 1.1) \times 10^5 \times 0.849/1000$$

$$= 419.4 + 76.41 = \mathbf{495.8\ kJ/kg.} \quad \textbf{(Ans.)}$$

(*ii*) Rankine engine efficiency :

$$\eta_{\text{rankine}} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{495.8}{(h_1 - h_{f_3})}$$

$$= \frac{495.8}{3037.6 - 428.8} = \mathbf{0.19 \text{ or } 19\%.} \quad \textbf{(Ans.)}$$

(*iii*) Indicated and brake, work per kg :

Indicated work/kg,

$$W_{\text{indicated}} = \frac{\text{I.P.}}{\dot{m}}$$

$$= \frac{1 \times 3600}{12.8} = \mathbf{281.25\ kJ/kg.} \quad \textbf{(Ans.)}$$

Brake work/kg,

$$W_{\text{brake}} = \frac{\text{B.P.}}{\dot{m}} = \frac{\eta_{\text{mech.}} \times \text{I.P.}}{\dot{m}}$$

$$= \frac{0.8 \times 1 \times 3600}{12.8}$$

$$= \mathbf{225\ kJ/kg.} \quad \textbf{(Ans.)}$$

(*iv*) Brake thermal efficiency :

Brake thermal efficiency

$$= \frac{W_{\text{brake}}}{h_1 - h_{f_3}} = \frac{225}{3037.6 - 428.8}$$

$$= \mathbf{0.086 \text{ or } 8.6\%.} \quad \textbf{(Ans.)}$$

(*v*) Relative efficiency :

Relative efficiency *on the basis of indicated work*

$$= \frac{\dfrac{W_{\text{indicated}}}{h_1 - h_{f_3}}}{\dfrac{W}{h_1 - h_{f_3}}} = \frac{W_{\text{indicated}}}{W}$$

$$= \frac{281.25}{495.8} = \mathbf{0.567 \text{ or } 56.7\%.} \quad \textbf{(Ans.)}$$

Relative efficiency *on the basis of brake work*

$$= \frac{\dfrac{W_{brake}}{(h_1 - h_{f_3})}}{\dfrac{W}{(h_1 - h_{f_3})}} = \frac{W_{brake}}{W}$$

$$= \frac{225}{495.8} = \mathbf{0.4538 \quad or \quad 45.38\%.} \quad \textbf{(Ans.)}$$

Example 2.7. *Superheated steam at a pressure of 10 bar and 400°C is supplied to a steam engine. Adiabatic expansion takes place to release point at 0.9 bar and it exhausts into a condenser at 0.3 bar. Neglecting clearance determine for a steam flow rate of 1.5 kg/s :*

(i) Quality of steam at the end of expansion and the end of constant volume operation.

(ii) Power developed.

(iii) Specific steam consumption.

(iv) Modified Rankine cycle efficiency.

Solution. Fig. 2.13 shows the *p-v* and *T-s* diagrams for modified Rankine cycle.

From steam tables :

1. ***At 10 bar, 400°C :*** $h_1 =$ 3263.9 kJ/kg,
   $v_1 =$ 0.307 m³/kg,
   $s_1 =$ 7.465 kJ/kg K

2. ***At 0.9 bar :*** $t_{s_2} =$ 96.7°C,
   $h_{g_2} =$ 2670.9 kJ/kg,
   $s_{g_2} =$ 7.3954 kJ/kg K,
   $v_{g_2} =$ 1.869 m³/kg

3. ***At 0.3 bar :*** $h_{f_3} =$ 289.3 kJ/kg,
   $v_{g_3} =$ 5.229 m³/kg

(i) (a) **Quality of steam at the end of expansion, T_{sup2} :**

For isentropic expansion 1–2, we have:

$$s_1 = s_2$$

$$= s_{g_2} + c_p \log_e \frac{T_{sup\,2}}{T_{s_2}}$$

$$7.465 = 7.3954 + 2.1 \log_e \frac{T_{sup2}}{(96.7 + 273)}$$

$$\left(\frac{7.465 - 7.3954}{2.1}\right) = \log_e \frac{T_{sup2}}{369.7}$$

or, $$\log_e \frac{T_{sup2}}{369.7} = 0.03314$$

$$\frac{T_{sup2}}{369.7} = 1.0337 \quad \text{or} \quad T_{sup2} = 382 \text{ K}$$

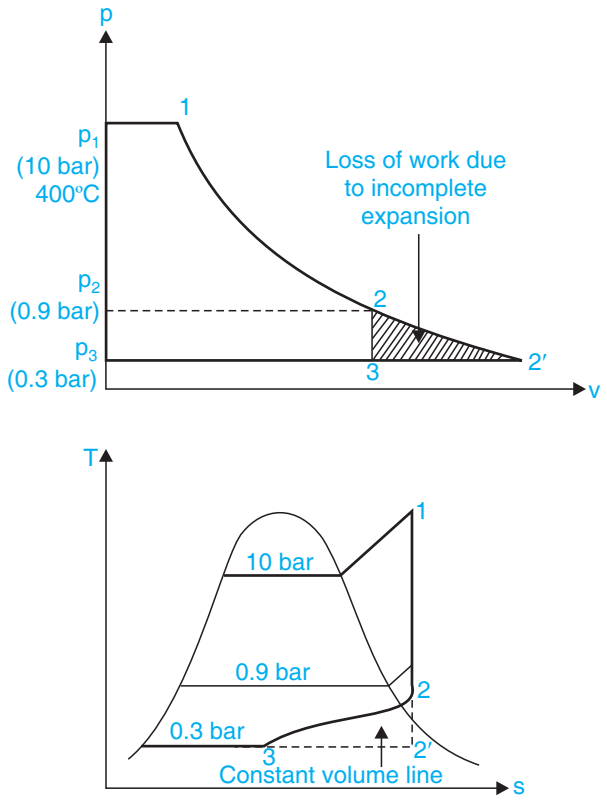


Fig. 2.13. *p-v* and *T-s* diagrams.

or $$t_{sup2} = 382 - 273 = \mathbf{109°C.} \quad \textbf{(Ans.)}$$

$\therefore$ $$h_2 = h_{g_2} + c_{ps} (T_{sup2} - T_{s_2})$$

$$= 2670.9 + 2.1 (382 - 366.5)$$

$$= \mathbf{2703.4 \text{ kJ/kg.}} \quad \textbf{(Ans.)}$$

(b) **Quality of steam at the end of constant volume operation, x_3 :**

For calculating v_2 using the relation:

$$\frac{v_{g_2}}{T_{s_2}} = \frac{v_2}{T_{sup2}} \text{ (Approximately), we get:}$$

$$\frac{1.869}{369.7} = \frac{v_2}{382}$$

or, $$v_2 = \frac{1.869 \times 382}{369.7} = 1.931 \text{ m}^3\text{/kg}$$

Also, $$v_2 = v_3 = x_3 \, v_{g_3}$$

$$1.931 = x_3 \times 5.229$$

or, $$\mathbf{x_3} = \frac{1.931}{5.229} = \mathbf{0.37.} \quad \textbf{(Ans.)}$$

(ii) **Power developed, P :**

Work done $= (h_1 - h_2) + (p_2 - p_3) \, v_2$

$$= (3263.9 - 2703.4) + \frac{(0.75 - 0.3) \times 10^5 \times 1.931}{1000}$$

$$= 560.5 + 86.9 = 647.4 \text{ kJ/kg}$$

$\therefore$ **Power developed**

= Steam flow rate × work done (per kg)

= 1 × 647.4 = **647.4 kW.** **(Ans.)**

(*iii*) **Specific steam consumption, ssc :**

$$\text{ssc} = \frac{3600}{\text{Power}} = \frac{1 \times 3600}{647.4}$$

$$= \mathbf{5.56 \text{ kg/kWh.}} \quad \textbf{(Ans.)}$$

(*iv*) **Modified Rankine cycle efficiency, η_{mR} :**

$$\eta_{mR} = \frac{(h_1 - h_2) + (p_2 - p_3)\, v_2}{h_1 - h_{f_3}}$$

$$= \frac{647.4}{3263.9 - 289.3} = \mathbf{0.217 \text{ or } 21.7\%.} \quad \textbf{(Ans.)}$$

2.6. REHEAT CYCLE

For attaining greater thermal efficiencies when the initial pressure of steam was raised beyond 42 bar it was found that resulting condition of steam after, expansion was increasingly wetter and exceeded the safe limit of 12% condensation. It, therefore, became necessary to *reheat* the steam after part of expansion was over so that the resulting condition after complete expansion fell within the region of permissible wetness.

The reheating or resuperheating of steam is now universally used when high pressure and temperature steam conditions such as 100 to 250 bar and 500°C to 600°C are employed for throttle. For plants of *still higher pressures and temperatures, a double reheating may be used*.

In actual practice reheat *improves* the cycle efficiency by about 5% for a 85/15 bar cycle. A *second reheat* will give a *much less gain* while the initial cost involved would be so high as to prohibit use of two stage reheat except in case of very high initial throttle conditions. The cost of reheat equipment consisting of boiler, piping and controls may be 5% to 10% more than of the conventional boilers and this additional expenditure is justified only if gain in thermal efficiency is sufficient to promise a return of this investment. *Usually a plant with a base load capacity of 50000 kW and initial steam pressure of 42 bar would economically justify the extra cost of reheating*.

The improvement in thermal efficiency due to reheat is greatly dependent upon the *reheat pressure* with respect to the original pressure of steam.

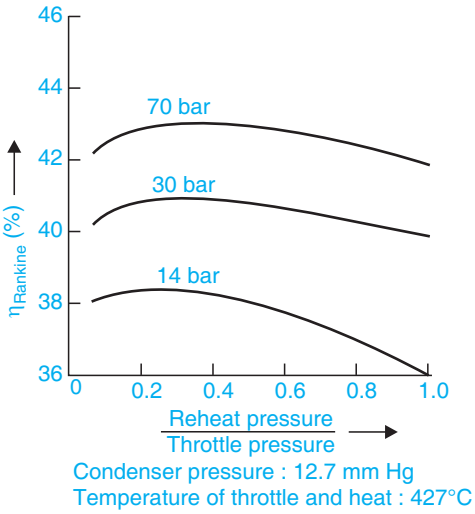


Fig. 2.14. Effect of reheat pressure selection on cycle efficiency.

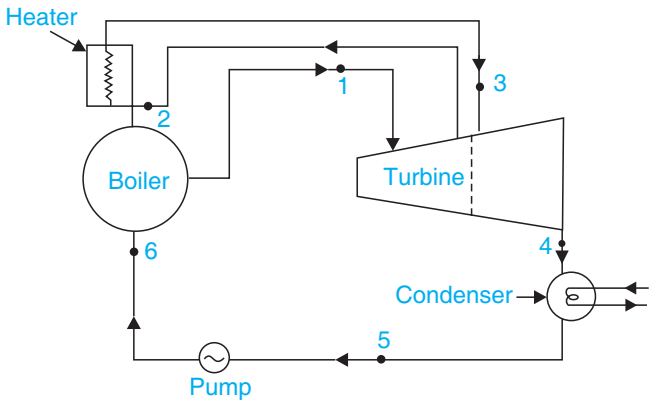


Fig. 2.15. Reheat cycle.

Fig. 2.15 shows a schematic diagram of a theoretical single stage reheat cycle. The corresponding representation of ideal reheating process on *T-s* and *h-s* chart are shown in Fig. 2.16 (*a*) and (*b*).

Refer to Fig. 2.16, (*a*). 5–1 shows the formation of steam in the boiler. The steam as at state point 1 (*i.e.,* pressure p_1 and temperature T_1) enters the turbine and expands isentropically to a certain pressure p_2 and temperature T_2. From this state point 2 the whole of steam is drawn out of the turbine and is reheated in a reheater to a temperature T_3. (Although there is an *optimum pressure* at which the steam should be removed for reheating, if the highest return is to be obtained, yet, for simplicity, the whole steam is removed from the high pressure exhaust, where the pressure is about one-fifth of boiler pressure, and after undergoing a 10% pressure drop, in circulating through the heater, it is returned to intermediate pressure or low pressure turbine). This reheated steam is then

readmitted to the turbine where it is expanded to condenser pressure isentropically.

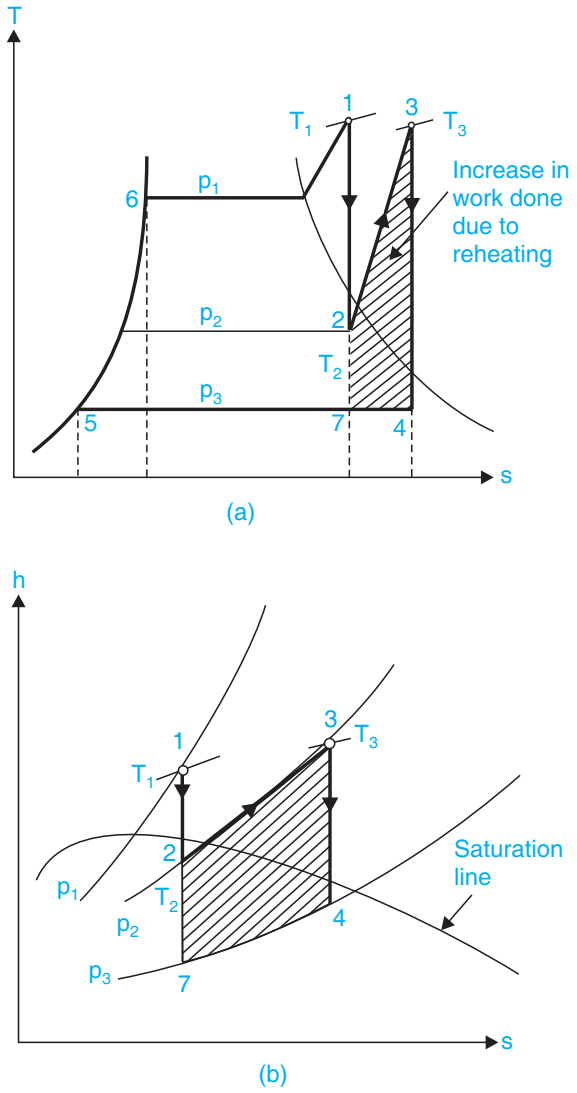


Fig. 2.16. Ideal reheating process on *T-s* and *h-s* charts.

Thermal efficiency with '*Reheating*' (neglecting pump work) :

Heat supplied $= (h_1 - h_{f_4}) + (h_3 - h_2)$

Heat rejected $= h_4 - h_{f_4}$

Work done by the turbine = Heat supplied – Heat rejected

$$= (h_1 - h_{f_4}) + (h_3 - h_2) - (h_4 - h_{f_4})$$

$$= (h_1 - h_2) + (h_3 - h_4)$$

Thus, theoretical thermal efficiency of reheat cycle is,

$$\eta_{\text{thermal}} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f_4}) + (h_3 - h_2)} \qquad ...(2.8)$$

If pump work, $W_p = \dfrac{v_f\,(p_1 - p_b)}{1000}$ kJ/kg

is considered, the *thermal efficiency* is given by :

$$\eta_{\text{thermal}} = \frac{[(h_1 - h_2) + (h_3 - h_4)] - W_p}{[(h_1 - h_{f_4}) + (h_3 - h_2)] - W_p} \qquad ...(2.9)$$

W_p is usually small and *neglected*.

Thermal efficiency *without reheating* is,

$$\eta_{\text{thermal}} = \frac{h_1 - h_7}{h_1 - h_{f_4}} \qquad (\because \quad h_{f_4} = h_{f_7}) \qquad ...(2.10)$$

Notes **1.** The reheater may be incorporated in the walls of the main boiler ; it may be a separately fired superheater or it may be heated by a coil carrying high-pressure superheated steam, this system being analogous to a steam jacket.

2. Reheating should be done at '*optimum pressure*' because if the steam is reheated early in its expansion then the additional *quantity of heat supplied will be small* and thus thermal efficiency gain will be small ; and if the reheating is done at a fairly low pressure, then, although a large amount of additional heat is supplied, the steam will have a high degree of superheat (as is clear from Mollier diagram), thus a large proportion of the heat supplied in the reheating process *will be thrown to waste in the condenser*.

Advantages of 'Reheating' :

1. There is an increased output of the turbine.
2. Erosion and corrosion problems in the steam turbine are eliminated/avoided.
3. There is an improvement in the thermal efficiency of the turbines.
4. Final dryness fraction of steam is improved.
5. There is an increase in the nozzle and blade efficiencies.

Disadvantages :

1. Reheating requires more maintenance.
2. The increase in thermal efficiency is not appreciable in comparison to the expenditure incurred in reheating.

Superheating of Steam :

The primary object of superheating steam and supplying it to the prime movers is *to avoid too much wetness at the end of expansion*. Use of inadequate degree of superheat in *steam engines* would *cause greater condensation* in the engine cylinder ; while in case of *turbines* the moisture content of steam would result in *undue blade erosion*. The *maximum wetness in the final condition of steam that may be tolerated without any appreciable harm to the turbine blades is about 12%*. Broadly each *1%* of moisture in steam

reduces the efficiency of that part of the turbine in which wet steam passes by 1% to 1.5% and in engines about 2%.

Advantages of Superheated steam :

1. Superheating reduces the initial condensation losses in steam engines.

2. Use of superheated steam results in *improving the plant efficiency* by effecting a *saving in cost of fuel*. This saving may be of the order of 6% to 7% due to first 38°C of superheat and 4% to 5% for next 38°C and so on. This saving results due to the fact that the heat content and consequently the capacity to do work in superheated steam is increased and the quantity of steam required for a given output of power is reduced. Although additional heat has to be added in the boiler there is reduction in the work to be done by the feed pump, the condenser pump and other accessories due to reduction in quantity of steam used. It is estimated that the *quantity of steam may be reduced by 10% to 15% for first 38°C of superheat and some what less for the next 38°C of superheat in the case of condensing turbines.*

3. When a superheater is used in a boiler it helps in *reducing the stack temperatures* by extracting heat from the flue gases before these are passed out of chimney.

☞Example 2.8. *Steam at a pressure of 15 bar abs. and 250°C is expanded through a turbine at first to a pressure of 4 bar abs. It is then reheated at constant pressure to the initial temperature of 250°C and is finally expanded to 0.1 bar abs. Using Mollier chart, estimate the work done per kg of steam flowing through the turbine and amount of heat supplied during the process of reheat. Compare the work output when the expansion is direct from 15 bar abs. to 0.1 bar abs. without any reheat. Assume all expansion processes to be isentropic.*

Solution. Refer to Fig. 2.17.

Pressure, $p_1 = 15$ bar ;

$p_2 = 4$ bar ;

$p_4 = 0.1$ bar.

Work done per kg of steam,

W = Total heat drop

$= [(h_1 - h_2) + (h_3 - h_4)]$ kJ/kg ...(*i*)

Amount of heat supplied during process of reheat,

$h_{reheat} = (h_3 - h_2)$ kJ/kg ...(*ii*)

From Mollier diagram or *h-s* chart,

$h_1 = 2920$ kJ/kg, $h_2 = 2660$ kJ/kg

$h_3 = 2960$ kJ/kg, $h_4 = 2335$ kJ/kg

Now, by putting the values in eqns. (*i*) and (*ii*), we get:

$W = (2920 - 2660) + (2960 - 2335)$

$= \mathbf{885\ kJ/kg.}$

Hence *work done per kg of steam* = **885 kJ/kg. (Ans.)**

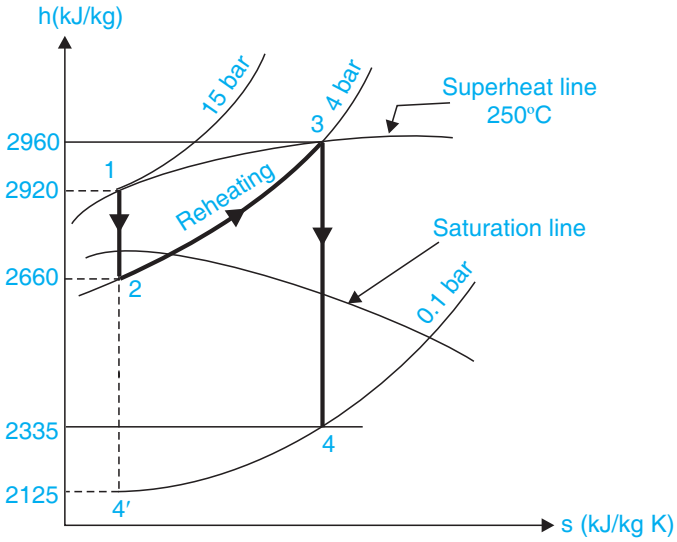


Fig. 2.17

Amount of heat supplied during reheat,

$h_{reheat} = (2960 - 2660) =$ **300 kJ/kg. (Ans.)**

If the expansion would have been continuous without reheating *i.e.,* 1 to 4′, the work output is given by:

$W_1 = h_1 - h_4'$

From Mollier diagram,

$h_4' = 2125$ kJ/kg

$\therefore \quad W_1 = 2920 - 2125 =$ **795 kJ/kg. (Ans.)**

Example 2.9. *A turbine is supplied with steam at a pressure of 32 bar and a temperature of 410°C. The steam then expands isentropically to a pressure of 0.08 bar. Find the dryness fraction at the end of expansion and thermal efficiency of the cycle.*

If the steam is reheated at 5.5 bar to a temperature of 400°C and then expanded isentropically to a pressure of 0.08 bar, what will be the dryness fraction and thermal efficiency of the cycle ?

Solution. First case. Refer to Fig. 2.18.

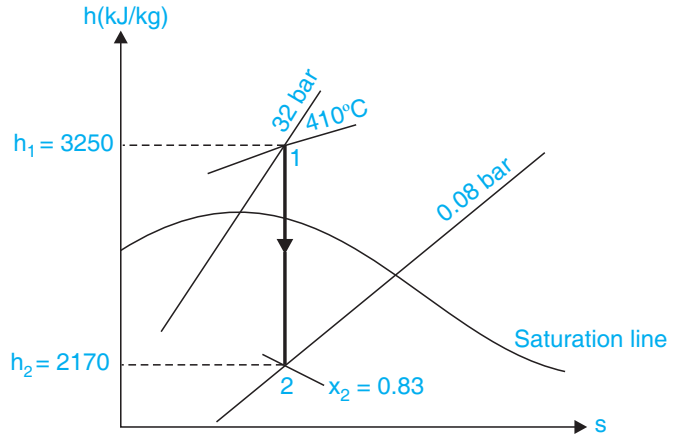


Fig. 2.18

From Mollier chart : $h_1 = 3250$ kJ/kg

$h_2 = 2170$ kJ/kg

Heat drop (or work done) $= h_1 - h_2$

$= 3250 - 2170$

$= 1080$ kJ/kg

Heat supplied $= h_1 - h_{f_2}$

$= 3250 - 173.9$

$[h_{f_2} = 173.9$ kJ/kg at 0.08 bar$]$

$= 3076.1$ kJ/kg

Thermal efficiency $= \dfrac{\text{Work done}}{\text{Heat supplied}}$

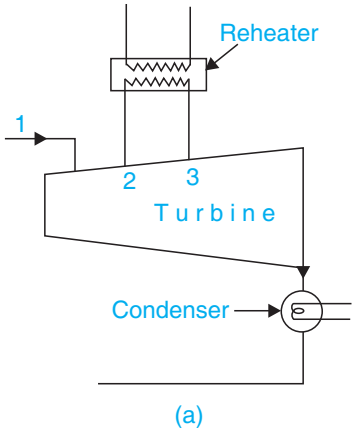
$= \dfrac{1080}{3076.1} = \mathbf{0.351}$

or **35.1%.** **(Ans.)**

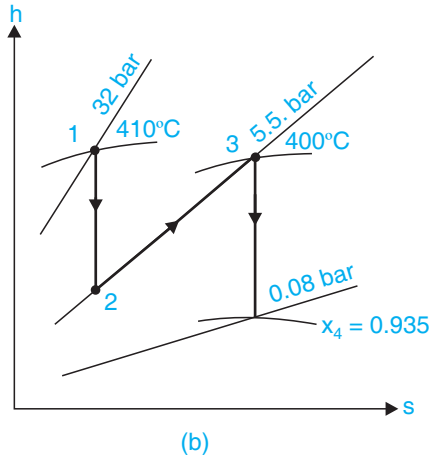
Exhaust steam condition, x_2

$= 0.83$ (From Mollier chart). **(Ans.)**

Second case. Refer to Fig. 2.19 (*b*).



(a)



(b)

Fig. 2.19

From Mollier chart :

$h_1 = 3250$ kJ/kg

$h_2 = 2807$ kJ/kg

$h_3 = 3263$ kJ/kg

$h_4 = 2426$ kJ/kg.

Work done $= (h_1 - h_2) + (h_3 - h_4)$

$= (3250 - 2807) + (3263 - 2426)$

$= 12080$ kJ/kg

Heat supplied $= (h_1 - h_{f_4}) + (h_3 - h_2)$

$= (3250 - 173.9) + (3263 - 2807)$

$\simeq 3532$ kJ/kg

Thermal efficiency

$= \dfrac{\text{Work done}}{\text{Heat supplied}}$

$= \dfrac{1280}{3532} = \mathbf{0.362}$ **or 36.2%.** **(Ans.)**

Condition of steam at the exhaust,

$x_4 = 0.935$

[From Mollier chart]. **(Ans.)**

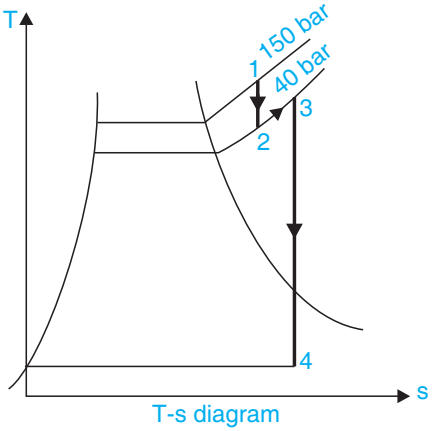
Example 2.10. *A steam power plant operates on a theoretical reheat cycle. Steam at boiler at 150 bar, 550°C expands through the high pressure turbine. It is reheated at a constant pressure of 40 bar to 550°C and expands through the low pressure turbine to a condenser at 0.1 bar. Draw T-s and h-s diagrams. Find :*

(i) Quality of steam at turbine exhaust ;

(ii) Cycle efficiency ;

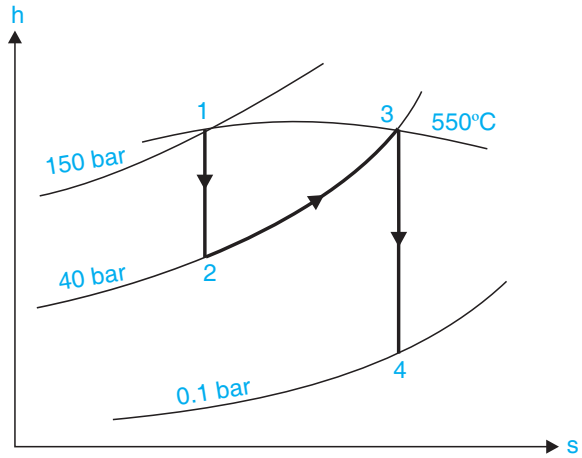
(iii) Steam rate in kg/kWh.

Solution. Refer to Fig. 2.20.



T-s diagram

(a)



h-s diagram
(b)

Fig. 2.20

From Mollier diagram (h-s diagram) :

h_1 = 3450 kJ/kg ;

h_2 = 3050 kJ/kg ;

h_3 = 3560 kJ/kg ;

h_4 = 2300 kJ/kg

h_{f_4} (from steam tables, at 0.1 bar)

= 191.8 kJ/kg

(*i*) **Quality of steam at turbine exhaust, x_4 :**

x_4 = **0.88** (From Mollier diagram)

(Ans.)

(*ii*) **Cycle efficiency, η_{cycle} :**

$$\eta_{cycle} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f_4}) + (h_3 - h_2)}$$

$$= \frac{(3450 - 3050) + (3560 - 2300)}{(3450 - 191.8) + (3560 - 3050)}$$

$$= \frac{1660}{3768.2}$$

= **0.4405 or 44.05%. (Ans.)**

(*iii*) **Steam rate in kg/kWh :**

$$\text{Steam rate} = \frac{3600}{(h_1 - h_2) + (h_3 - h_4)}$$

$$= \frac{3600}{(3450 - 3050) + (3560 - 2300)}$$

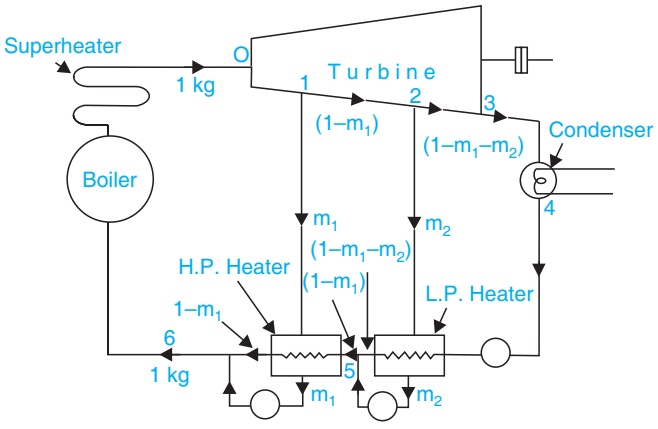
$$= \frac{3600}{1660} = \textbf{2.17 kg/kWh.} \quad \textbf{(Ans.)}$$

2.7. REGENERATIVE CYCLE

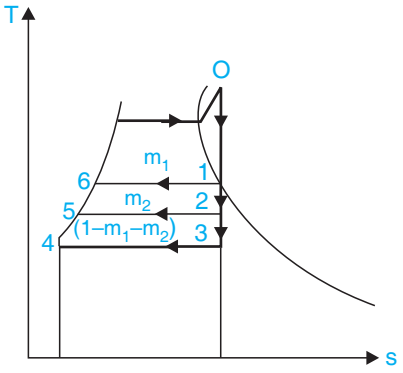
In the Rankine cycle it is observed that the condensate which is fairly at low temperature has an irreversible mixing with hot boiler water and this results in decrease of cycle efficiency. Methods are, therefore, adopted to heat the feed water from the hot well of condenser irreversibly by interchange of heat within the system and thus improving the cycle efficiency. This heating method is called regenerative feed heat and the cycle is called *regenerative cycle*.

The principle of regeneration can be practically utilised by extracting steam from the turbine at several locations and supplying it to the regenerative heaters. The resulting cycle is known as *regenerative or bleeding cycle.* The heating arrangement comprises of : (*i*) For medium capacity turbines—not more than 3 heaters ; (*ii*) For high pressure high capacity turbines—not more than 5 to 7 heaters ; and (*iii*) For turbines of supercritical parameters 8 to 9 heaters. *The most advantageous condensate heating temperature is selected depending on the turbine throttle conditions and this determines the number of heaters to be used.* The final condensate heating temperature is kept 50 to 60°C below the boiler saturated steam temperature so as to prevent evaporation of water in the feed mains following a drop in the boiler drum pressure. The conditions of steam bled for each heater are selected so that the temperature of saturated steam will be 4 to 10°C higher than the final condensate temperature.

Fig. 2.21 (*a*) shows a diagrammatic layout of a condensing steam power plant in which a surface condenser is used to condense all the steam that is not extracted for feed water heating. The turbine is double extracting and the boiler is equipped with a superheater. The cycle diagram (T-s) would appear as shown in Fig. 2.21 (*b*). This arrangement constitutes a *regenerative cycle*.



(a)



(b)

Fig. 2.21. Regenerative cycle.

Let, m_1 = kg of high pressure (H.P.) steam per kg of steam flow,

m_2 = kg of low pressure (L.P.) steam extracted per kg of steam flow

$(1 - m_1 - m_2)$ = kg of steam entering condenser per kg of steam flow.

Energy/Heat balance equation for H.P. heater :

$$m_1 (h_1 - h_{f_6}) = (1 - m_1) (h_{f_6} - h_{f_5})$$

or, $$m_1[(h_1 - h_{f_6}) + (h_{f_6} - h_{f_5})] = (h_{f_6} - h_{f_5})$$

or, $$m_1 = \frac{h_{f_6} - h_{f_5}}{h_1 - h_{f_5}} \quad ...(2.11)$$

Energy/Heat balance equation for L.P. heater :

$$m_2 (h_2 - h_{f_5}) = (1 - m_1 - m_2) (h_{f_5} - h_{f_3})$$

or, $$m_2[(h_2 - h_{f_5}) + (h_{f_5} - h_{f_3})] = (1 - m_1) (h_{f_5} - h_{f_3})$$

or, $$m_2 = \frac{(1 - m_1) (h_{f_5} - h_{f_3})}{(h_2 - h_{f_3})} \quad ...(2.12)$$

All enthalpies may be determined ; therefore m_1 and m_2 may be found. The maximum temperature to which the water can be heated is dictated by that of bled steam. The condensate from the bled steam is added to feed water.

Neglecting pump work :

The heat supplied externally in the cycle

$$= (h_0 - h_{f_6})$$

Isentropic work done $= m_1 (h_0 - h_1) + m_2 (h_0 - h_2) + (1 - m_1 - m_2) (h_0 - h_3)$

The thermal efficiency of regenerative cycle is,

$$\eta_{thermal} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{m_1 (h_0 - h_1) + m_2 (h_0 - h_2) + (1 - m_1 - m_2) (h_0 - h_3)}{(h_0 - h_{f_6})} \quad ...(2.13)$$

The work done by the turbine may also be calculated by summing up the products of the steam flow and the corresponding heat drop in the turbine stages.

i.e., Work done $= (h_0 - h_1) + (1 - m_1) (h_1 - h_2) + (1 - m_1 - m_2) (h_2 - h_3)$

Advantages of Regenerative cycle over Simple Rankine cycle :

1. The heating process in the boiler tends to become reversible.
2. The thermal stresses set up in the boiler are minimised. This is due to the fact that temperature ranges in the boiler are reduced.
3. The thermal efficiency is improved because the average temperature of heat addition to the cycle is increased.
4. Heat rate is reduced.
5. The blade height is less due to the reduced amount of steam passed through the low pressure stages.
6. Due to many extractions there is an improvement in the turbine drainage and it reduces erosion due to moisture.
7. A small size condenser is required.

Disadvantages :

1. The plant becomes more complicated.
2. Because of addition of heaters greater maintenance is required.
3. For given power a large capacity boiler is required.
4. The heaters are costly and the gain in thermal efficiency is not much in comparison to the heavier costs.

Note In the absence of precise information (regarding actual temperature of the feed water entering and leaving the heaters and of the condensate temperatures) the following assumptions should always be made while doing calculations:

(*i*) Each heater is ideal and bled steam just condenses.

(*ii*) The feed water is heated to saturation temperature at the pressure of bled steam.

(*iii*) Unless otherwise stated the work done by the pumps in the system is considered negligible.

(*iv*) There is equal temperature rise in all the heaters (usually 10°C to 15°C).

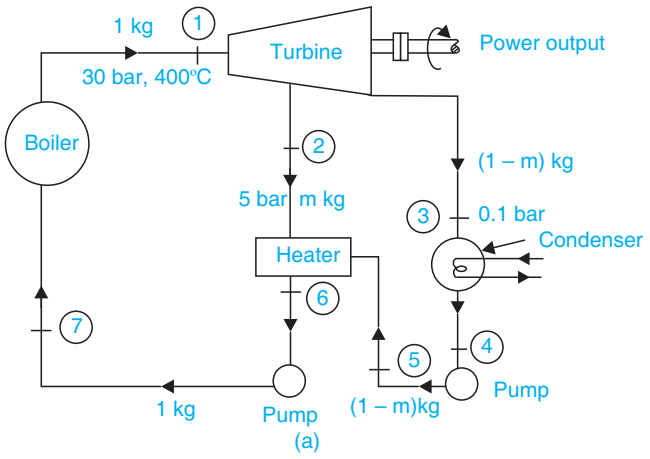
☞**Example 2.11.** *In a single-heater regenerative cycle the steam enters the turbine at 30 bar, 400°C and the exhaust pressure is 0.10 bar. The feed water heater is a direct contact type which operates at 5 bar. Find :*

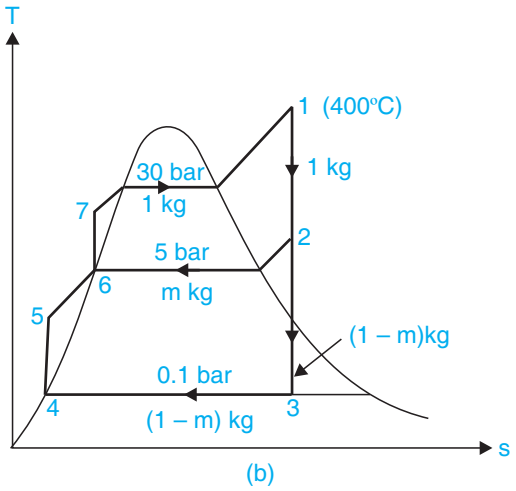
(*i*) *The efficiency and the steam rate of the cycle.*

(*ii*) *The increase in mean temperature of heat addition, efficiency and steam rate as compared to the Rankine cycle (without regeneration).*

Pump work may be neglected.

Solution. Fig. 2.22 shows the flow, *T-s* and *h-s* diagrams.





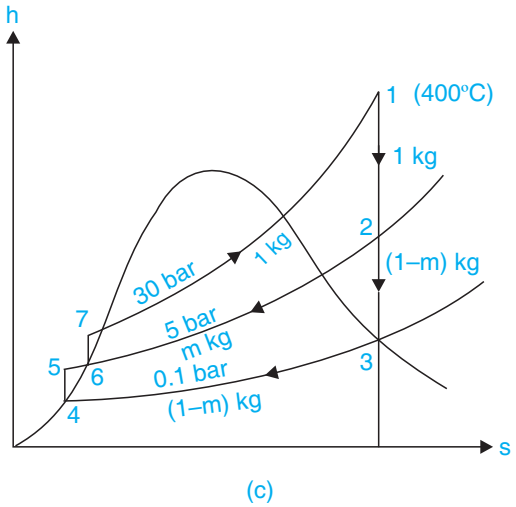


Fig. 2.22

From steam tables :

At 30 bar, 400°C : $h_1 = 3230.9$ kJ/kg,

$s_1 = 6.921$ kJ/kg K $= s_2 = s_3$,

At 5 bar : $s_f = 1.8604$ kJ/kg K,

$s_g = 6.8192$ kJ/kg K,

$h_f = 640.1$ kJ/kg

Since $s_2 > s_g$, the state 2 must lie in the superheated region. From the table for superheated steam

$t_2 = 172°C$,

$h_2 = 2796$ kJ/kg.

At 0.1 bar : $s_f = 0.649$ kJ/kg K,

$s_{f_g} = 7.501$ kJ/kg K,

$h_f = 191.8$ kJ/kg K,

$h_{f_g} = 2392.8$ kJ/kg K.

Now, $s_2 = s_3$

i.e., $6.921 = s_{f_3} + x_3\, s_{fg_3}$

$= 0.649 + x_3 \times 7.501$

$\therefore \quad x_3 = \dfrac{6.921 - 0.649}{7.501} = 0.836$

$\therefore \quad h_3 = h_{f_3} + x_3\, h_{fg_3}$

$= 191.8 + 0.836 \times 2392.8$

$= 2192.2$ kJ/kg

Since pump work is neglected

$h_{f_4} = 191.8$ kJ/kg $= h_{f_5}$

$h_{f_6} = 640.1$ (at 5 bar) $= h_{f_7}$

Energy balance for heater gives

$m\,(h_2 - h_{f_6}) = (1 - m)\,(h_{f_6} - h_{f_5})$

$m\,(2796 - 640.1) = (1 - m)\,(640.1 - 191.8)$

$= 448.3\,(1 - m)$

$2155.9\, m = 448.3 - 448.3\, m$

$\therefore \quad m = 0.172$ kg

$\therefore$ Turbine work,

$W_T = (h_1 - h_2) + (1 - m)\,(h_2 - h_3)$

$= (3230.9 - 2796)$

$+ (1 - 0.172)\,(2796 - 2192.2)$

$= 434.9 + 499.9 = 934.8$ kJ/kg

Heat supplied, $Q_1 = h_1 - h_{f_6} = 3230.9 - 640.1$

$= 2590.8$ kJ/kg.

(*i*) $\eta_{\text{cycle}} = \dfrac{W_T}{Q_1} = \dfrac{934.8}{2590.8}$

$= \mathbf{0.3608\ or\ 36.08\%.}$ **(Ans.)**

Steam rate $= \dfrac{3600}{934.8} = \mathbf{3.85\ kg/kWh.}$ **(Ans.)**

(*ii*) $$T_{m_1} = \frac{h_1 - h_{f_7}}{s_1 - s_7} = \frac{2590.8}{6.921 - 1.8604}$$

$= 511.9$ K $= 238.9°$C.

T_{m_1} (without regeneration)

$$= \frac{h_1 - h_{f_4}}{s_1 - s_4} = \frac{3230.9 - 191.8}{6.921 - 0.649}$$

$$= \frac{3039.1}{6.272} = 484.5 \text{ K} = 211.5°\text{C}.$$

Increase in T_{m_1} due to regeneration

$= 238.9 - 211.5 =$ **27.4°C.** **(Ans.)**

W_T (without regeneration)

$= h_1 - h_3 = 3230.9 - 2192.2$

$= 1038.7$ kJ/kg

Steam rate without regeneration

$$= \frac{3600}{1038.7} = 3.46 \text{ kg/kWh}$$

$\therefore$ *Increase in steam rate due to regeneration*

$= 3.85 - 3.46$

$=$ **0.39 kg/kWh.** **(Ans.)**

η_{cycle} (without regeneration)

$$= \frac{h_1 - h_3}{h_1 - h_{f_4}} = \frac{1038.7}{3230.9 - 191.8}$$

$=$ **0.3418 or 34.18%.**

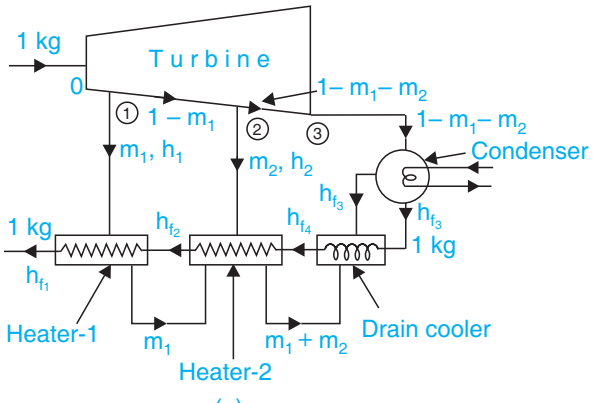
Increase in cycle efficiency due to regeneration

$= 36.08 - 34.18 =$ **1.9%.** **(Ans.)**

Example 2.12. *Steam is supplied to a turbine at 30 bar and 350°C. The turbine exhaust pressure is 0.08 bar. The main condensate is heated regeneratively in two stages by steam bled from the turbine at 5 bar and 1.0 bar respectively. Calculate masses of steam bled off at each pressure per kg of steam entering the turbine and the theoretical thermal efficiency of the cycle.*

Make any suitable assumptions. Assume drain cooler is also used.

Solution. Refer to Fig. 2.23.



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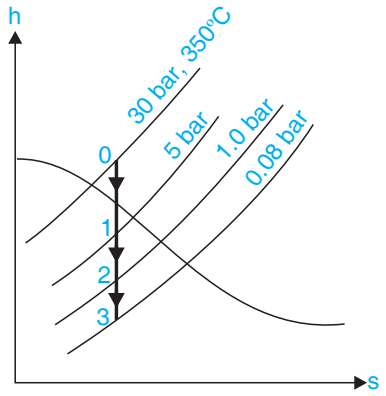


(b)

Fig. 2.23

The following ***assumptions*** are made :

1. The condensate is heated to the saturation temperature in each heater.

2. The drain water from H.P. (high pressure) heater passes into the steam space of the L.P. (low pressure) heater without loss of heat.

3. The combined drains from the L.P. heater are cooled in a drain cooler to the condenser temperature.

4. The expansion of the steam in the turbine is adiabatic and frictionless.

Enthalpy at 30 bar, 350°C, $h_0 = 3115.3$ kJ/kg.

After adiabatic expansion (from Mollier chart)

Enthalpy at 5 bar, $h_1 = 2720$ kJ/kg

Enthalpy at 1.0 bar, $h_2 = 2450$ kJ/kg

Enthalpy at 0.08 bar, $h_3 = 2120$ kJ/kg

From steam tables : $h_{f_1} = 640.1$ kJ/kg (at 5.0 bar)

$h_{f_2} = 417.5$ kJ/kg (at 1.0 bar)

$h_{f_3} = 173.9$ kJ/kg (at 0.08 bar)

At heater No. 1 :

$$m_1 h_1 + h_{f_2} = m_1 h_{f_1} + h_{f_1}$$

$$\mathbf{m_1} = \frac{h_{f_1} - h_{f_2}}{h_1 - h_{f_1}}$$

$$= \frac{640.1 - 417.5}{2720 - 640.1}$$

$=$ **0.107 kJ/kg of entering steam.** **(Ans.)**

At heater No. 2 :

$$m_2 h_2 + m_1 h_{f_1} + h_{f_4} = (m_1 + m_2)\, h_{f_2} + h_{f_2} \quad ...(i)$$

At drain cooler :

$$(m_1 + m_2)\, h_{f_2} + h_{f_3} = h_{f_4} + (m_1 + m_2)\, h_{f_3}$$

$$\therefore \quad h_{f_4} = (m_1 + m_2)\,(h_{f_2} - h_{f_3}) + h_{f_3} \quad ...(ii)$$

Inserting the value of h_{f_4} in eqn. (*i*), we get:

$$m_2h_2 + m_1h_{f_1} + (m_1 + m_2)(h_{f_2} - h_{f_3}) + h_{f_3}$$
$$= (m_1 + m_2)\, h_{f_2} + h_{f_2}$$
$$m_2h_2 + m_1h_{f_1} + (m_1 + m_2)h_{f_2} - (m_1 + m_2)h_{f_3} + h_{f_3}$$
$$= (m_1 + m_2)h_{f_2} + h_{f_2}$$
$$m_2h_2 + m_1h_{f_1} - m_1h_{f_3} - m_2h_{f_3} + h_{f_3} = h_{f_2}$$
$$m_2(h_2 - h_{f_3}) = (h_{f_2} - h_{f_3}) - m_1(h_{f_1} - h_{f_3})$$
$$\therefore \quad \mathbf{m_2} = \frac{(h_{f_2} - h_{f_3}) - m_1(h_{f_1} - h_{f_3})}{(h_2 - h_{f_3})}$$
$$= \frac{(417.5 - 173.9) - 0.107\,(640.1 - 173.9)}{(2450 - 173.9)}$$
$$= \frac{193.7}{2276.1} = \mathbf{0.085\ kJ/kg.} \quad \textbf{(Ans.)}$$

Work done
$$= 1\,(h_0 - h_1) + (1 - m_1)(h_1 - h_2) + (1 - m_1 - m_2)(h_2 - h_3)$$
$$= 1\,(3115.3 - 2720) + (1 - 0.107)(2720 - 2450) + (1 - 0.107 - 0.085)(2450 - 2120)$$
$$= 395.3 + 241.11 + 266.64 = 903.05\ \text{kJ/kg}$$

Heat supplied/kg $= h_0 - h_{f_1}$
$$= 3115.3 - 640.1 = 2475.2\ \text{kJ/kg}$$

$\therefore$ *Thermal efficiency of the cycle*

$$= \frac{\text{Work done}}{\text{Heat supplied}} = \frac{903.05}{2475.2}$$
$$= \mathbf{0.3648\ or\ 36.48\%.} \quad \textbf{(Ans.)}$$

☞Example 2.13. *Steam at a pressure of 20 bar and 250°C enters a turbine and leaves it finally at a pressure of 0.05 bar. Steam is bled off at pressures of 5.0, 1.5 and 0.3 bar. Assuming (i) that the condensate is heated in each heater up to the saturation temperature of the steam in that heater, (ii) that the drain water from each heater is cascaded through a trap into the next heater on the low pressure side of it, (iii) that the combined drains from the heater operating at 0.3 bar are cooled in a drain cooler to condenser temperature, calculate the following :*

(i) Mass of bled steam for each heater per kg of steam entering the turbine.

(ii) Thermal efficiency of the cycle.

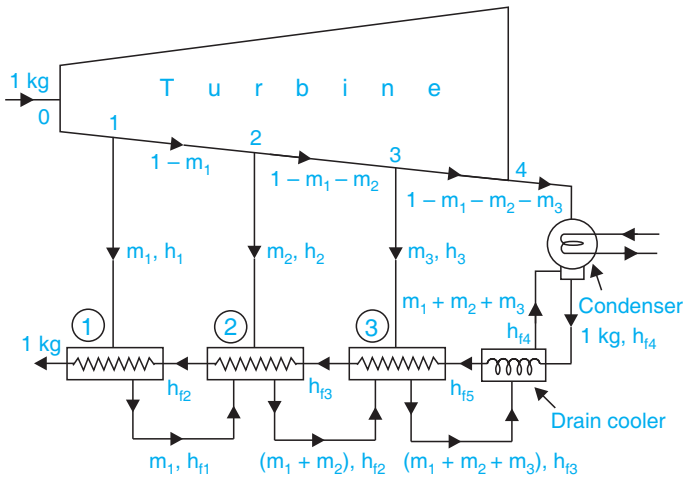
(iii) Thermal efficiency of the Rankine cycle.

(iv) Theoretical gain due to regenerative feed heating.

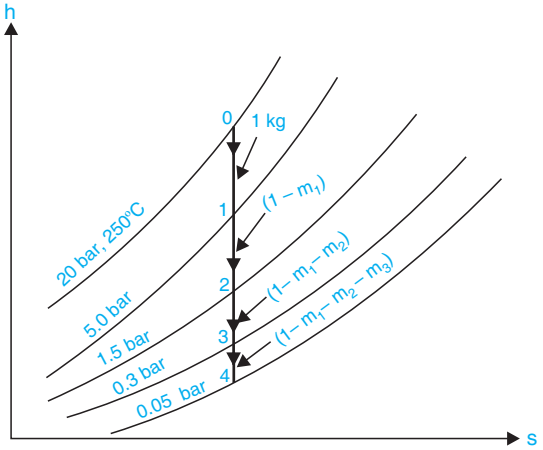
(v) Steam consumption in kg/kWh with or without regenerative feed heating.

(vi) Quantity of steam passing through the last stage nozzle of a 50000 kW turbine with and without regenerative feed heating.

Solution. Refer to Fig. 2.24 (*a*), (*b*).



(a)



(b)

Fig. 2.24

$h_0 = 2905$ kJ/kg,
$h_1 = 2600$ kJ/kg,
$h_2 = 2430$ kJ/kg
$h_3 = 2210$ kJ/kg,
$h_4 = 2000$ kJ/kg

From steam tables :

At 5 bar : $h_{f_1} = 640.1$ kJ/kg

At 1.5 bar : $h_{f_2} = 467.1$ kJ/kg

At 0.3 bar : $h_{f_3} = 289.3$ kJ/kg

At 0.05 bar : $h_{f_4} = 137.8$ kJ/kg.

(*i*) Mass of bled steam for each heater per kg of steam :

Using heat balance equation :

At heater No. 1 :

$$m_1 h_1 + h_{f_2} = m_1 h_{f_1} + h_{f_1}$$

$$\therefore \quad \mathbf{m_1} = \frac{h_{f_1} - h_{f_2}}{h_1 - h_{f_1}} = \frac{640.1 - 467.1}{2600 - 640.1}$$

$$= \mathbf{0.088\ kJ/kg\ of\ entering\ steam.}\ \textbf{(Ans.)}$$

At heater No. 2 :

$$m_2 h_2 + h_{f_3} + m_1 h_{f_1} = h_{f_2} + (m_1 + m_2) h_{f_2}$$

$$\mathbf{m_2} = \frac{(h_{f_2} + h_{f_3}) - m_1 (h_{f_1} - h_{f_2})}{(h_2 - h_{f_2})}$$

$$= \frac{(467.1 - 289.3) - 0.088\,(640.1 - 467.1)}{(2430 - 467.1)}$$

$$= \frac{162.57}{1962.9}$$

$$= \mathbf{0.0828\ kJ/kg\ of\ entering\ steam.}$$

(Ans.)

At heater No. 3 :

$$m_3 h_3 + h_{f_5} + (m_1 + m_2) h_{f_2} = h_{f_3} + (m_1 + m_2 + m_3) h_{f_3} \quad ...(i)$$

At drain cooler :

$$(m_1 + m_2 + m_3) h_{f_3} + h_{f_4} = h_{f_5} + (m_1 + m_2 + m_3) h_{f_4}$$

$$\therefore \quad h_{f_5} = (m_1 + m_2 + m_3)\,(h_{f_3} - h_{f_4}) + h_{f_4} \quad ...(ii)$$

Inserting the value of h_{f_5} in eqn. (i), we get:

$$m_3 h_3 + (m_1 + m_2 + m_3)\,(h_{f_3} - h_{f_4}) + h_{f_4} + (m_1 + m_2)$$

$$h_{f_2} = h_{f_3} + (m_1 + m_2 + m_3) h_{f_3}$$

$$\therefore \quad \mathbf{m_3} = \frac{(h_{f_3} - h_{f_4}) - (m_1 + m_2)\,(h_{f_2} - h_{f_4})}{h_3 - h_{f_4}}$$

$$= \frac{(289.3 - 137.8) - (0.088 + 0.0828)\,(467.1 - 137.8)}{(2210 - 137.8)}$$

$$= \frac{151.5 - 56.24}{2072.2}$$

$$= \mathbf{0.046\ kJ/kg\ of\ entering\ steam.}\ \textbf{(Ans.)}$$

Work done/kg (neglecting pump work)

$$= (h_0 - h_1) + (1 - m_1)\,(h_1 - h_2) + (1 - m_1 - m_2)\,(h_2 - h_3) + (1 - m_1 - m_2 - m_3)\,(h_3 - h_4)$$

$$= (2905 - 2600) + (1 - 0.088)\,(2600 - 2430) + (1 - 0.088 - 0.0828)\,(2430 - 2210) + (1 - 0.088 - 0.0828 - 0.046)\,(2210 - 2000)$$

$$= 305 + 155.04 + 182.42 + 164.47 = 806.93\ \text{kJ/kg}$$

Heat supplied/kg $= h_0 - h_{f_1} = 2905 - 640.1$

$$= 2264.9\ \text{kJ/kg.}$$

(ii) **Thermal efficiency of the cycle :**

$$\eta_{\text{Thermal}} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{806.93}{2264.9}$$

$$= \mathbf{0.3563\ or\ 35.63\%.}\ \textbf{(Ans.)}$$

(iii) **Thermal efficiency of Rankine cycle :**

$$\eta_{\text{Rankine}} = \frac{h_0 - h_4}{h_0 - h_{f_4}} = \frac{2905 - 2000}{2905 - 137.8}$$

$$= \mathbf{0.327\ or\ 32.7\%.}\ \textbf{(Ans.)}$$

(iv) **Theoretical gain due to regenerative feed heating**

$$= \frac{35.63 - 32.7}{35.63}$$

$$= \mathbf{0.0822\ or\ 8.22\%.}\ \textbf{(Ans.)}$$

(v) **Steam consumption with regenerative feed heating**

$$= \frac{1 \times 3600}{\text{Work done / kg}} = \frac{1 \times 3600}{806.93}$$

$$= \mathbf{4.46\ kg/kWh.}\ \textbf{(Ans.)}$$

Steam consumption without regenerative feed heating

$$= \frac{1 \times 3600}{\text{Work done / kg without regeneration}}$$

$$= \frac{1 \times 3600}{h_0 - h_4}$$

$$= \frac{1 \times 3600}{2905 - 2000} = \mathbf{3.97\ kg/kWh.}\ \textbf{(Ans.)}$$

(vi) **Quantity of steam passing through the last stage of a 50000 kW turbine with regenerative feedheating**

$$= 4.46\,(1 - m_1 - m_2 - m_3) \times 50000$$

$$= 4.46\,(1 - 0.088 - 0.0828 - 0.046) \times 50000$$

$$= \mathbf{174653.6\ kg/h.}\ \textbf{(Ans.)}$$

Same without regenerative arrangement

$$= 3.97 \times 50000 = \mathbf{198500\ kg/h.}\ \textbf{(Ans.)}$$

2.8. BINARY VAPOUR CYCLE

Carnot cycle gives the highest thermal efficiency which is given by $\frac{T_1 - T_2}{T_1}$. To approach this cycle in an actual engine it is necessary that whole of heat must be supplied at constant temperature T_1 and rejected at T_2. This can be achieved only by using a vapour in the wet field but not in the superheated. The efficiency depends on temperature T_1 since T_2 is fixed by the natural sink to which heat is rejected. This means that T_1 should be as large as possible, consistent with the vapour being saturated.

If we use steam as the working medium the temperature rise is accompanied by rise in pressure and at critical temperature of 374.15°C the pressure is as high as

226 bar (approx.) which will create many difficulties in design, operation and control. It would be desirable to use some fluid other than steam which has more desirable thermodynamic properties than water. An ideal fluid for this purpose should have a very high critical temperature combined with low pressure. Mercury, diphenyloxide and similar compounds, aluminium bromide and zinc ammonium chloride are fluids which possess the required properties in varying degrees. Mercury is the only working fluid which has been successfully used in practice. It has high critical temperature (588.4°C) and correspondingly low critical pressure (21 bar abs.). *The mercury alone cannot be used as its saturation temperature at atmospheric pressure is high (357°C). Hence binary vapour cycle is generally used to increase the overall efficiency of the plant*. Two fluids (mercury and water) are used in cascade in the binary cycle for production of power.

The *few more properties* required for an ideal binary fluid used in high temperature limit are listed below :

1. It should have high critical temperature at reasonably low pressure.
2. It should have high heat of vaporisation to keep the weight of fluid in the cycle to minimum.
3. Freezing temperature should be below room temperature.
4. It should have chemical stability throughout the working cycle.
5. It must be non-corrosive to the metals normally used in power plants.
6. It must have an ability to wet the metal surfaces to promote the heat transfer.
7. The vapour pressure at a desirable condensation temperature should be nearly atmospheric which will eliminate requirement of power for maintenance of vacuum in the condenser.
8. After expansion through the prime mover the vapour should be nearly saturated so that a desirable heat transfer co-efficient can be obtained which will reduce the size of the condenser required.
9. It must be available in large quantities at reasonable cost.
10. It should not be toxic and, therefore, dangerous to human life.

Although mercury does not have all the required properties, it is more favourable than any other fluid investigated. It is most stable under all operating conditions.

Although, mercury does not cause any corrosion to metals, but it is extremely dangerous to human life, therefore, elaborate precautions must be taken to prevent the escape of vapour. The major *disadvantage* associated with mercury is that it *does not wet surface of the metal and forms a serious resistance to heat flow*. This difficulty can be considerably reduced by adding magnesium and titanium (2 parts in 100000 parts) in mercury.

Thermal properties of mercury :

Mercury fulfils practically all the *desirable thermodynamic properties* stated above.

1. Its freezing point is – 3.3°C and boiling point is – 354.4°C at atmospheric pressure.
2. The pressure required when the temperature of vapour is 540°C is only 12.5 bar (approx.) and, therefore, heavy construction is not required to get high initial temperature.
3. Its liquid saturation curve is very steep, approaching the isentropic of the Carnot cycle.
4. It has no corrosive or erosive effects upon metals commonly used in practice.
5. Its critical temperature is so far removed from any possible upper temperature limit with existing metals as to cause no trouble.

Some *undesirable properties* of mercury are listed below :

1. Since the latent heat of mercury is quite low over a wide range of desirable condensation temperatures, therefore, several kg of mercury must be circulated per kg of water evaporated in binary cycle.
2. The cost is a considerable item as the quantity required is 8 to 10 times the quantity of water circulated in binary system.
3. Mercury vapour in large quantities is poisonous, therefore, the system must be perfect and tight.

Fig. 2.25 shows the schematic line diagram of binary vapour cycle using mercury and water as working fluids. The processes are represented on *T-s* diagram as shown in Fig. 2.26.

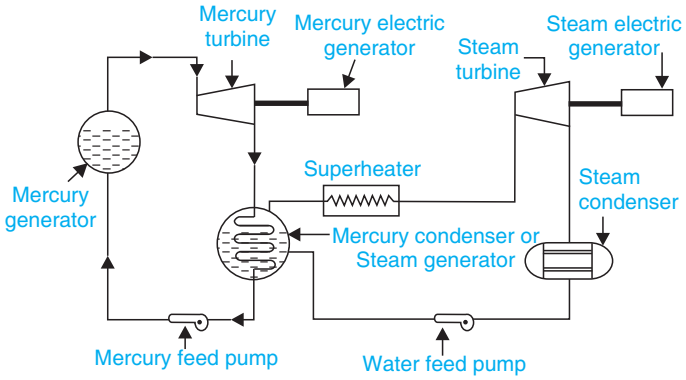


Fig. 2.25. Line diagram of binary vapour cycle.

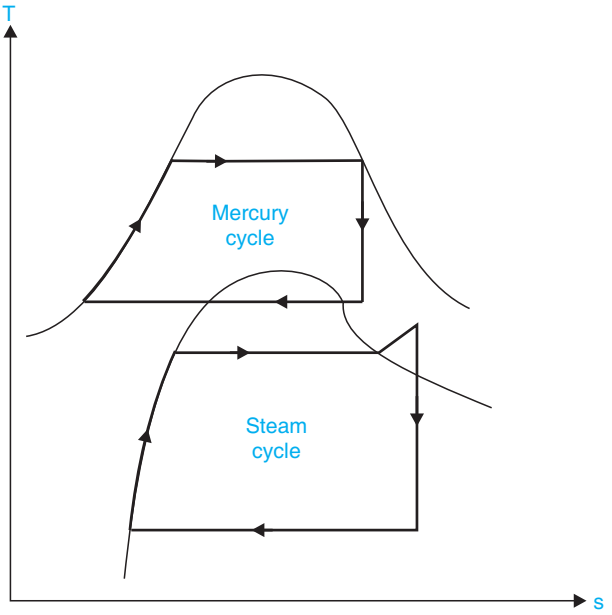


Fig. 2.26. Binary vapour cycle on *T-s* diagram.

Analysis of Binary vapour cycle :

h_{hg_1} = Heat supplied per kg of Hg (mercury) vapour formed in the mercury boiler.

h_{hg_2} = Heat lost by one kg of Hg vapour in the mercury condenser.

h_s = Heat given per kg of steam generated in the mercury condenser or steam boiler.

W_{hg} = Work done per kg of Hg in the cycle.

W_s = Work done per kg of steam in the steam cycle.

η_s = Thermal efficiency of the steam cycle.

η_{hg} = Thermal efficiency of the Hg cycle.

m = Mass of Hg in the Hg cycle per kg of steam circulated in the steam cycle.

The heat losses to the surroundings, in the following analysis, are neglected and steam generated is considered one kg and Hg in the circuit is m kg per kg of water in the steam cycle.

Heat supplied in the Hg boiler,

$$h_t = m \times h_{hg_1} \qquad ...(2.14)$$

Work done in the mercury cycle

$$= m \cdot W_{hg} \qquad ...(2.15)$$

Work done in the steam cycle

$$= 1 \times W_s \qquad ...(2.16)$$

Total work done in the binary cycle is given by

$$W_t = m\, W_{hg} + W_s \qquad ...(2.17)$$

$\therefore$ Overall efficiency of the binary cycle is given by:

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{W_t}{h_t}$$

$$= \frac{m W_{hg} + W_s}{m\, h_{hg_1}} \qquad ...(2.18)$$

Thermal efficiency of the mercury cycle is given by:

$$\eta_{hg} = \frac{m W_{hg}}{m\, h_{hg_1}} = \frac{W_{hg}}{h_{hg_1}}$$

$$= \frac{h_{hg_1} - h_{hg_2}}{h_{hg_1}} = 1 - \frac{h_{hg_2}}{h_{hg_1}} \qquad ...(2.19)$$

$$= \frac{m\, h_{hg_1} - h_s}{m\, h_{hg_1}} = 1 - \frac{1}{m} \cdot \frac{h_s}{h_{hg_1}} \qquad ...(2.20)$$

Heat lost by mercury vapour = Heat gained by steam

$$\therefore \quad m\, h_{hg_2} = 1 \times h_s \qquad ...(2.21)$$

Substituting the value of m from equation (2.21) into equation (2.20), we get

$$\eta_{hg} = 1 - \frac{h_{hg_2}}{h_{hg_1}} \qquad ...(2.22)$$

The thermal efficiency of the steam cycle is given by:

$$\eta_s = \frac{W_s}{h_s} = \frac{h_{s_1} - h_{s_2}}{h_{s_1}} = \frac{h_{s_1} - h_{s_2}}{m\, h_{hg_2}} \qquad ...(2.23)$$

From the equations (2.18), (2.20), (2.21), (2.22) and (2.23), we get

$$\eta = \eta_{hg}\,(1 - \eta_s) + \eta_s \qquad ...(2.24)$$

To solve the problems eqns. (2.19), (2.23), (2.24) are used.

In the design of binary cycle, another important problem is the limit of exhaust pressure of the mercury (location of optimum exhaust pressure) which will provide maximum work per kg of Hg circulated in the system and high thermal efficiency of the cycle. It is not easy to decide as number of controlling factors are many.

☞**Example 2.14.** *A binary vapour cycle operates on mercury and steam. Standard mercury vapour at 4.5 bar is supplied to the mercury turbine, from which it exhausts at 0.04 bar. The mercury condenser generates saturated steam at 15 bar which is expanded in a steam turbine to 0.04 bar.*

(i) Determine the overall efficiency of the cycle.

(ii) If 48000 kg/h of steam flows through the steam turbine, what is the flow through the mercury turbine ?

(*iii*) *Assuming that all processes are reversible, what is the useful work done in the binary vapour cycle for the specified steam flow ?*

(*iv*) *If the steam leaving the mercury condenser is superheated to a temperature of 300°C in a superheater located in the mercury boiler and if the internal efficiencies of the mercury and steam turbines are 0.84 and 0.88 respectively, calculate the overall efficiency of the cycle. The properties of standard mercury are given below :*

p (bar)	*t (°C)*	h_f *(kJ/kg)*	h_g *(kJ/kg)*	s_f *(kJ/kg K)*	s_g *(kJ/kg K)*	v_f (m^3/kg)	v_g (m^3/kg)
4.5	*450*	*62.93*	*355.98*	*0.1352*	*0.5397*	79.9×10^{-6}	*0.068*
0.04	*216.9*	*29.98*	*329.85*	*0.0808*	*0.6925*	76.5×10^{-6}	*5.178*

Solution. The binary vapour cycle is shown in Fig. 2.27.

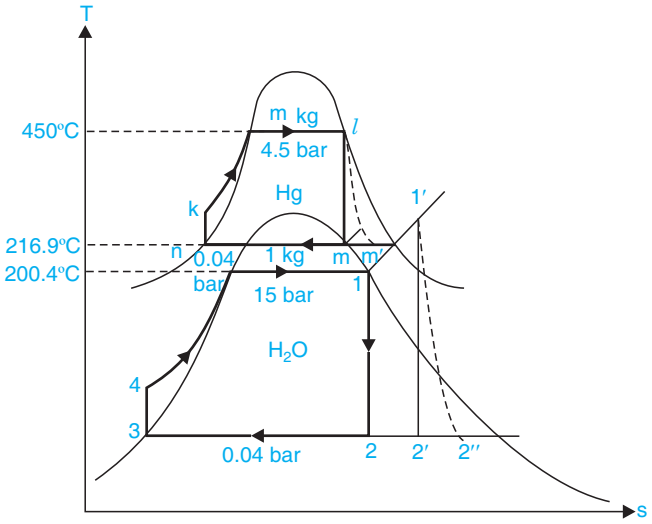


Fig. 2.27

Mercury cycle :

$$h_l = 355.98 \text{ kJ/kg}$$

$$s_l = 0.5397 = s_m = s_f + x_m\, s_{fg}$$

or $$0.5397 = 0.0808 + x_m\,(0.6925 - 0.0808)$$

$$\therefore \quad x_m = \frac{(0.5397 - 0.0808)}{(0.6925 - 0.0808)} = 0.75$$

$$h_m = h_f + x_m\, h_{fg}$$
$$= 29.98 + 0.75 \times (329.85 - 29.98)$$
$$= 254.88 \text{ kJ/kg}$$

Work obtained from mercury turbine

$$(W_T)_{Hg} = h_l - h_m = 355.98 - 254.88$$
$$= 101.1 \text{ kJ/kg}$$

Pump work in mercury cycle,

$$(W_P)_{Hg} = h_{f_k} - h_{f_n} = 76.5 \times 10^{-6} \times (4.5 - 0.04) \times 100$$
$$= 0.0341 \text{ kJ/kg}$$

$$\therefore \quad W_{net} = 101.1 - 0.0341 \simeq 101.1 \text{ kJ/kg}$$

$$Q_1 = h_l - h_{f_k} = 355.98 - 29.98$$
$$= 326 \text{ kJ/kg} \qquad (\because \ h_{f_n} \simeq h_{f_k})$$

$$\therefore \quad \eta_{Hg\ cycle} = \frac{W_{net}}{Q_1} = \frac{101.1}{326} = 0.31 \quad \text{or} \quad 31\%.$$

Steam cycle :

At 15 bar : $h_1 = 2789.9$ kJ/kg, $s_1 = 6.4406$ kJ/kg

At 0.04 bar : $h_f = 121.5$ kJ/kg, $h_{f_g} = 2432.9$ kJ/kg,

$s_f = 0.432$ kJ/kg K,

$s_{fg_2} = 8.052$ kJ/kg K, $v_f = 0.001\ m^3$/kg

Now, $$s_1 = s_2$$

$$6.4406 = s_f + x_2\, s_{fg} = 0.423 + x_2 \times 8.052$$

$$\therefore \quad x_2 = \frac{6.4406 - 0.423}{8.052} = 0.747$$

$$h_2 = h_f + x_2\, h_{f_g}$$
$$= 121.5 + 0.747 \times 2432.9$$
$$= 1938.8 \text{ kJ/kg}$$

Work obtained from steam turbine,

$$(W_T)_{steam} = h_1 - h_2 = 2789.9 - 1938.8$$
$$= 851.1 \text{ kJ/kg}$$

Pump work in steam cycle,

$$(W_P)_{steam} = h_{f_4} - h_{f_3} = 0.001\,(15 - 0.04) \times 100$$
$$= 1.496 \text{ kJ/kg} \simeq 1.5 \text{ kJ/kg}$$

or $$h_{f_4} = h_{f_3} + 1.5 = 121.5 + 1.5$$
$$= 123 \text{ kJ/kg}$$

$$Q_1 = h_1 - h_{f_2} = 2789.9 - 123$$
$$= 2666.9 \text{ kJ/kg}$$

$$(W_{net})_{steam} = 851.1 - 1.5 = 849.6 \text{ kJ/kg}$$

$$\therefore \quad \eta_{steam\ cycle} = \frac{W_{net}}{Q_1} = \frac{849.6}{2666.6} = 0.318 \text{ or } 31.8\%.$$

(*i*) **Overall efficiency of the binary cycle :**

Overall efficiency of the binary cycle

$$= \eta_{Hg_{cycle}} + \eta_{steam\ cycle} - \eta_{Hg_{cycle}} \times \eta_{steam\ cycle}$$
$$= 0.31 + 0.318 - 0.31 \times 0.318$$
$$= 0.5294 \text{ or } 52.94\%$$

Hence *overall efficiency of the binary cycle*

$$= \mathbf{52.94\%.} \quad \textbf{(Ans.)}$$

$\eta_{overall}$ can also be found out as follows :

Energy balance for a mercury condenser-steam boiler gives :

$$m(h_m - h_{f_n}) = 1\,(h_1 - h_{f_4})$$

where m is the amount of mercury circulating for 1 kg of steam in the bottom cycle

$$\therefore \quad m = \frac{h_1 - h_{f_4}}{h_m - h_{f_n}} = \frac{2666.9}{254.88 - 29.98}$$
$$= 11.86 \text{ kg}$$
$$(Q_1)_{total} = m\,(h_l - h_{f_k}) = 11.86 \times 326$$
$$= 3866.36 \text{ kJ/kg}$$
$$(W_T)_{total} = m\,(h_l - h_m) + (h_1 - h_2)$$
$$= 11.86 \times 101.1 + 851.1 = 2050.1 \text{ kJ/kg}$$

$(W_P)_{total}$ may be *neglected*

$$\eta_{overall} = \frac{W_T}{Q_1} = \frac{2050.1}{3866.36} = 0.53 \text{ or } 53\%.$$

(*ii*) Flow through mercury turbine :

If 48000 kg/h of steam flows through the steam turbine, the flow rate of mercury would be

$$w_{Hg} = 48000 \times 11.86 = \mathbf{569280\ kg/h.} \quad \textbf{(Ans.)}$$

(*iii*) Useful work in binary vapour cycle :

Useful work, $(W_T)_{total} = 2050.1 \times 48000$
$$= 9840.5 \times 10^4 \text{ kJ/h}$$
$$= \frac{9840.5 \times 10^4}{3600}$$
$$= 27334.7 \text{ kW}$$
$$= \mathbf{27.33\ MW.} \quad \textbf{(Ans.)}$$

(*iv*) Overall efficiency under new conditions :

Considering the efficiencies of turbines, we have :

$$(W_T)_{Hg} = h_l - h_{m'} = 0.84 \times 101.1$$
$$= 84.92 \text{ kJ/kg}$$
$$\therefore \quad h_{m'} = h_l - 84.92 = 355.98 - 84.92$$
$$= 271.06 \text{ kJ/kg}$$
$$\therefore \quad m'\,(h_{m'} - h_{n'}) = (h_1 - h_{f_4})$$

or
$$m' = \frac{h_1 - h_{f_4}}{h_{m'} - h_{n'}} = \frac{2666.9}{271.06 - 29.98}$$
$$= 11.06 \text{ kg}$$

$$(Q_1)_{total} = m'\,(h_l - h_{f_k}) + 1\,(h_1' - h_1)$$

[***At 15 bar, 300°C :***

$$h_g = 3037.6 \text{ kJ/kg},\ s_g = 6.918 \text{ kJ/kg K}]$$
$$= 11.06 \times 326 + (3037.6 - 2789.9)$$
$$= 3853.26 \text{ kJ/kg}$$
$$s_1' = 6.918 = s_2' = 0.423 + x_2' \times 8.052$$
$$\therefore \quad x_2' = \frac{6.918 - 0.423}{8.052} = 0.80.$$
$$h_2' = 121.5 + 0.807 \times 2432.9$$
$$= 2084.8 \text{ kJ/kg}$$
$$(W_T)_{steam} = h_1' - h_2' = 0.88\,(3037.6 - 2084.8)$$
$$= 838.46 \text{ kJ/kg}$$
$$(W_T)_{total} = 11.06 \times 84.92 + 838.46$$
$$= 1777.67 \text{ kJ/kg}$$

Neglecting pump work,

$$\eta_{overall} = \frac{1777.67}{3853.26} = \mathbf{0.4613 \text{ or } 46.13\%.} \quad \textbf{(Ans.)}$$

GAS POWER CYCLES

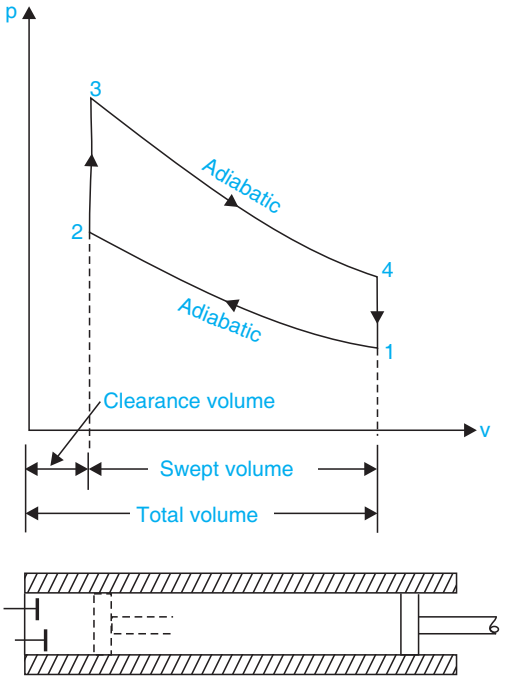
2.9. OTTO CYCLE

This cycle is so named as it was conceived by 'Otto'. On this cycle, petrol, gas and many types of oil engines work. It is the standard of comparison for internal combustion engines.

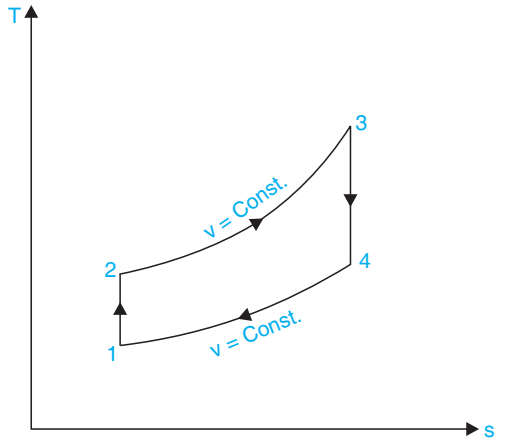
Fig. 2.28 (*a*) and (*b*) shows the theoretical *p-v* diagram and *T-s* diagrams of this cycle respectively.

The point 1 represents that cylinder is full of air with volume V_1, pressure p_1 and absolute temperature T_1.

- Line 1–2 represents the *adiabatic compression* of air due to which p_1, V_1 and T_1 change to p_2, V_2 and T_2 respectively.
- Line 2-3 shows the *supply of heat to the air at constant volume* so that p_2 and T_2 change to p_3 and T_3 (V_3 being the same as V_2).
- Line 3–4 represents the *adiabatic expansion* of the air. During expansion p_3, V_3 and T_3 change to final values of p_4, V_4 or V_1 and T_4 respectively.
- Line 4–1 shows the *rejection of heat* by air at constant volume till original state (point 1) reaches.



(a) p-v diagram



(b) T-s diagram

Fig. 2.28. Otto cycle.

Consider 1 kg of air (working substance) :

Heat supplied at constant volume = $c_v(T_3 - T_2)$.

Heat rejected at constant volume = $c_v (T_4 - T_1)$.

But, work done = Heat supplied – Heat rejected

$= c_v (T_3 - T_2) - c_v (T_4 - T_1)$

$$\therefore \quad \text{Efficiency} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{c_v (T_3 - T_2) - c_v (T_4 - T_1)}{c_v (T_3 - T_2)}$$

$$= 1 - \frac{T_4 - T_1}{T_3 - T_2} \qquad ...(i)$$

Let compression ratio, $r_c\ (= r) = \dfrac{v_1}{v_2}$

and expansion ratio, $r_e\ (= r) = \dfrac{v_4}{v_3}$

(These two ratios are *same* in this cycle)

As $\dfrac{T_2}{T_1} = \left(\dfrac{v_1}{v_2}\right)^{\gamma - 1}$

Then, $T_2 = T_1 \,.\, (r)^{\gamma - 1}$

Similarly, $\dfrac{T_3}{T_4} = \left(\dfrac{v_4}{v_3}\right)^{\gamma - 1}$

or $T_3 = T_4 \,.\, (r)^{\gamma - 1}$

Inserting the values of T_2 and T_3 in equation (i), we get:

$$\eta_{otto} = 1 - \frac{T_4 - T_1}{T_4 \,.\, (r)^{\gamma - 1} - T_1 \,.\, (r)^{\gamma - 1}}$$

$$= 1 - \frac{T_4 - T_1}{r^{\gamma - 1}(T_4 - T_1)}$$

$$= 1 - \frac{1}{(r)^{\gamma - 1}} \qquad ...(2.25)$$

This expression is known as the ***air standard efficiency*** *of the Otto cycle.*

It is clear from the above expression that efficiency increases with the increase in the value of r, which means we can have maximum efficiency by increasing r to a considerable extent, but *due to practical difficulties its value is limited to about 8.*

The net **work done per kg** in the Otto cycle can also be expressed in terms of pv. If p is expressed in bar *i.e.,* 10^5 N/m^2, then work done

$$W = \left(\frac{p_3 v_3 - p_4 v_4}{\gamma - 1} - \frac{p_2 v_2 - p_1 v_1}{\gamma - 1}\right) \times 10^2 \text{ kJ} \qquad ...(2.26)$$

Also, $\dfrac{p_3}{p_4} = r^{\gamma} = \dfrac{p_2}{p_1}$

$$\therefore \quad \frac{p_3}{p_2} = \frac{p_4}{p_1} = r_p$$

where r_p stands for *pressure ratio*.

and $v_1 = r v_2 = v_4 = r v_3 \qquad \left[\because \dfrac{v_1}{v_2} = \dfrac{v_4}{v_3} = r\right]$

$$\therefore \quad W = \frac{1}{\gamma - 1}\left[p_4 r\left(\frac{p_3 v_3}{p_4 r} - v_3\right) - p_1 r\left(\frac{p_2 v_2}{p_1 r} - v_2\right)\right]$$

$$= \frac{rv_2}{\gamma - 1}[p_4 (r^{\gamma - 1} - 1) - p_1 (r^{\gamma - 1} - 1)]$$

$$= \frac{v_1}{\gamma - 1}[(r^{\gamma - 1} - 1)(p_4 - p_1)]$$

$$= \frac{p_1 v_1}{\gamma - 1}[(r^{\gamma - 1} - 1)(r_p - 1)] \quad ...[2.26\ (a)]$$

Mean effective pressure is given by :

$$p_m = \left[\left(\frac{p_3 v_3 - p_4 v_4}{\gamma - 1} - \frac{p_2 v_2 - p_1 v_1}{\gamma - 1}\right) \div (v_1 - v_2)\right] \text{ bar}$$

Also, $$p_m = \frac{\left[\frac{p_1 v_1}{\gamma - 1}(r^{\gamma - 1} - 1)(r_p - 1)\right]}{(v_1 - v_2)}$$

$$= \frac{\frac{p_1 v_1}{\gamma - 1}[(r^{\gamma - 1} - 1)(r_p - 1)]}{(v_1 - v_2)}$$

$$= \frac{\frac{p_1 v_1}{\gamma - 1}[(r^{\gamma - 1} - 1)(r_p - 1)]}{v_1 - \frac{v_1}{r}}$$

$$= \frac{\frac{p_1 v_1}{\gamma - 1}[(r^{\gamma - 1} - 1)(r_p - 1)]}{v_1\left(\frac{r - 1}{1}\right)}$$

i.e., $$= \frac{p_1 r[(r^{\gamma - 1} - 1)(r_p - 1)]}{(\gamma - 1)(r - 1)}. \quad ...(2.27)$$

Example 2.15. *The efficiency of an Otto cycle is 60% and* $\gamma = 1.5$. *What is the compression ratio ?*

Solution. Efficiency of Otto cycle, $\eta = 60\%$

Ratio of specific heats, $\gamma = 1.5$

Compression ratio, $\mathbf{r} = ?$

Efficiency of Otto cycle is given by:

$$\eta_{Otto} = 1 - \frac{1}{(r)^{\gamma - 1}}$$

$$0.6 = 1 - \frac{1}{(r)^{1.5 - 1}}$$

or, $$\frac{1}{(r)^{0.5}} = 0.4 \quad \text{or} \quad (r)^{0.5} = \frac{1}{0.4} = 2.5$$

or, $$r = 6.25$$

Hence, *compression ratio* = **6.25.** **(Ans.)**

Example 2.16. *In a constant volume 'Otto cycle', the pressure at the end of compression is 15 times that at the start, the temperature of air at the beginning of compression is 38°C and maximum temperature attained in the cycle is 1950°C. Determine :*

(i) Compression ratio.

(ii) Thermal efficiency of the cycle.

(iii) Work done per kg of air.

Take γ *for air = 1.4.*

Solution. Refer to Fig. 2.29.

Initial temperature, $T_1 = 38 + 273 = 311$ K

Maximum temperature, $T_3 = 1950 + 273 = 2223$ K.

(i) **Compression ratio, r :**

For adiabatic compression 1–2,

$$p_1 v_1^{\gamma} = p_2 v_2^{\gamma} \quad \text{or} \quad \left(\frac{v_1}{v_2}\right)^{\gamma} = \frac{p_2}{p_1}$$

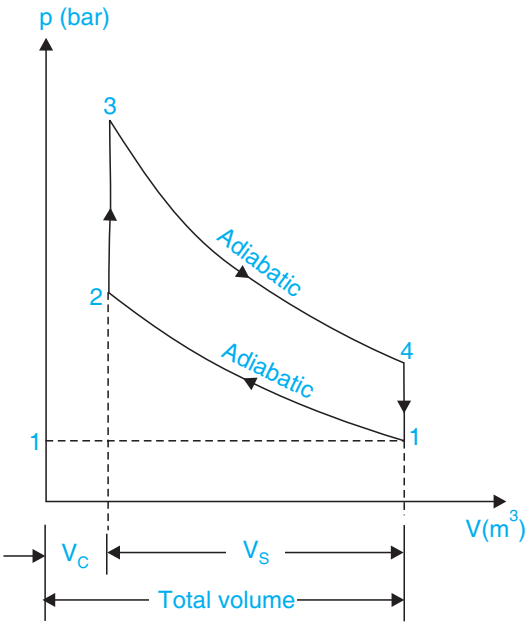
But, $$\frac{p_2}{p_1} = 15 \quad ...(\text{given})$$

$\therefore$ $$(r)^{\gamma} = 15 \quad \left[\because\ r = \frac{v_1}{v_2}\right]$$

or $$(r)^{1.4} = 15$$

or $$r = (15)^{\frac{1}{1.4}} = (15)^{0.714} = 6.9$$

Hence *compression ratio* = **6.9.** **(Ans.)**



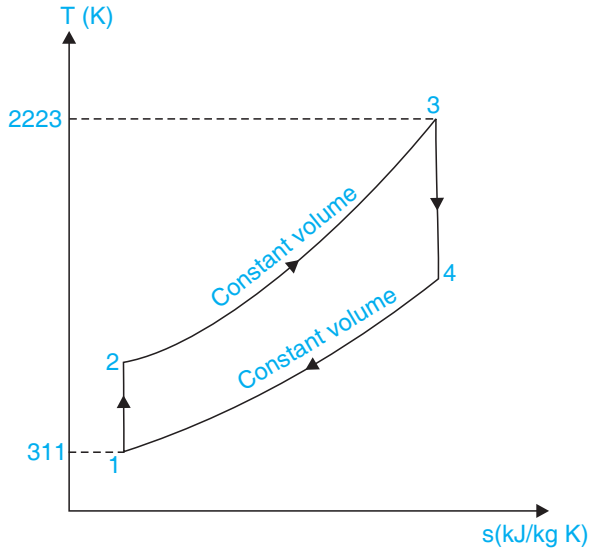


Fig. 2.29

(*ii*) **Thermal efficiency :**

Thermal efficiency,

$$\eta_{th} = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(6.9)^{1.4-1}}$$

$$= \mathbf{0.538 \text{ or } 53.8\%.} \quad \textbf{(Ans.)}$$

(*iii*) **Work done :**

Again, for adiabatic compression,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = (r)^{\gamma-1}$$

$$= (6.9)^{1.4-1} = (6.9)^{0.4} = 2.16$$

or $$T_2 = T_1 \times 2.16 = 311 \times 2.16$$

$$= 671.7 \text{ K or } 398.7°\text{C}$$

For adiabatic expansion process 3-4:

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = (r)^{\gamma-1}$$

$$= (6.9)^{0.4} = 2.16$$

or $$T_4 = \frac{T_3}{2.16} = \frac{2223}{2.16} = 1029 \text{ K or } 756°\text{C}$$

Heat supplied per kg of air

$$= c_v(T_3 - T_2) = 0.717(2223 - 671.7)$$

$$\left[c_v = \frac{R}{\gamma - 1} = \frac{0.287}{1.4 - 1} = 0.717 \text{ kJ/ kg K}\right]$$

$$= 1112.3 \text{ kJ/kg or air}$$

Heat rejected per kg of air

$$= c_v(T_4 - T_1) = 0.717(1029 - 311)$$

$$= 514.8 \text{ kJ/kg of air}$$

$\therefore$ *Work done*

= Heat supplied – heat rejected

$$= 1112.3 - 514.8$$

$$= \mathbf{597.5 \text{ kJ or } 597500 \text{ Nm.}} \quad \textbf{(Ans.)}$$

☞**Example 2.17.** *An engine working on Otto cycle has a volume of 0.45 m³, pressure 1 bar and temperature 30°C at the beginning of compression stroke. At the end of compression stroke, the pressure is 11 bar. 210 kJ of heat is added during constant volume heating process. Determine :*

(i) Pressures, temperatures and volumes at salient points in the cycle.

(ii) Percentage clearance.

(iii) Efficiency.

(iv) Net work per cycle.

(v) Mean effective pressure.

(vi) Ideal power developed by the engine if the number of working cycles per minute is 210.

Assume the cycle is reversible.

Solution. Refer to Fig. 2.30

Volume,

$$V_1 = 0.45 \text{ m}^3$$

Initial pressure,

$$p_1 = 1 \text{ bar}$$

Initial temperature,

$$T_1 = 30 + 273 = 303 \text{ K}$$

Pressure at the end of compression stroke,

$$p_2 = 11 \text{ bar}$$

Heat added at constant volume

$$= 210 \text{ kJ}$$

Number of working cycles/min.

$$= 210.$$

(*i*) **Pressures, temperatures and volumes at salient points :**

For adiabatic compression 1–2:

$$p_1V_1^{\gamma} = p_2V_2^{\gamma}$$

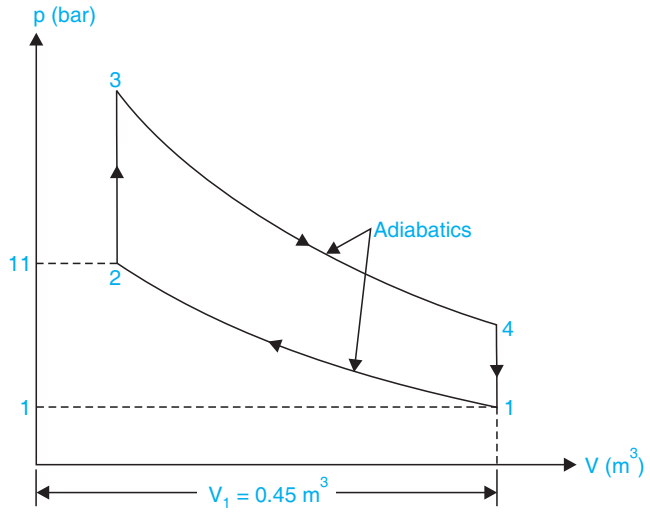


Fig. 2.30

or $$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r)^{\gamma}$$

or $$r = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} = \left(\frac{11}{1}\right)^{\frac{1}{1.4}} = (11)^{0.714} = 5.5$$

Also, $$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r)^{\gamma-1}$$

$$= (5.5)^{1.4-1} = 1.977 \simeq 1.98$$

$\therefore$ $T_2 = T_1 \times 1.98 = 303 \times 1.98$

$= \mathbf{600\ K.}$ **(Ans.)**

Applying gas laws to points 1 and 2, we get

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

$\therefore$ $$V_2 = \frac{T_2}{T_1} \times \frac{p_1}{p_2} \times V_1 = \frac{600 \times 1 \times 0.45}{303 \times 11}$$

$= \mathbf{0.081\ m^3.}$ **(Ans.)**

The heat supplied during the process 2–3 is given by :

$$Q_s = m\, c_v\, (T_3 - T_2)$$

where $$m = \frac{p_1V_1}{RT_1} = \frac{1 \times 10^5 \times 0.45}{287 \times 303} = 0.517 \text{ kg}$$

$\therefore$ $210 = 0.517 \times 0.71\ (T_3 - 600)$

or, $$T_3 = \frac{210}{0.517 \times 0.71} + 600$$

$= \mathbf{1172\ K.}$ **(Ans.)**

For the constant volume process 2–3

$$\frac{p_3}{T_3} = \frac{p_2}{T_2}$$

$\therefore$ $$p_3 = \frac{T_3}{T_2} \times p_2 = \frac{1172}{600} \times 11$$

$= \mathbf{21.48\ bar.}$ **(Ans.)**

$V_3 = V_2 = \mathbf{0.081\ m^3.}$ **(Ans.)**

For the adiabatic (or isentropic) process 3–4

$$p_3V_3^{\gamma} = p_4V_4^{\gamma}$$

$$p_4 = p_3 \times \left(\frac{V_3}{V_4}\right)^{\gamma} = p_3 \times \left(\frac{1}{r}\right)^{\gamma}$$

$$= 21.48 \times \left(\frac{1}{5.5}\right)^{1.4}$$

$= \mathbf{1.97\ bar.}$ **(Ans.)**

Also, $$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1}$$

$$= \left(\frac{1}{5.5}\right)^{1.4-1} = 0.505$$

$\therefore$ $T_4 = 0.505\ T_3 = 0.505 \times 1172$

$= \mathbf{591.8\ K.}$ **(Ans.)**

$V_4 = V_1 = \mathbf{0.45\ m^3.}$ **(Ans.)**

(*ii*) **Percentage clearance :**

Percentage clearance

$$= \frac{V_c}{V_s} = \frac{V_2}{V_1 - V_2} \times 100$$

$$= \frac{0.081}{0.45 - 0.081} \times 100$$

$= \mathbf{21.95\%.}$ **(Ans.)**

(*iii*) **Efficiency :**

The heat rejected per cycle is given by:

$$Q_r = mc_v(T_4 - T_1)$$

$= 0.517 \times 0.71\ (591.8 - 303)$

$= \mathbf{106\ kJ}$

The air-standard efficiency of the cycle is given by

$$\eta_{otto} = \frac{Q_s - Q_r}{Q_s} = \frac{210 - 106}{210}$$

$= \mathbf{0.495\ or\ 49.5\%.}$ **(Ans.)**

[It can also be calculated as follows :

$$\eta_{otto} = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(5.5)^{1.4-1}}$$

$= \mathbf{0.495\ or\ 49.5\%.}$ **(Ans.)**]

(*iv*) **Mean effective pressure, p_m :**

The mean effective pressure is given by:

$$p_m = \frac{W\ (\text{work done})}{V_s(\text{swept volume})} = \frac{Q_s - Q_r}{(V_1 - V_2)}$$

$$= \frac{(210 - 106) \times 10^3}{(0.45 - 0.081) \times 10^5}$$

$= \mathbf{2.818\ bar.}$ **(Ans.)**

(*v*) **Power developed, P :**

Power developed, P = work done per second

= work done per cycle

× number of cycles per second

$= (210 - 106) \times (210/60)$

$= \mathbf{364\ kW.}$ **(Ans.)**

2.10. DIESEL CYCLE

This cycle was introduced by Dr. R. Diesel in 1897. It differs from Otto cycle, in, that heat is supplied at *constant pressure* instead of at constant volume. Fig. 2.31 (*a*) and

(*b*) shows the *p-v* and *T-s* diagrams of this cycle respectively.

This cycle comprises of the following *operations* :

(*i*) 1–2.....Adiabatic compression.

(*ii*) 2–3.....Addition of heat at constant pressure.

(*iii*) 3–4.....Adiabatic expansion.

(*iv*) 4–1.....Rejection of heat at constant volume.

Point 1 represents that the cylinder is full of air. Let p_1, V_1 and T_1 be the corresponding pressure, volume and absolute temperature. The piston then compresses the air adiabatically (*i.e.* pV^γ = constant) till the values become p_2, V_2 and T_2 respectively (at the end of the stroke) at point 2. Heat is then added from a hot body at a constant pressure. During this addition of heat let volume increases from V_2 to V_3 and temperature T_2 to T_3, corresponding to point 3. This point (3) is called the *point of cut-off*. The air then expands adiabatically to the conditions p_4, V_4 and T_4 respectively corresponding to point 4. Finally, the air rejects the heat to the cold body at constant volume till the point 1 where it returns to its original state.

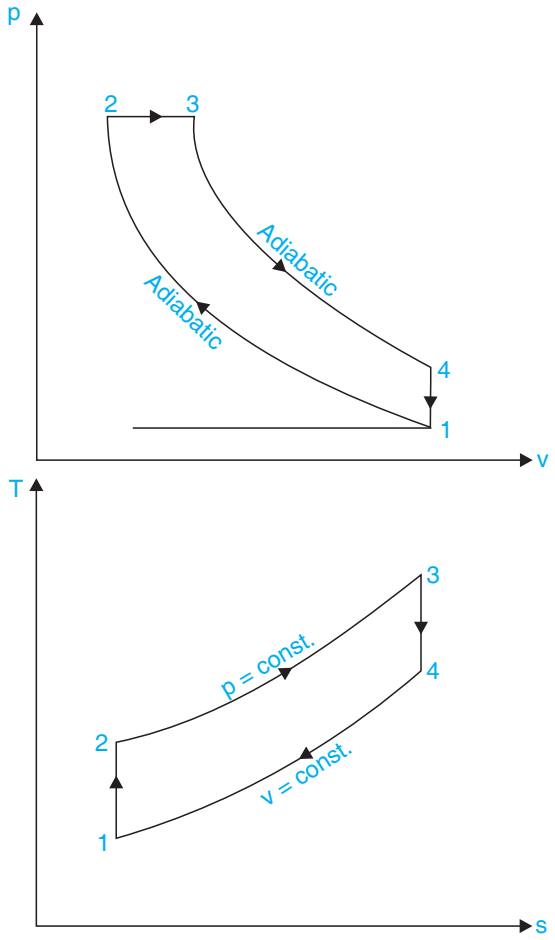


Fig. 2.31

Consider 1 kg of air.

Heat supplied at constant pressure = $c_p(T_3 - T_2)$

Heat rejected at constant volume = $c_v(T_4 - T_1)$

Work done = Heat supplied – Heat rejected

$= c_v(T_3 - T_2) - c_v(T_4 - T_1)$

$$\text{Air standard } \eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{c_p(T_3 - T_2) - c_v(T_4 - T_1)}{c_p(T_3 - T_2)}$$

$$= 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)} \qquad ...(i)$$

$$\left[\because \frac{c_p}{c_v} = \gamma\right]$$

Let compression ratio,

$$r = \frac{v_1}{v_2} \text{ and cut-off ratio,}$$

$$\rho = \frac{v_3}{v_2} \text{ i.e., } \frac{\text{Volume at cut-off}}{\text{Clearance volume}}$$

Now, during adiabatic compression 1–2,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1} = (r)^{\gamma - 1}$$

or, $$T_2 = T_1 \,.\, (r)^{\gamma - 1}$$

During constant pressure process 2–3,

$$\frac{T_3}{T_2} = \frac{v_3}{v_2} = \rho$$

or, $$T_3 = \rho \,.\, T_2 = \rho \,.\, T_1 \,.\, (r)^{\gamma - 1}$$

During adiabatic expansion 3–4,

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma - 1} = \left(\frac{r}{\rho}\right)^{\gamma - 1}$$

$$\left(\because \frac{v_4}{v_3} = \frac{v_1}{v_3} = \frac{v_1}{v_2} \times \frac{v_2}{v_3} = \frac{r}{\rho}\right)$$

$$\therefore \quad T_4 = \frac{T_3}{\left(\frac{r}{\rho}\right)^{\gamma - 1}} = \frac{\rho \,.\, T_1 (r)^{\gamma - 1}}{\left(\frac{r}{\rho}\right)^{\gamma - 1}} = T_1 \,.\, \rho^\gamma$$

By inserting values of T_2, T_3 and T_4 in equation (*i*), we get:

$$\eta = 1 - \frac{(T_1 \,.\, \rho^\gamma - T_1)}{(\rho \,.\, T_1 \,.\, (r)^{\gamma - 1} - T_1 \,.\, (r)^{\gamma - 1})}$$

$$= 1 - \frac{(\rho^\gamma - 1)}{\gamma (r)^{\gamma - 1} (\rho - 1)}$$

$$= 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \left[\frac{\rho^\gamma - 1}{\rho - 1}\right] \qquad ...(2.28)$$

It may be observed that equation (2.28) for efficiency of diesel cycle is different from that of the Otto cycle only in bracketed factor. This factor is *always greater than unity*, because $\rho > 1$. Hence *for a given compression ratio, the Otto cycle is more efficient*.

The *network* for diesel cycle can be expressed in terms of *pv* as follows :

$$W = p_2(v_3 - v_2) + \frac{p_3v_3 - p_4v_4}{\gamma - 1} - \frac{p_2v_2 - p_1v_1}{\gamma - 1}$$

$$= p_2v_2(\rho - 1) + \frac{p_3\rho v_2 - p_4rv_2}{\gamma - 1} - \frac{p_2v_2 - p_1rv_2}{\gamma - 1}$$

$$= \frac{v_2[p_2(\rho - 1)(\gamma - 1) + p_2\rho - p_4r - (p_2 - p_1r)]}{\gamma - 1}$$

$$(\because \quad p_2 = p_3)$$

$$= \frac{v_2\left[p_2(\rho - 1)(\gamma - 1) + p_2\left(\rho - \frac{p_4}{p_2}r\right) - p_2\left(1 - \frac{p_1r}{p_2}\right)\right]}{\gamma - 1}$$

$$= \frac{p_1v_1r^{\gamma - 1}[(\rho - 1)(\gamma - 1) + \rho - \rho^{\gamma}r^{1-\gamma} - (1 - r^{1-\gamma})]}{\gamma - 1}$$

$$= \frac{p_1v_1r^{\gamma - 1}[\gamma(\rho - 1) - r^{1-\gamma}(\rho^{\gamma} - 1)]}{(\gamma - 1)} \qquad ...(2.29)$$

Mean effective pressure is given by:

$$p_m = \frac{p_1v_1r^{\gamma - 1}[\gamma(\rho - 1) - r^{1-\gamma}(\rho^{\gamma} - 1)]}{(\gamma - 1)v_1\left(\frac{r - 1}{r}\right)}$$

$$= \frac{p_1r^{\gamma}[\gamma(\rho - 1) - r^{1-\gamma}(\rho^{\gamma} - 1)]}{(\gamma - 1)(r - 1)} . \qquad ...(2.30)$$

2.11. DUAL COMBUSTION CYCLE

This cycle (also called the *limited pressure cycle or mixed cycle*) is a combination of Otto and Diesel cycles, in a way, that heat is added partly at constant volume and partly at constant pressure ; *the advantage of which is that more time is available to fuel (which is injected into the engine cylinder before the end of compression stroke) for combustion. Because of laging characteristics of fuel this cycle is invariably used for diesel and hot spot ignition engines.*

The dual combustion cycle (Fig. 2.32) consists of the following *operations :*

(*i*) 1–2. Adiabatic compression.
(*ii*) 2–3. Addition of heat at constant volume.
(*iii*) 3–4. Addition of heat at constant pressure.
(*iv*) 4–5. Adiabatic expansion.
(*v*) 5–1. Rejection of heat at constant volume.

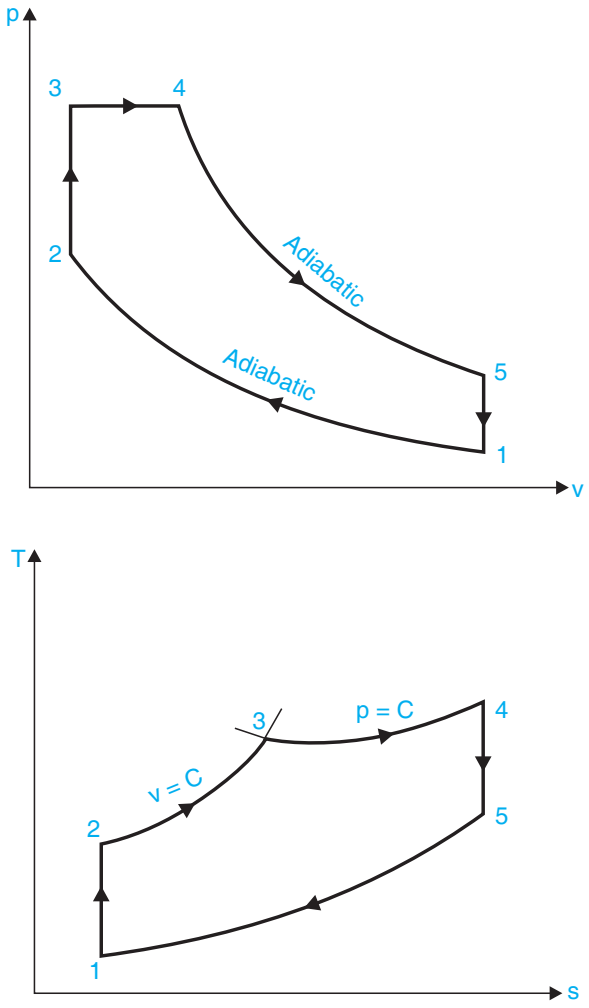


Fig. 2.32. Diesel cycle.

Consider 1 kg of air.

Total heat supplied

= Heat supplied during the operation 2–3
+ Heat supplied during the operation 3–4

$= c_v(T_3 - T_2) + c_p(T_4 - T_3)$

Heat rejected during operation 5–1 $= c_v(T_5 - T_1)$

Work done = Heat supplied – Heat rejected

$= c_v(T_3 - T_2) + c_p(T_4 - T_3) - c_v(T_5 - T_1)$

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{c_v(T_3 - T_2) + c_p(T_4 - T_3) - c_v(T_5 - T_1)}{c_v(T_3 - T_2) + c_p(T_4 - T_3)}$$

$$= 1 - \frac{c_v(T_5 - T_1)}{c_v(T_3 - T_2) + c_p(T_4 - T_3)}$$

$$= 1 - \frac{c_v (T_5 - T_1)}{(T_3 - T_2) + \gamma (T_4 - T_3)} \quad ...(i)$$

$$\left(\because \quad \gamma = \frac{c_p}{c_v}\right)$$

Compression ratio, $r = \frac{v_1}{v_2}$

During adiabatic compression process 1–2,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1} = (r)^{\gamma - 1} \quad ...(ii)$$

During constant volume heating process,

$$\frac{p_3}{T_3} = \frac{p_2}{T_2}$$

or, $$\frac{T_3}{T_2} = \frac{p_3}{p_2} = \beta,$$

where β is known as ***pressure or explosion ratio.***

or, $$T_2 = \frac{T_3}{\beta} \quad ...(iii)$$

During adiabatic expansion process,

$$\frac{T_4}{T_5} = \left(\frac{v_5}{v_4}\right)^{\gamma - 1} = \left(\frac{r}{\rho}\right)^{\gamma - 1} \quad ...(iv)$$

$$\left(\because \quad \frac{v_5}{v_4} = \frac{v_1}{v_4} = \frac{v_1}{v_2} \times \frac{v_2}{v_4} = \frac{v_1}{v_2} \times \frac{v_3}{v_4} = \frac{r}{\rho}, \right.$$
$$\left. \rho \text{ being the cut-off ratio} \right)$$

During constant pressure heating process,

$$\frac{v_3}{T_3} = \frac{v_4}{T_4}$$

$$T_4 = T_3 \frac{v_4}{v_3} = \rho\, T_3 \quad ...(v)$$

Putting the value of T_4 in the equation (iv), we get:

$$\frac{\rho T_3}{T_5} = \left(\frac{r}{\rho}\right)^{\gamma - 1} \quad \text{or} \quad T_5 = \rho \,.\, T_3 \left(\frac{\rho}{r}\right)^{\gamma - 1}$$

Putting the value of T_2 in equation (ii), we get:

$$\frac{\frac{T_3}{\beta}}{T_1} = (r)^{\gamma - 1}$$

$$T_1 = \frac{T_3}{\beta} \cdot \frac{1}{(r)^{\gamma - 1}}$$

Now inserting the values of T_1, T_2, T_4 and T_5 in equation (i), we get:

$$\eta = 1 - \frac{\left[\rho \,.\, T_3 \left(\frac{\rho}{r}\right)^{\gamma - 1} - \frac{T_3}{\beta} \cdot \frac{1}{(r)^{\gamma - 1}}\right]}{\left[\left(T_3 - \frac{T_3}{\beta}\right) + \eta(\rho T_3 - T_3)\right]}$$

$$= 1 - \frac{\frac{1}{(r)^{\gamma - 1}}\left(\rho^{\gamma} - \frac{1}{\beta}\right)}{\left(1 - \frac{1}{\beta}\right) + \gamma(\rho - 1)}$$

i.e., $$\eta = 1 - \frac{1}{(r)^{\gamma - 1}} \cdot \frac{(\beta \,.\, \rho^{\gamma} - 1)}{[(\beta - 1) + \beta\gamma(\rho - 1)]} \quad ...(2.31)$$

Work done is given by,

$$W = p_3(v_4 - v_3) + \frac{p_4 v_4 - p_5 v_5}{\gamma - 1} - \frac{p_2 v_2 - p_1 v_1}{\gamma - 1}$$

$$= p_3 v_3(\rho - 1) + \frac{(p_3 \rho v_3 - p_5 r v_3) - (p_2 v_3 - p_1 r v_3)}{\gamma - 1}$$

$$= \frac{p_3 v_3(\rho - 1)(\gamma - 1) + p_4 v_3\left(\rho - \frac{p_5}{p_4} r\right) - p_2 v_3\left(1 - \frac{p_1}{p_2} r\right)}{\gamma - 1}$$

Also, $$\frac{p_3}{p_4} = \left(\frac{v_4}{v_3}\right)^{\gamma} = \left(\frac{\rho}{r}\right)^{\gamma}$$

and $$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = r^{\gamma}$$

also, $$p_3 = p_4,\ v_2 = v_3,\ v_5 = v_1$$

$$\therefore \quad W = \frac{v_3[p_3(\rho - 1)(\gamma - 1) + p_3(\rho - \rho^{\gamma} r^{1 - \gamma}) - p_2(1 - r^{1 - \gamma})]}{(\gamma - 1)}$$

$$= \frac{p_2 v_2[\beta(\rho - 1)(\gamma - 1) + \beta(\rho - \rho^{1 - \gamma}) - (1 - r^{1 - \gamma})]}{(\gamma - 1)}$$

$$= \frac{p_1 (r)^{\gamma} v_1 / \gamma[\beta\gamma(\rho - 1) + (\beta - 1) - r^{1 - \gamma}(\beta\rho^{\gamma - 1})]}{\gamma - 1}$$

$$= \frac{p_1 v_1 r^{\gamma - 1}[\beta\gamma(\rho - 1) + (\beta - 1) - r^{\gamma - 1}(\beta\rho^{\gamma - 1})]}{\gamma - 1} \quad ...(2.32)$$

Mean effective pressure,

$$p_m = \frac{W}{v_1 - v_2} = \frac{W}{v_1\left(\frac{r - 1}{r}\right)}$$

$$= \frac{p_1 v_1[r^{1 - \gamma}\beta\gamma(\rho - 1) + (\beta - 1) - r^{1 - \gamma}(\beta\rho^{\gamma} - 1)]}{(\gamma - 1) v_1\left(\frac{r - 1}{r}\right)}$$

$$= \frac{p_1 (r)^{\gamma}[\beta(\rho - 1) + (\beta - 1) - r^{1 - \gamma}(\beta\rho^{\gamma} - 1)]}{(\gamma - 1)(r - 1)} \quad ...(2.33)$$

DIESEL CYCLE

Example 2.18. *A diesel engine has a compression ratio of 15 and heat addition at constant pressure takes place at 6% of stroke. Find the air standard efficiency of the engine. Take γ for air as 1.4.*

Solution. Refer to Fig. 2.33.

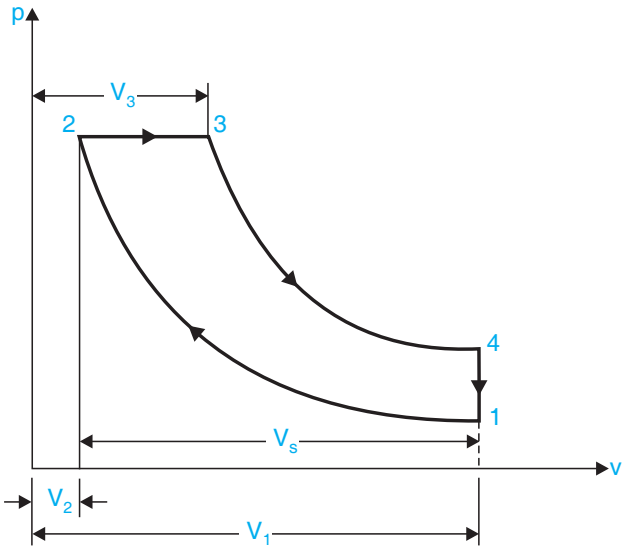


Fig. 2.33

Compression ratio, $r \left(= \frac{V_1}{V_2}\right) = 15$

γ for air = 1.4

Air standard efficiency of diesel cycle is given by:

$$\eta_{diesel} = 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \left[\frac{\rho^{\gamma} - 1}{\rho - 1}\right] \qquad ...(i)$$

where, ρ = Cut-off ratio = $\frac{V_3}{V_2}$

But $V_3 - V_2 = \frac{6}{100} V_s$ (V_s = stroke volume)

$= 0.06 (V_1 - V_2) = 0.06 (15 V_2 - V_2)$

$= 0.84 V_2$ or $V_3 = 1.84 V_2$

$\therefore \quad \rho = \frac{V_3}{V_2} = \frac{1.84 V_2}{V_2} = 1.84$

Putting the value in eqn. (*i*), we get:

$$\eta_{diesel} = 1 - \frac{1}{1.4 (15)^{1.4 - 1}} \left[\frac{(1.84)^{1.4} - 1}{1.84 - 1}\right]$$

$= 1 - 0.2417 \times 1.605$

$=$ **0.612 or 61.2%.** **(Ans.)**

Example 2.19. *The stroke and cylinder diameter of a compression ignition engine are 250 mm and 150 mm respectively. If the clearance volume is 0.0004 m^3 and fuel injection takes place at constant pressure for 5% of the stroke determine the efficiency of the engine. Assume the engine working on the diesel cycle.*

Solution. Refer to Fig. 2.31.

Length of stroke,

$L = 250$ mm $= 0.25$ m

Diameter of cylinder,

$D = 150$ mm $= 0.15$ m

Clearance volume,

$V_2 = 0.0004$ m^3

Swept volume,

$V_s = \pi/4\ D^2 L = \pi/4 \times 0.15^2 \times 0.25$

$= 0.004418$ m^3

Total cylinder volume

= Swept volume + Clearance volume

$= 0.004418 + 0.0004 = 0.004818$ m^3

Volume at point of cut-off,

$$V_3 = V_2 + \frac{5}{100} V_s$$

$$= 0.0004 + \frac{5}{100} \times 0.004418$$

$= 0.000621$ m^3

$\therefore$ Cut-off ratio,

$$\rho = \frac{V_3}{V_2} = \frac{0.000621}{0.0004} = 1.55$$

Compression ratio,

$$r = \frac{V_1}{V_2} = \frac{V_s + V_2}{V_2}$$

$$= \frac{0.004418 + 0.0004}{0.0004} = 12.04$$

Hence, $\eta_{diesel} = 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \left[\frac{\rho^{\gamma} - 1}{\rho - 1}\right]$

$$= 1 - \frac{1}{1.4 \times (12.04)^{1.4 - 1}} \left[\frac{(1.55)^{1.4} - 1}{1.55 - 1}\right]$$

$= 1 - 0.264 \times 1.54$

$=$ **0.593 or 59.3%.** **(Ans.)**

Example 2.20. *Calculate the percentage loss in the ideal efficiency of a diesel engine with compression ratio 14 if the fuel cut-off is delayed from 5% to 8%.*

Solution. Let the clearance volume be *unity*.

Then, compression ratio,

$r = 14$

Now, when the fuel is cut-off at 5%, we have

$$\frac{\rho - 1}{r - 1} = \frac{5}{100} \quad \text{or} \quad \frac{\rho - 1}{14 - 1} = 0.05$$

or $\rho - 1 = 13 \times 0.05 = 0.65$

$\therefore \quad \rho = 1.65$

$$\eta_{diesel} = 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \left[\frac{\rho^{\gamma} - 1}{\rho - 1}\right]$$

$$= 1 - \frac{1}{1.4 (14)^{1.4 - 1}} \left[\frac{(1.65)^{1.4} - 1}{1.65 - 1}\right]$$

$= 1 - 0.248 \times 1.563 = 0.612$ or 61.2%

When the fuel is cut-off at 8%, we have:

$$\frac{\rho - 1}{r - 1} = \frac{8}{100} \quad \text{or} \quad \frac{\rho - 1}{14 - 1} = \frac{8}{100} = 0.08$$

$$\therefore \qquad \rho = 1 + 1.04 = 2.04$$

$$\eta_{diesel} = 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \left[\frac{\rho^{\gamma} - 1}{\rho - 1} \right]$$

$$= 1 - \frac{1}{1.4\,(14)^{1.4 - 1}} \left[\frac{(2.04)^{1.4} - 1}{2.04 - 1} \right]$$

$$= 1 - 0.248 \times 1.647$$

$$= \mathbf{0.591 \quad or \quad 59.1\%.} \quad \textbf{(Ans.)}$$

Hence *percentage loss in efficiency* due to delay in fuel cut-off

$$= 61.2 - 59.1 = \mathbf{2.1\%.} \quad \textbf{(Ans.)}$$

Example 2.21. *The mean effective pressure of a Diesel cycle is 7.5 bar and compression ratio is 12.5. Find the percentage cut-off of the cycle if its initial pressure is 1 bar.*

Solution. Mean effective pressure,

$$p_m = 7.5 \text{ bar}$$

Compression ratio,

$$r = 12.5$$

Initial pressure,

$$p_1 = 1 \text{ bar}$$

Refer to Fig. 2.31.

The mean effective pressure is given by:

$$p_m = \frac{p_1 r^{\gamma} [\gamma (\rho - 1) - r^{1 - \gamma} (\rho^{\gamma} - 1)]}{(\gamma - 1)(r - 1)}$$

$$7.5 = \frac{1 \times (12.5)^{1.4} [1.4\,(\rho - 1) - (12.5)^{1 - 1.4} (\rho^{1.4} - 1)]}{(1.4 - 1)(12.5 - 1)}$$

$$7.5 = \frac{34.33[1.4\,\rho - 1.4 - 0.364\rho^{1.4} + 0.364]}{4.6}$$

$$7.5 = 7.46\,(1.4\,\rho - 1.036 - 0.364\,\rho^{1.4})$$

$$1.005 = 1.4\,\rho - 1.036 - 0.364\,\rho^{1.4}$$

or, $\quad 2.04 = 1.4\,\rho - 0.364\,\rho^{1.4}$

or, $\quad 0.346\,\rho^{1.4} - 1.4\,\rho + 2.04 = 0$

Solving by trial and error method, we get:

$$\rho = 2.24$$

$$\therefore \quad \text{percentage cut-off} = \frac{\rho - 1}{r - 1} \times 100$$

$$= \frac{2.24 - 1}{12.5 - 1} \times 100 = \mathbf{10.78\%.} \quad \textbf{(Ans.)}$$

☞**Example 2.22.** *An engine with 200 mm cylinder diameter and 300 mm stroke works on theoretical Diesel cycle. The initial pressure and temperature of air used are 1 bar and 27°C. The cut-off is 8% of the stroke. Determine :*

(i) Pressures and temperatures at all salient points.

(ii) Theoretical air standard efficiency.

(iii) Mean effective pressure.

(iv) Power of the engine if the working cycles per minute are 380.

Assume that compression ratio is 15 and working fluid is air.

Consider all conditions to be ideal.

Solution. Refer to Fig. 2.34.

Cylinder diameter, $\quad D = 200$ mm or 0.2 m

Stroke length, $\quad L = 300$ mm or 0.3 m

Initial pressure, $\quad p_1 = 1.0$ bar

Initial temperature, $\quad T_1 = 27 + 273 = 300$ K

$$\text{Cut-off} = \frac{8}{100} V_s = 0.08\, V_s$$

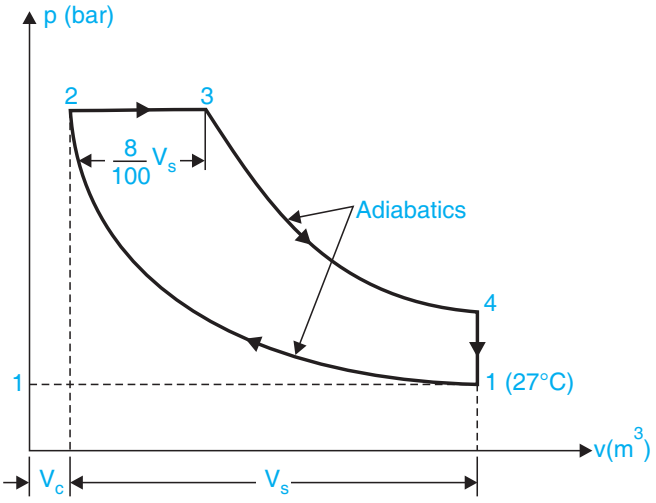


Fig. 2.34

(i) Pressures and temperatures at salient points :

Now, stroke volume,

$$V_s = \pi/4\, D^2 L = \pi/4 \times 0.2^2 \times 0.3$$

$$= 0.00942 \text{ m}^3$$

$$V_1 = V_s + V_c = V_s + \frac{V_s}{r - 1} \qquad \left[\because \; V_c = \frac{V_s}{r - 1} \right]$$

$$= V_s \left(1 + \frac{1}{r - 1} \right) = \frac{r}{r - 1} \times V_s$$

i.e., $\quad V_1 = \frac{15}{15 - 1} \times V_s = \frac{15}{14} \times 0.00942$

$$= \mathbf{0.0101 \text{ m}^3.} \quad \textbf{(Ans.)}$$

Mass of the air in the cylinder can be calculated by using the gas equation,

$$p_1V_1 = mRT_1$$

$$m = \frac{p_1V_1}{RT_1} = \frac{1\times10^5\times0.0101}{287\times300}$$

$$= 0.0117 \text{ kg/cycle}$$

For the adiabatic (or isentropic) process 1–2,

$$p_1V_1^{\gamma} = p_2V_2^{\gamma} \quad \text{or} \quad \frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r)^{\gamma}$$

$$\therefore \quad p_2 = p_1 \cdot (r)^{\gamma} = 1 \times (15)^{1.4}$$

$$= \mathbf{44.31 \text{ bar.}} \quad \textbf{(Ans.)}$$

$$\text{Also,} \quad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r)^{\gamma-1} = (15)^{1.4-1} = 2.954$$

$$\therefore \quad T_2 = T_1 \times 2.954 = 300 \times 2.954$$

$$= \mathbf{886.2 \text{ K.}} \quad \textbf{(Ans.)}$$

$$V_2 = V_c = \frac{V_s}{r-1} = \frac{0.00942}{15-1}$$

$$= \mathbf{0.0006728 \text{ m}^3\text{.}} \quad \textbf{(Ans.)}$$

$$p_2 = p_3 = \mathbf{44.31 \text{ bar.}} \quad \textbf{(Ans.)}$$

$$\% \text{ Cut-off ratio} = \frac{\rho-1}{r-1}$$

$$\frac{8}{100} = \frac{\rho-1}{15-1}$$

i.e., $$\rho = 0.08 \times 14 + 1 = 2.12$$

$$\therefore \quad V_3 = \rho\, V_2 = 2.12 \times 0.0006728$$

$$= \mathbf{0.001426 \text{ m}^3\text{.}} \quad \textbf{(Ans.)}$$

V_3 can also be calculated as follows:

$$V_3 = 0.08V_s + V_c = 0.08 \times 0.00942 + 0.0006728$$

$$= 0.001426 \text{ m}^3$$

For the constant pressure process 2–3:

$$\frac{V_3}{T_3} = \frac{V_2}{T_2}$$

$$\therefore \quad T_3 = T_2 \times \frac{V_3}{V_2} = 886.2 \times \frac{0.001426}{0.0006728}$$

$$= \mathbf{1878.3 \text{ K.}} \quad \textbf{(Ans.)}$$

For the isentropic process 3–4

$$p_3V_3^{\gamma} = p_4V_4^{\gamma}$$

$$p_4 = p_3 \times \left(\frac{V_3}{V_4}\right)^{\gamma} = p_3 \times \frac{1}{(7.07)^{1.4}}$$

$$= \frac{44.31}{(7.07)^{1.4}} = \mathbf{2.866 \text{ bar.}} \quad \textbf{(Ans.)}$$

$$\left[\because \quad \frac{V_4}{V_3} = \frac{V_4}{V_2} \times \frac{V_2}{V_3} = \frac{V_1}{V_2} \times \frac{V_2}{V_3} = \frac{r}{\rho}, \quad (\because \quad V_4 = V_1)\right.$$

$$\left. = \frac{15}{2.12} = 7.07\right]$$

$$\text{Also,} \quad \frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{1}{7.07}\right)^{1.4-1} = 0.457$$

$$\therefore \quad T_4 = T_3 \times 0.457 = 1878.3 \times 0.457$$

$$= \mathbf{858.38 \text{ K.}} \quad \textbf{(Ans.)}$$

$$V_4 = V_1 = \mathbf{0.0101 \text{ m}^3\text{.}} \quad \textbf{(Ans.)}$$

(*ii*) **Theoretical air standard efficiency :**

$$\eta_{\text{diesel}} = 1 - \frac{1}{\gamma(r)^{\gamma-1}}\left[\frac{\rho^{\gamma}-1}{\rho-1}\right]$$

$$= 1 - \frac{1}{1.4\,(15)^{1.4-1}}\left[\frac{(2.12)^{1.4}-1}{2.12-1}\right]$$

$$= 1 - 0.2418 \times 1.663$$

$$= \mathbf{0.598 \text{ or } 59.8\%\text{.}} \quad \textbf{(Ans.)}$$

(*iii*) **Mean effective pressure, p_m :**

Mean effective pressure of Diesel cycle is given by:

$$p_m = \frac{p_1(r)^{\gamma}[\gamma(\rho-1) - r^{1-\gamma}(\rho^{\gamma}-1)}{(\gamma-1)(r-1)}$$

$$= \frac{1\times(15)^{1.4}[1.4(2.12-1) - (15)^{1-1.4}(2.12^{1.4}-1)]}{(1.4-1)(15-1)}$$

$$= \frac{44.31[1.568 - 0.338\times1.863]}{0.4\times14}$$

$$= \mathbf{7.424 \text{ bar.}} \quad \textbf{(Ans.)}$$

(*iv*) **Power of the engine, P :**

Work done per cycle

$$= p_mV_s = \frac{7.424\times10^5\times0.00942}{10^3} = 6.99 \text{ kJ/cycle}$$

Work done per second

= Work done per cycle × No. of cycles per second

= 6.99 × 380/60 = 44.27 kJ/s = 44.27 kW

Hence *power of the engine* = **44.27 kW.** **(Ans.)**

DUAL CYCLE

Example 2.23. *The swept volume of a diesel engine working on dual cycle is 0.0053 m^3 and clearance volume is 0.00035 m^3. The maximum pressure is 65 bar. Fuel injection ends at 5% of the stroke. The temperature and pressure at the start of the compression are 80°C and 0.9 bar. Determine the air standard efficiency of the cycle. Take γ for air = 1.4.*

Solution. Refer to Fig. 2.35.

Swept volume,	$V_s = 0.0053 \text{ m}^3$
Clearance volume,	$V_c = V_3 = V_2 = 0.00035 \text{ m}^3$
Maximum pressure,	$p_3 = p_4 = 65$ bar
Initial temperature,	$T_1 = 80 + 273 = 353$ K
Initial pressure,	$p_1 = 0.9$ bar

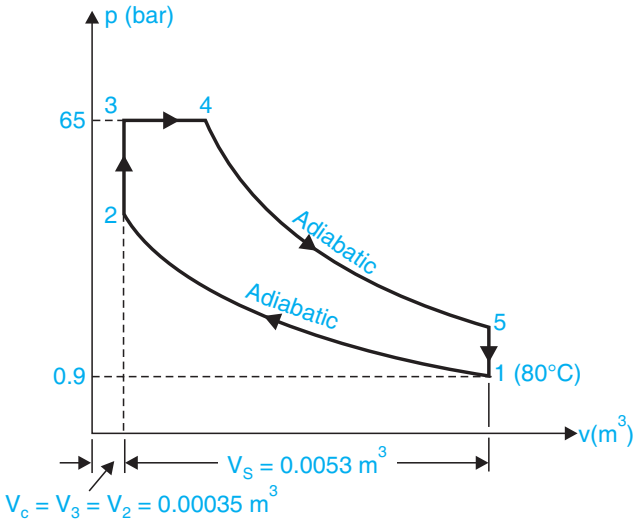


Fig. 2.35

η_{dual} :

The efficiency of a dual combustion cycle is given by:

$$\eta_{dual} = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{\beta \cdot \rho^{\gamma} - 1}{(\beta - 1) + \beta\gamma(\rho - 1)}\right] \quad ...(i)$$

Compression ratio,

$$r = \frac{V_1}{V_2} = \frac{V_s + V_c}{V_c} = \frac{0.0053 + 0.00035}{0.00035}$$

$$= 16.14$$

$[\because \quad V_2 = V_3 = V_c$ = clearance volume]

Cut-off-ratio,

$$\rho = \frac{V_4}{V_3} = \frac{\frac{5}{100}V_s + V_3}{V_3} = \frac{0.05\,V_3 + V_c}{V_c}$$

$$= \frac{0.05 \times 0.0053 + 0.00035}{0.00035}$$

$$= 1.757 \text{ say } 1.76$$

Also during the compression operation 1–2,

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$$

or, $$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (16.15)^{1.4} = 49.14$$

or, $$p_2 = p_1 \times 49.14 = 0.9 \times 49.14 = 44.22 \text{ bar}$$

Pressure or explosion ratio,

$$\beta = \frac{p_3}{p_2} = \frac{62}{44.22} = 1.47$$

Putting the value of r, ρ and β in equation (i), we get:

$$\eta_{dual} = 1 - \frac{1}{(16.14)^{1.4-1}}\left[\frac{1.47 \times (1.76)^{1.4} - 1}{(1.47 - 1) + 1.47 \times 1.4\,(1.76 - 1)}\right]$$

$$= 7 - 0.328\left[\frac{3.243 - 1}{0.47 + 1.564}\right]$$

$$= \mathbf{0.6383 \text{ or } 63.83\%.} \quad \textbf{(Ans.)}$$

2.12. GAS TURBINE CYCLES

Refer to articles 5.11 and 5.12.

HIGHLIGHTS

1. Carnot cycle efficiency = $\frac{T_1 - T_2}{T_1}$.
2. Rankine cycle is the theoretical cycle on which steam prime movers work.

   Rankine efficiency = $\frac{h_1 - h_2}{h_1 - h_{f_4}}$.
3. Expression for efficiency of Rankine cycle in terms of temperatures,

$$\eta_{Rankine} = \frac{c_{pw}(T_1 - T_2)\left(1 + \frac{x_1 h_{fg_1}}{T_1}\right) - T_2 \cdot c_{pw} \log_e \frac{T_1}{T_2}}{c_{pw}(T_1 - T_2) + x_1 h_{fg_1}}.$$

4. Modified Rankine efficiency = $\frac{(h_1 - h_2) + (p_1 - p_2)\,v_2}{h_1 - h_{f_3}}$.
5. The theoretical thermal efficiency of reheat cycle is given by:

$$\eta_{thermal} = \frac{[(h_1 - h_2) + (h_3 - h_4)] - W_p}{[(h_1 - h_{f_4}) + (h_3 - h_2)] - W_p}$$

Pump work W_p is usually small and neglected.

6. $$\eta_{Otto} = 1 - \frac{1}{(r)^{\gamma-1}} .$$
7. $$\eta_{Diesel} = 1 - \frac{1}{\gamma(r)^{\gamma-1}}\left[\frac{\rho^{\gamma} - 1}{\rho - 1}\right]$$

   and $$p_m = \frac{p_1 r^{\gamma}[\gamma(\rho - 1) - r^{1-\gamma}(\rho^{\gamma} - 1)]}{(\gamma - 1)(r - 1)} .$$
8. $$\eta_{Dual} = 1 - \frac{1}{(r)^{\gamma-1}}\frac{(\beta.\rho^{\gamma} - 1)}{[(\beta - 1) + \beta\gamma(\rho - 1)]}$$

$$p_m = \frac{p_1 (r)^{\gamma}[\beta(\rho - 1) + (\beta - 1) - r^{1-\gamma}(\beta\rho^{\gamma} - 1)]}{(\gamma - 1)(r - 1)} .$$

THEORETICAL QUESTIONS

1. Describe the different operations of Rankine-cycle. Derive also the expression for its efficiency.
2. How does a modified Rankine cycle differ from a Rankine cycle ? Write also the expression of modified Rankine efficiency.

3. State the methods of increasing the thermal efficiency of a Rankine cycle.
4. Explain with the help of neat diagrams a 'Regenerative Cycle'. Derive also an expression for its thermal efficiency.
5. State the advantages of regenerative cycle over simple Rankine cycle.
6. Explain with a neat diagram the working of a Binary vapour cycle.
7. Derive expressions for efficiencies of the following :
   (*i*) Diesel cycle (*ii*) Dual combustion cycle
   (*iii*) Open cycle (constant pressure) gas turbine.

UNSOLVED EXAMPLES

1. A simple Rankine cycle works between pressure of 30 bar and 0.04 bar, the initial condition of steam being dry saturated, calculate the cycle efficiency, work ratio and specific steam consumption.
   [**Ans.** 35%, 0.997, 3.84 kg/kWh]
2. A steam power plant works between 40 bar and 0.05 bar. If the steam supplied is dry saturated and the cycle of operation is Rankine, find :
   (*i*) Cycle efficiency.
   (*ii*) Specific steam consumption.
   [**Ans.** (*i*) 35.5%, (*ii*) 3.8 kg/kWh]
3. Compare the Rankine efficiency of a high pressure plant operating from 80 bar and 400°C and a low pressure plant operating from 40 bar 400°C, if the condenser pressure in both cases is 0.07 bar. [**Ans.** 0.391 and 0.357]
4. A steam power plant working on Rankine cycle has the range of operation from 40 bar dry saturated to 0.05 bar. Determine :
   (*i*) The cycle efficiency (*ii*) Work ratio
   (*iii*) Specific fuel consumption.
   [**Ans.** (*i*) 35.64%, (*ii*) 0.9957, (*iii*) 3.8 kg/kWh]
5. In a Rankine cycle, the steam at inlet to turbine is saturated at a pressure of 30 bar and the exhaust pressure is 0.25 bar. Determine :
   (*i*) The pump work (*ii*) Turbine work
   (*iii*) Rankine efficiency (*iv*) Condenser heat flow
   (*v*) Dryness at the end of expansion.
   Assume flow rate of 10 kg/s.
   [**Ans.** (*i*) 30 kW, (*ii*) 7410 kW, (*iii*) 29.2%, (*iv*) 17900 kW, (*v*) 0.763]
6. In a regenerative cycle the inlet conditions are 40 bar and 400°C. Steam is bled at 10 bar in regenerative heating. The exit pressure is 0.8 bar. Neglecting pump work determine the efficiency of the cycle. [**Ans.** 0.296]
7. A turbine with one bleeding for regenerative heating of feed water is admitted with steam having enthalpy of 3200 kJ/kg and the exhausted steam has an enthalpy of 2200 kJ/kg. The ideal regenerative feed water heater is fed with 11350 kg/h of bled steam at 3.5 bar (whose enthalpy is 2600 kJ/h). The feed water (condensate from the condenser) with an enthalpy of 134 kJ/kg is pumped to the heater. It leaves the heater dry saturated at 3.5 bar. Determine the power developed by the turbine.
   [**Ans.** 16015 kW]
8. A binary-vapour cycle operates on mercury and steam. Saturated mercury vapour at 4.5 bar is supplied to the mercury turbine, from which it exhausts at 0.04 bar. The mercury condenser generates saturated steam at 15 bar which is expanded in a steam turbine to 0.04 bar.
   (*i*) Find the overall efficiency of the cycle.
   (*ii*) If 50000 kg/h of steam flows through the steam turbine, what is the flow through the mercury turbine ?
   (*iii*) Assuming that all processess are reversible, what is the useful work done in the binary vapour cycle for the specified steam flow ?
   (*iv*) If the steam leaving the mercury condenser is superheated to a temperature of 300°C in a superheater located in the mercury boiler, and if the internal efficiencies of the mercury and steam turbines are 0.85 and 0.87 respectively, calculate the overall efficiency of the cycle. The properties of saturated mercury are as follows :

p (bar)	t (°C)	h_f (kJ/kg)	h_g (kJ/kg)	s_f (kJ/kg K)	s_g (kJ/kg K)	v_f (m^3/kg)	v_g (m^3/kg)
4.5	450	62.93	355.98	0.1352	0.5397	79.9×10^{-6}	0.068
0.04	216.9	29.98	329.85	0.0808	0.6925	76.5×10^{-3}	5.178

   [**Ans.** (*i*) 52.94%, (*ii*) 59.35×10^4 kg/h, (*iii*) 28.49 MW, (*iv*) 46.2%]
9. The efficiency of an Otto cycle is 50% and γ is 1.5. What is the compression ratio ? [**Ans.** 4]
10. An engine working on Otto cycle has a volume of 0.5 m^3, pressure 1 bar and temperature 27°C at the commencement of compression stroke. At the end of compression stroke, the pressure is 10 bar. Heat added during the constant volume process is 200 kJ. Determine:
    (*i*) Percentage clearance (*ii*) Air standard efficiency
    (*iii*) Mean effective pressure
    (*iv*) Ideal power developed by the engine if the engine runs at 400 r.p.m. so that there are 200 complete cycles per minutes.
    [**Ans.** (*i*) 23.76% ; (*ii*) 47.2% ; (*iii*) 2.37 bar ; (*iv*) 321 kW]
11. The compression ratio in an air-standard Otto cycle is 8. At the beginning of compression process, the pressure is

1 bar and the temperature is 300 K. The heat transfer to the air per cycle is 1900 kJ/kg of air. Calculate :

(*i*) Thermal efficiency

(*ii*) The mean effective pressure.

[**Ans.** (*i*) 56.47% ; (*ii*) 14.24 bar]

12. An engine 200 mm bore and 300 mm stroke works on Otto cycle. The clearance volume is 0.0016 m^3. The initial pressure and temperature are 1 bar and 60°C. If the maximum pressure is limited to 24 bar, find :

(*i*) The air-standard efficiency of the cycle

(*ii*) The mean effective pressure for the cycle.

Assume ideal conditions.

[**Ans.** (*i*) 54.08% ; (*ii*) 1.972 bar]

13. Calculate the air standard efficiency of a four stroke Otto cycle engine with the following data :

Piston diameter (bore) = 137 mm ;

Length of stroke = 130 mm ;

Clearance volume 0.00028 m^3.

Express clearance as a percentage of swept volume.

[**Ans.** 56.1% ; 14.6%]

14. In an ideal Diesel cycle, the temperatures at the beginning of compression, and the end of compression and at the end of the heat addition are 97°C, 789°C and 1839°C. Find the efficiency of the cycle. [**Ans.** 59.6%]

15. An air-standard Diesel cycle has a compression ratio of 18, and the heat transferred to the working fluid per cycle is 1800 kJ/kg. At the beginning of the compression stroke, the pressure is 1 bar and the temperature is 300 K. Calculate : (*i*) Thermal efficiency, (*ii*) The mean effective pressure. [**Ans.** (*i*) 61% ; (*ii*) 13.58 bar]

16. The following data belong to a Diesel cycle :

Compression ratio = 16 : 1 ; Heat added = 2500 kJ/kg ; Lowest pressure in the cycle = 1 bar ; Lowest temperature in the cycle = 27°C. Determine :

(*i*) Thermal efficiency of the cycle.

(*ii*) Mean effective pressure.

[**Ans.** (*i*) 45% ; (*ii*) 16.8 bar]

17. The compression ratio of an air-standard Dual cycle is 12 and the maximum pressure in the cycle is limited to 70 bar. The pressure and temperature of cycle at the beginning of compression process are 1 bar and 300 K. Calculate : (*i*) Thermal efficiency, (*ii*) Mean effective pressure.

Assume : Cylinder bore = 250 mm, stroke length = 300 mm, c_p = 1.005, c_v = 0.718 and γ = 1.4.

[**Ans.** (*i*) 61.92% ; (*ii*) 9.847 bar]

18. The compression ratio of a Dual cycle is 10. The temperature and pressure at the beginning of the cycle are 1 bar and 27°C. The maximum pressure of the cycle is limited to 70 bar and heat supplied is limited to 675 kJ/kg of air. Find the thermal efficiency of the cycle.

[**Ans.** 59.5%]

19. An air standard dual cycle has a compression ratio of 16, and compression begins at 1 bar, 50°C. The maximum pressure is 70 bar. The heat transferred to air at constant pressure is equal to that at constant volume. Determine :

(*i*) The cycle efficiency.

(*ii*) The mean effective pressure of the cycle.

Take : c_p = 1.005 kJ/kg K, c_v = 0.718 kJ/kg K.

[**Ans.** (*i*) 66.5% ; (*ii*) 4.76 bar]

20. In an air standard gas turbine engine, air at a temperature of 15°C and a pressure of 1.01 bar enters the compressor, where it is compressed through a pressure ratio of 5. Air enters the turbine at a temperature of 815°C and expands to original pressure of 1.01 bar. Determine the ratio of turbine work to compressor work and the thermal efficiency when the engine operates on ideal Brayton cycle.

Take : γ = 1.4, c_p = 1.005 kJ/kg K. [**Ans.** 2.393 ; 37.03%]

21. In an open cycle constant pressure gas turbine air enters the compressor at 1 bar and 300 K. The pressure of air after the compression is 4 bar. The isentropic efficiencies of compressor and turbine are 78% and 85% respectively. The air-fuel ratio is 80 : 1. Calculate the power developed and thermal efficiency of the cycle if the flow rate of air is 2.5 kg/s.

Take c_p = 1.005 kJ/kg K and γ = 1.4 for air and c_{pg} = 1.147 kJ/kg K and γ = 1.33 for gases. R = 0.287 kJ/kg K. Calorific value of fuel = 42000 kJ/kg.

[**Ans.** 204.03 kW/kg of air ; 15.54%]

22. A gas turbine has a pressure ratio of 6/1 and a maximum cycle temperature of 600°C. The isentropic efficiencies of the compressor and turbine are 0.82 and 0.85 respectively. Calculate the power output in kilowatts of an electric generator geared to the turbine when the air enters the compressor at 15°C at the rate of 15 kg/s.

Take : c_p = 1.005 kJ/kg K and γ = 1.4 for the compression process, and take c_p = 1.11 kJ/kg K and η = 1.333 for the expansion process. [**Ans.** 920 kW]

23. The gas turbine has an overall pressure ratio of 5 : 1 and a maximum cycle temperature of 550°C. The turbine drives the compressor and an electric generator, the mechanical efficiency of the drive being 97%. The ambient temperature is 20°C and the isentropic efficiencies of the compressor and turbine are 0.8 and 0.83 respectively. Calculate the power output in kilowatts for an air flow of 15 kg/s. Calculate also the thermal efficiency and the work ratio.

Neglect changes is kinetic energy, and the loss of pressure in combustion chamber. [**Ans.** 655 kW ; 12% ; 0.168]

Steam Power Plant

3

3.1. Introduction. 3.2. Classification of steam power plants. 3.3. Layout of a modern steam power plant. 3.4. Essential requirements of steam power station design. 3.5. Selection of site for steam power station. 3.6. Capacity of steam power plant. 3.7. Choice of steam conditions. 3.8. Fuel handling—Introduction—Requirements of good coal handling plant—Coal handling systems—Coal handling—Layout of a fuel handling equipment. **3.9. Combustion equipment for steam boilers**—General aspects—Combustion equipment for solid fuels—selection considerations—Burning of coal—Burners. **3.10. Fluidised bed combustion (FBC). 3.11. Ash handling**—Ash handling equipment—Ash handling systems. **3.12. Dust collection**—Introduction—Removal of smoke—Removal of dust and dust collectors—Efficiency of dust collectors—Installation of dust collectors—Uses of ash and dust—General layout of ash handling and dust collection system—Flyash—Its composition, disposal and applications. **3.13. Chimney draught**—Definition and classification of draught—Natural draught—Chimney height and diameter—Condition for maximum discharge through a chimney—Efficiency of a chimney—Draught losses—Artificial draught—Forced draught—Induced draught—Balanced draught—Advantages of mechanical draught—Steam jet draught—Worked examples. **3.14. Boilers**—Introduction—Classification of boilers—Comparison between 'fire-tube and water-tube' boilers— Selection of a boiler—Essentials of a good steam boiler—Boiler terms—Fire tube boilers—Water tube boilers—High pressure boilers. **3.15. Accessories**—Feed pumps—Injector—Economiser—Air preheater—Superheater—Steam separator. **3.16. Feed water heaters and evaporators**—Feed water heaters—Miscellaneous heaters—Evaporators—Typical utility cycle layout. **3.17. Performance of boilers**—Evaporative capacity—Equivalent evaporation—Factor of evaporation—Boiler efficiency—Heat looses in a boiler plant. **3.18. Steam nozzles**—Introduction—Steam flow through nozzles—Discharge through the nozzle and conditions for its maximum value—Nozzle efficiency—Supersaturated or metastable expansion of steam in a nozzle. **3.19. Steam turbines**—Introduction—Classification of steam turbines—Advantages of steam turbine over the steam engines—Description of common types of turbines—Methods of reducing wheel or rotor speed—Difference between impulse and reaction turbines—Impulse turbines—Reaction turbines—Turbine efficiencies—Types of power in steam turbine practice—Energy losses in steam turbines—Steam turbine governing and control—Special forms of turbines. **3.20. Steam condensers**—Introduction—Vacuum—Organs of a steam condensing plant—Classification of condensers—Jet condensers—Surface condensers—Reasons for inefficiency in surface condensers—Comparison between jet and surface condensers—Selection of condenser—Sources of air in condensers—Effects of air leakage in condenser—Method for obtaining maximum vacuum in condensers—Vacuum measurement—Vacuum efficiency—Condenser efficiency—Determination of mass of cooling water—Heat transmission through walls of tubes of a surface condenser—Methods of cleaning condenser tubes. **3.21. Cooling ponds and cooling towers**—Introduction—River or sea—Cooling ponds—Spray ponds—Cooling towers—Dry cooling towers— Maintenance of cooling towers. **3.22. Feed water treatment**—Classification of impurities in water—Troubles caused by the impurities in water—Methods of feed water treatment—pH value of water. **3.23. Piping system**—Requirements of steam piping system—Materials used for pipes—Insulation of steam piping—Steam pipe fittings—Pipe expansion bends. **3.24. Advantages and disadvantages of steam power plants. 3.25. Miscellaneous**—Plant arrangement—Useful life of steam power plant components—Steam power plant pumps—Cost of steam power plant—Comparison of various types of power plants—Thermal power stations in India—Indian boilers act—*Highlights—Theoretical Questions—Unsolved Examples—Competitive Examinations Questions.*

3.1. INTRODUCTION

A ***steam power plant*** *converts the chemical energy of the fossil fuels (coal, oil, gas) into mechanical / electrical energy.* This is achieved by raising the steam in the boilers, expanding it through the turbines and coupling the turbines to the generators which convert mechanical energy to electrical energy as shown in Fig. 3.1.

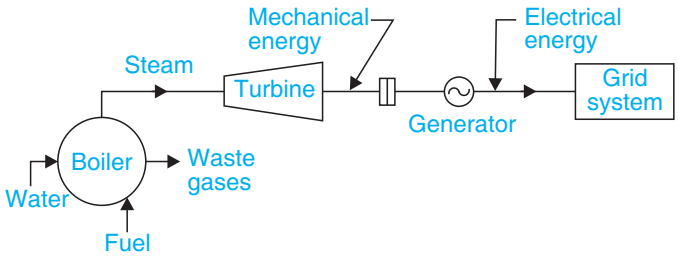


Fig. 3.1. Production of electric energy by steam power plant.

The following two purposes can be served by a steam power plant :

1. To produce electric power.

2. To produce steam for industrial purposes besides producing electric power. The steam may be used for varying purposes in the industries such as *textiles, food manufacture, paper mills*, *sugar mills* and *refineries* etc.

3.2. CLASSIFICATION OF STEAM POWER PLANTS

The steam power plants may be classified as follows :

1. Central stations.

2. Industrial power stations or captive power stations.

1. Central stations. The electrical energy available from these stations is meant for general sale to the customers who wish to purchase it. Generally, these stations are *condensing type* where the exhaust steam is discharged into a condenser instead of into the atmosphere. In the condenser the pressure is maintained below the atmospheric pressure and the exhaust steam is condensed.

2. Industrial power stations or captive power-stations. This type of power station is run by a manufacturing company for its own use and its output is not available for general sale. Normally these plants are *non-condensing* because a large quantity of steam (low pressure) is required for different manufacturing operations.

In the *condensing steam power plants* the following *advantages* accrue :

(*i*) The amount of energy extracted per kg of steam is *increased* (a given size of the engine or turbine develops more power).

(*ii*) The steam which has been condensed into water in the condenser, can be recirculated to the boilers with the help of pumps.

In non-condensing steam power plants a continuous supply of fresh feed water is required which becomes a problem at places where there is a shortage of pure water.

3.3. LAYOUT OF A MODERN STEAM POWER PLANT

Refer to Fig. 3.2. The layout of a modern steam power plant comprises of the following *four circuits* :

1. Coal and ash circuit.
2. Air and gas circuit.
3. Feed water and steam flow circuit.
4. Cooling water circuit.

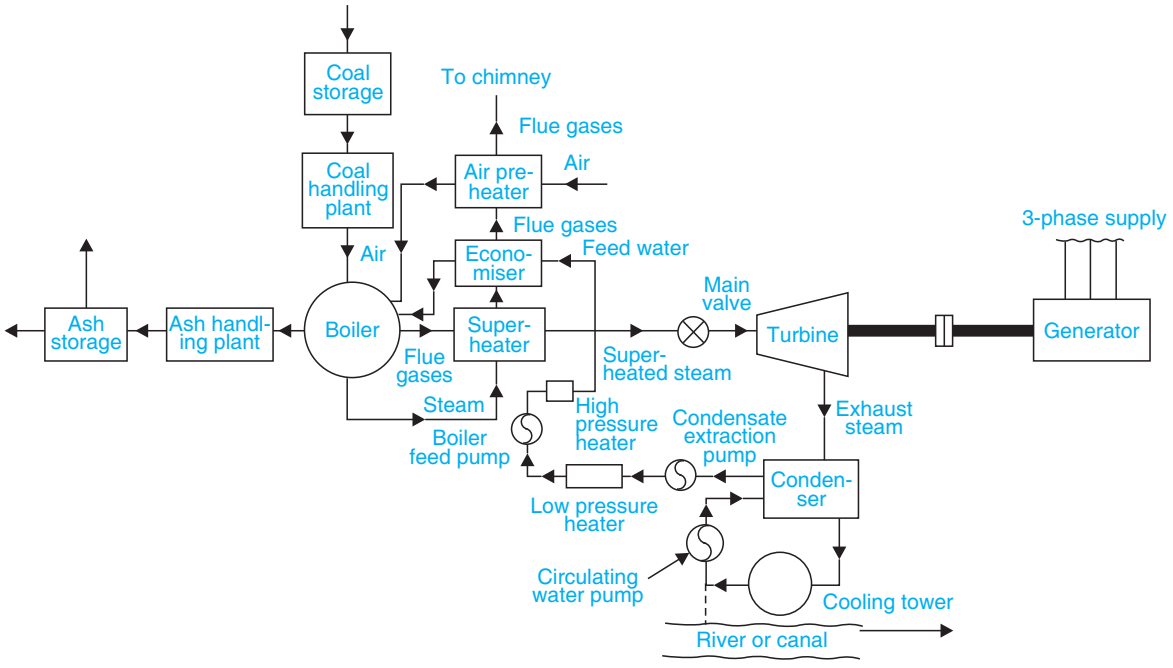


Fig. 3.2. Layout of a steam power plant.

Coal and ash circuit. Coal arrives at the storage yard and after necessary handling, passes on to the furnaces through the *fuel feeding device*. Ash resulting from combustion of coal collects at the back of the boiler and is removed to the ash storage yard through *ash handling equipment*.

Air and gas circuit. Air is taken in from atmosphere through the action of a forced or induced draught fan and passes on to the furnace through the *air preheater*, where it has been heated by the heat of flue gases which pass to the chimney *via* the preheater. The flue gases after passing around boiler tubes and superheater tubes in the furnace pass through a *dust* catching device or precipitator, then through the economiser, and finally through the air preheater before being exhausted to the atmosphere.

Feed water and steam flow circuit. In the water and steam circuit condensate leaving the condenser is first heated in a closed feed water heater through extracted steam from the lowest pressure extraction point of the turbine. It then passes through the *deaerator* and a few more water heaters before going into the boiler through *economiser*.

In the boiler drum and tubes, water circulates due to the difference between the density of water in the lower temperature and the higher temperature sections of the boiler. Wet steam from the drum is further heated up in the superheater before being supplied to the prime mover. After expanding in high pressure turbine steam is taken to the reheat boiler and brought to its original dryness or superheat before being passed on to the low pressure turbine. From there it is exhausted through the condenser into the hot well. The condensate is heated in the feed heaters using the steam trapped (bled steam) from different points of turbine.

A part of steam and water is lost while passing through different components and this is compensated by supplying additional feed water. This feed water should be purified before hand, to avoid the scaling of the tubes of the boiler.

Cooling water circuit. The cooling water supply to the condenser helps in maintaining a low pressure in it. The water may be taken from a natural source such as river, lake or sea or the same water may be cooled and circulated over again. In the later case the cooling arrangement is made through spray pond or cooling tower.

Components of a Modern Steam Power Plant. A modern steam power plant comprises of the following *components* :

1. Boiler
   (*i*) Superheater (*ii*) Reheater
   (*iii*) Economiser (*iv*) Air-heater
2. Steam turbine
3. Generator
4. Condenser
5. Cooling towers
6. Circulating water pump
7. Boiler feed pump
8. Wagon tippler
9. Crusher house
10. Coal mill
11. Induced draught fans
12. Ash precipitators
13. Boiler chimney
14. Forced draught fans
15. Water treatment plant
16. Control room
17. Switch yard.

3.4. ESSENTIAL REQUIREMENTS OF STEAM POWER STATION DESIGN

The *essential requirements of steam power station design are* :

1. Reliability
2. Minimum capital cost
3. Minimum operating and maintenance cost
4. Capacity to meet peak load effectively
5. Minimum losses of energy in transmission
6. Low cost of energy supplied to the consumers
7. Reserve capacity to meet future demands.

The above essential requirements depend to a large extent on the following :

(*i*) Simplicity of design
(*ii*) Subdivision of plant and apparatus
(*iii*) Use of automatic equipment
(*iv*) Extensibility.

3.5. SELECTION OF SITE FOR STEAM POWER STATION

The following points should be taken into consideration while *selecting the site* for a steam power station :

1. Availability of raw material
2. Nature of land
3. Cost of land
4. Availability of water
5. Transport facilities
6. Ash disposal facilities
7. Availability of labour
8. Size of the plant
9. Load centre
10. Public problems
11. Future extensions.

1. Availability of raw material. Modern steam power stations using coal or oil as fuel require huge quantity of it per annum. A thermal power plant of 400 MW capacity requires 5000 to 6000 tonnes of coal per day. Therefore, it is necessary to locate the plant as far as

possible near the coalfields in order to save the transportation charges. Besides transportation charges, a plant located away from the coalfields, cannot always depend on the coal deliveries in time (*i*) as there may be failure of transportation system, (*ii*) there may be strike etc. at the mines. For these reasons a considerable amount of coal must be stored at the power stations, this results in :

(*i*) increased investment ;

(*ii*) increased space required at the site of the plant for the storage ;

(*iii*) losses in storage ; and

(*iv*) additional staff requirement.

If it is not possible to locate the plant near the coalfields then the plant should be located as near the railway station as possible. Even if this is not possible then at least arrangement should be made for railway siding to the power plant so that the coal wagons can be shunted from the station to the site of power plant. This applies to plants using oil as fuel, as well.

2. Nature of land. The type of the land to be selected should have *good bearing capacity* as it has to withstand the *dead load* of the plant and the *forces transmitted to the foundation* due to the machine operations. The minimum bearing capacity of the land should be 1 MN/m^2.

3. Cost of land. Considerable area is required for the power stations. The cost of the land for that purpose should be reasonable. The large plants in the heart of big cities and near the load centre are not economical as the cost of land is very high.

4. Availability of water. Steam power stations use water as the working fluid which is repeatedly evaporated and condensed. Theoretically there should be no loss of water, but in fact some make up water is required. Besides this, considerable amount of water is required for condensers. A large quantity of water is also required for disposing the ash if hydraulic system is used. It is, therefore, necessary to locate the power plant near the water source which will be able to supply the required quantity of water throughout the year.

5. Transport facilities. Availability of proper transport facilities is another important consideration in locating the thermal power station. It is always necessary to have a railway line available near the power station for bringing in heavy machinery for installation and for bringing the fuel.

6. Ash disposal facilities. The ash handling problem is more serious than coal handling because it comes out in hot condition and it is highly corrosive. Its effect on atmospheric pollution are more serious as the human health is concerned. Therefore, there must be sufficient space to dispose of large quantity of ash.

In a power station of 400 MW capacity 10 hectares area is required per year if the ash is dumped to a height of 6.5 metres.

7. Availability of labour. During construction of plant enough labour is required. The labour should be available at the proposed site at cheap rate.

8. Size of the plant. The expenses involved in electric transmission from a *small plant* are *relatively severe*, owing to the impracticability of using high voltages, so that the electric transmission feature alone becomes dominant in the location of the plant. It case of *large plants*, the costs of transporting enormous quantities of coal and water are considerably high ; therefore, the plant must be located near the pit head provided the required water quantity must be available as near as possible. The large plants should be located close to the railroad offering adequate services. The economic significance of the large plant with small one is much greater than the mere ratio of size.

9. Load centre. A power station must be located *near the loads* to which it is supplying power. However, a plant cannot be located near all loads. As such C.G. of the loads is determined with reference to two arbitrarily chosen axes, this C. G. is known as the load centre (see Fig. 3.3).

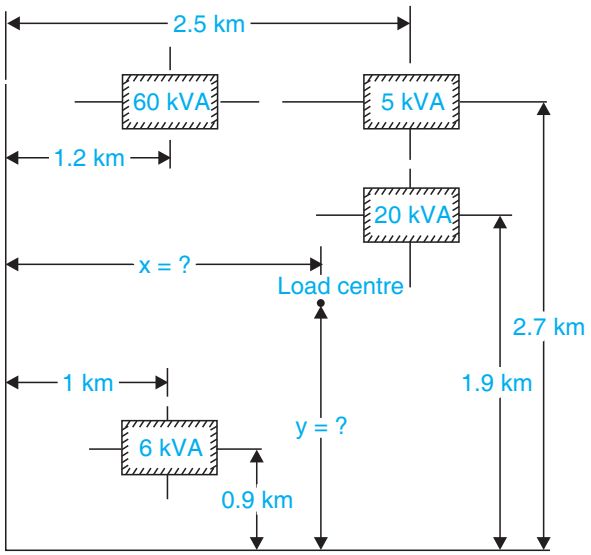


Fig. 3.3. Load centre.

The power plant should be located, as far as possible near the load centre in order to *minimize the cost of transmission lines and also the losses occurring in them.*

10. Public problems. In order to avoid the nuisance from smoke, fly ash and heat discharged from the power plant, it should be located far away from the towns.

11. Future extensions. The choice of the site should allow for economical extensions consistent with the estimated growth of load.

12. Consent of town planning department must be sought in case urban area is selected for the purpose.

3.6. CAPACITY OF STEAM POWER PLANT

The power plant capacity can be determined by studying *the load duration curve and the anticipated future demands. The minimum capacity of the plant must be equal to at least the peak load.*

(*i*) In case of "*Small loads*", it may be economical to install two units of equipment, each being capable of supplying the maximum demand independently. In the event of failure of one unit or during maintenance etc., at least one unit can be used to maintain uninterrupted supply of energy.

(*ii*) In case of "*medium power plants*", usually the number of units is more than two with the total installed capacity equal to the *maximum demand plus the capacity of two large units.*

(*iii*) "*Large power plants*" are generally *conservately rated*. In the case of steam turbines, there is an overload capacity of 10 to 15% of the rated capacity. With a number of units, peak load can be easily adjusted by overloading some units temporarily.

The power plant load can be reduced by dropping the supply voltage. Thus a 5 per cent reduction in supply voltage results in similar reduction in the load. An electric supply undertaking has to maintain the voltage within 10 per cent of the declared pressure as per Indian Electricity Act ; So *during peak hours the voltage can be reduced within the allowable limits in order to meet the demand without use of additional units.* By using this technique saving of capital cost is materialised.

When a new unit is to be added to the existing power station, its size is decided on the following considerations :

1. Effect of additional unit on the thermal efficiency of the plant.
2. Expected rate of increase of maximum demand over the next few years.
3. The room available for the additional unit.
4. The suitability of the generator to the existing system regarding temperature, pressure etc.

Rating of Units :

Normally the output of units is classified under the following heads :

(*i*) Economical rating

(*ii*) Maximum continuous rating.

A generator need not operate most economically at full load. For the most economical operation, the present trend is towards economical running at 75–85 per cent of full load.

Maximum continuous rating of a generating unit is the maximum load at which it can be run continuously for several hours. It is normally 10–15 per cent less than the maximum capacity of the unit.

3.7. CHOICE OF STEAM CONDITIONS

The choice of steam conditions depends upon the following factors :

1. Price of coal.
2. Capital cost of the plant.
3. Time available for erection.
4. Thermal efficiency obtainable.
5. The station 'load factor'.

The present trend is towards adoption of high pressures and high temperatures. The effect of increased pressure and temperature on the efficiency and cost of plant is illustrated with the help of Figs. 3.4 and 3.5. It is evident from the curves that :

(*i*) *With the increase in pressure the efficiency obeys the 'law of diminishing returns'.*

(*ii*) With the increase in temperature the efficiency obeys the '*straight line law*' indicating the desirability of adopting the highest possibe temperature. The strength of material available limits the adoption of high temperatures. Beyond 500°C there is a very rapid change in the physical properties of the material and the problem becomes complicated. *With the increase in pressures the degree of superheat should be decreased in order to keep the total temperature within limits.*

For entirely new stations, present practice favours the use of steam pressures around 60 bar, but there is a profitable field for higher pressures of the order of 100 bar, when the problem is that of *increasing thermal efficiency of existing medium pressure units.*

It may be noted that *consumption of steam per kilo-watt hour decreases with the increased pressure.*

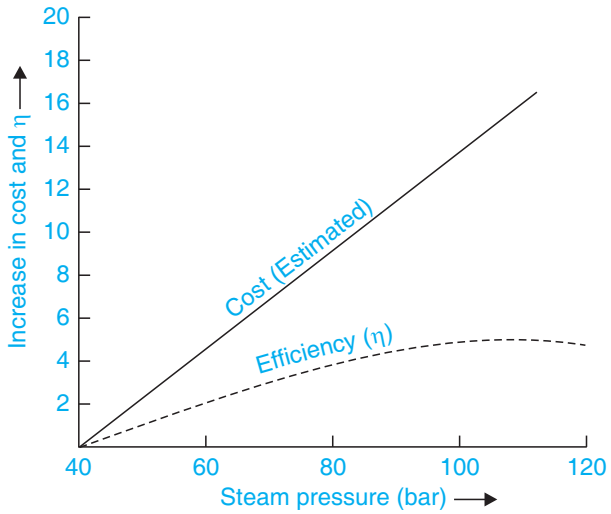


Fig. 3.4. Effect of steam pressure on cost and η (efficiency)

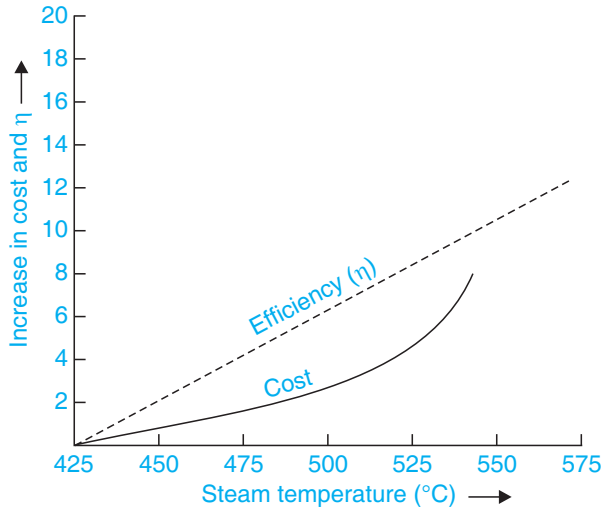


Fig. 3.5. Effect of steam temperature on cost and η (efficiency).

Fig. 3.6 shows that *as the average output of plant units increases the percentage total capital cost decreases.*

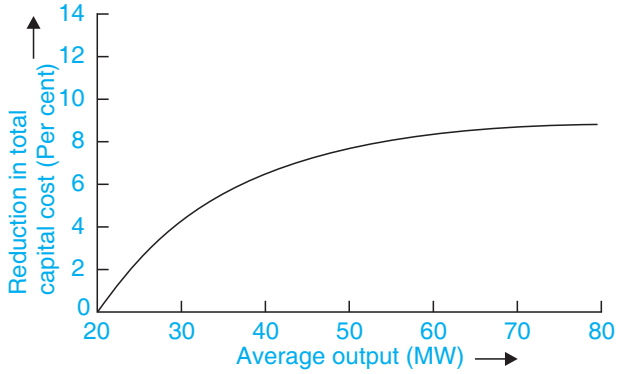


Fig. 3.6

Fig. 3.7 indicates that *steam consumption decreases with increase in the capacity of the unit.*

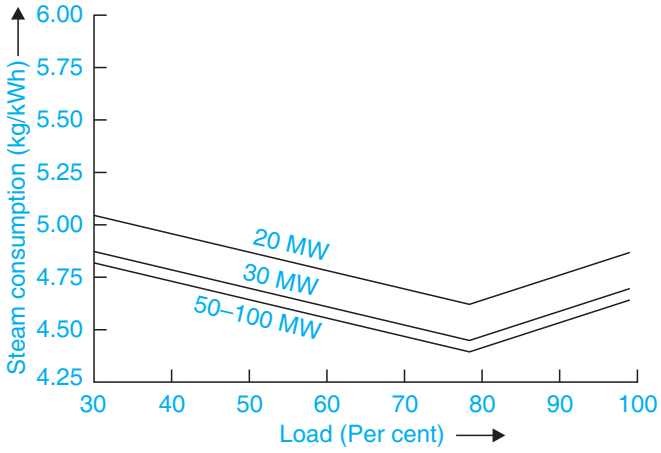


Fig. 3.7

3.8. FUEL HANDLING

3.8.1. Introduction

Three types of fuels can be burnt in any type of steam generating plant : 1. Solid fuel such as *coal* ; 2. Liquid fuel as oil and 3. Gaseous fuel as gas. Supply of these fuels to the power plants from various sources is one of the important considerations for a power plant engineer. The handling of these fuels is an important aspect. The following factors should be considered in selecting the fuel handling system :

1. Plant fuel rate.
2. Plant location in respect of fuel shipping.
3. Storage area available.

Fuel handling plant needs extra attention, while designing a thermal power station, as almost 50 to 60 per cent of the total operating cost consists of fuel purchasing and handling. *Fuel system is designed in accordance with the type and nature of fuel.*

Continuously increasing demand for power at lower cost calls for setting up of higher capacity power stations. Rise in capacity of the plant poses a problem in coal supply system from coal mines to the power stations. The coal from coal mines may be transported by the following means :

1. Transportation by sea or river,
2. Transportation by rail,
3. Transportation by ropeways,
4. Transportation by road, and
5. Transportation of coal by pipeline.

The pipeline coal transport system offers the following *advantages* :

1. It provides simplicity in installation and increased safety in operation.
2. More economical than other modes of transport when dealing with large volume of coal over long distances.
3. This system is continuous as it remains unaffected by the vagaries of climate and weather.
4. High degree of reliability.
5. Loss of coal during transport due to theft and pilferage is totally eliminated.
6. Manpower requirement is low.

3.8.2. Requirements of Good Coal Handling Plant

1. It should need minimum maintenance.
2. It should be reliable.
3. It should be simple and sound.
4. It should require a minimum of operatives.

5. It should be able to deliver requisite quantity of coal at the destination during peak periods.

6. There should be minimum wear in running the equipment due to abrasive action of coal particles.

3.8.3. Coal Handling Systems

"*Mechanical handling*" of coal is preferred over "*manual handling*" due to the following *reasons* :

1. Higher reliability.
2. Less labour required.
3. Economical for medium and large capacity plants.
4. Operation is easy and smooth.
5. Can be easily started and can be economically adjusted according to the need.
6. With reduced labour, management and control of the plant becomes easy and smooth.
7. Minimum labour is put to unhealthy condition.
8. Losses in transport are minimised.

Disadvantages :

1. Needs continuous maintenance and repair.
2. Capital cost of the plant is increased.
3. In mechanical handling some power generated is usually consumed, resulting in less net power available for supply to consumers.

3.8.4. Coal Handling

Refer to Fig. 3.8.

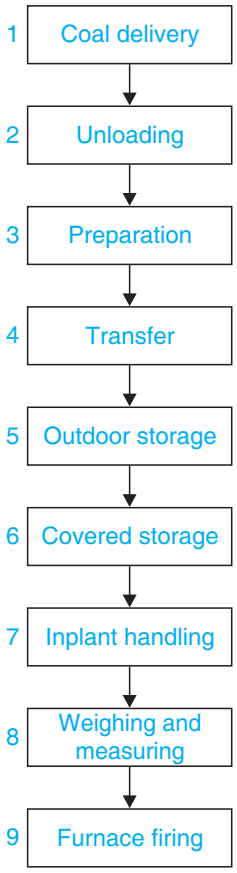


Fig. 3.8. Various stages in coal handling.

The following stages/steps are involved in handling the coal :

1. Coal delivery
2. Unloading
3. Preparation
4. Transfer
5. Storage of coal
6. Inplant handling
7. Weighing and measuring
8. Furnace firing.

Fig. 3.9 shows the outline of coal handling equipment.

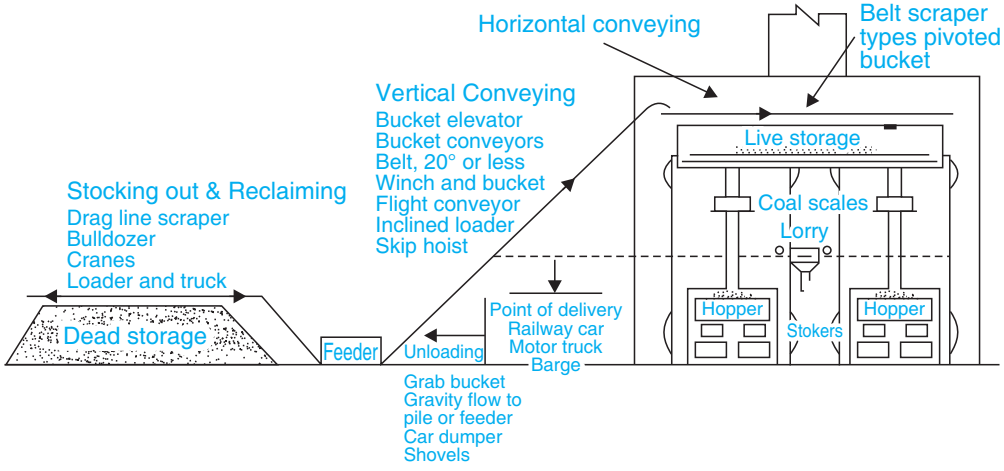


Fig. 3.9. Outline of coal handling equipment.

1. Coal delivery. From the supply points the coal may be delivered to power station though rail, road, river or sea.

— Plants situated near the river or sea may make use of navigation facilities.

— Stations which cannot make use of navigation facilities may be supplied coal either by rail or trucks. Transportation of coal by *trucks* is usually used in case the *mines are not far off* or when the necessary *railway facilities are not available*. In case rail transport is to be adopted, the necessary siding for receiving the coal should be brought as near the station as possible.

2. Unloading. The type of coal unloading equipment used in the plant depends upon the type of out-plant handling mode as road, rail or ship. If coal is delivered by trucks, there is no need of unloading device as the trucks may dump the coal to the outdoor storage. Coal is easily handled if the lift trucks with scoop are used (see Fig. 3.10).

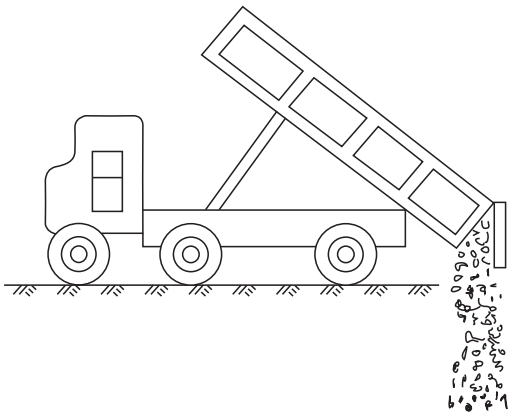


Fig. 3.10. Lift truck with scoop.

When the coal is transported by sea, the unloading equipment normally used is given below :

(*i*) Portable conveyors

(*ii*) Coal accelerators

(*iii*) Coal towers

(*iv*) Unloading bridges

(*v*) Self unloading boats.

3. Preparation. If the coal when delivered is in the form of lumps (not of proper size), the coal preparation may be carried out by :

(*i*) Breakers (*ii*) Crushers

(*iii*) Sizers (*iv*) Dryers

(*v*) Magnetic separators.

4. Transfer. 'Transfer' means the handling of coal between the unloading point and the final storage point from where it is discharged to the firing equipment. The following equipment may be used for transfer of coal :

1. Belt conveyors
2. Screw conveyors
3. Vee bucket elevator and conveyor
4. Pivoted bucket conveyor
5. Grab bucket conveyor
6. Flight conveyers (or scrapers)
7. Skip hoists
8. Mass flow conveyor
9. Chutes.

***(i)* Belt conveyor.** Refer to Fig. 3.11. A belt conveyor is very suitable means of transporting large quantities of coal over large distances. It consists of an endless belt (made of rubber, convas or balata) running over a pair of end drums or pulleys and supported by a series of rollers (known as idlers) provided at regular intervals. The return idlers which support the empty belt are plain rollers and are spaced wide apart. The initial cost of the system is not high. The inclination at which coal can be successfully elevated by belt conveyor is about 20°. Average speed of the belt conveyor is 60 to 100 metres per minute. The load carrying capacity of the belt may vary from 50 to 100 tonnes/hour and it can easily be transferred through 400 metres. It is used in *medium and large power plants.*

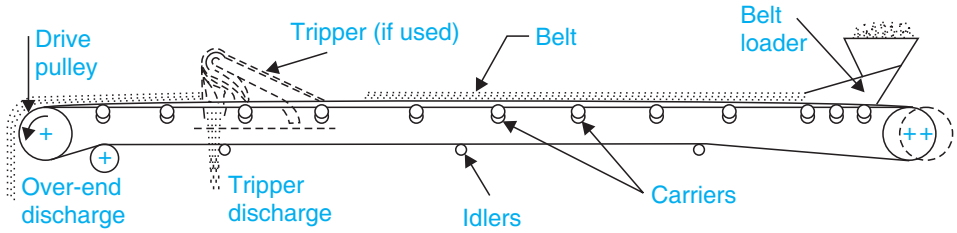


Fig. 3.11. Belt conveyor.

Advantages :

1. Most economical method of coal transport in medium and large capacity plants.
2. Its operation is smooth and clean.
3. Repair and maintenance costs minimum.
4. Large quantities of coal can be discharged quickly and continuously.
5. Power consumption minimum.

6. The rate of coal transfer can be easily varied by just varying the belt speed.

7. Coal being transferred is protected.

Disadvantages :

1. Not suitable for greater heights and short distances.

2. As the maximum inclination at which coal can be transferred by this arrangement is limited, in order to transfer coal at considerable heights as involved in modern stations, the *length of the conveyor becomes excessive.*

***(ii)* Screw conveyor.** Refer to Fig. 3.12. It consists of an endless helicoid screw fitted to a shaft. The driving mechanism is connected to one end of the shaft and the other end of the shaft is supported in an enclosed ball bearing. The screw while rotating in a trough/housing transfers coal from one end to the other end. The following particulars relate to this conveyor.

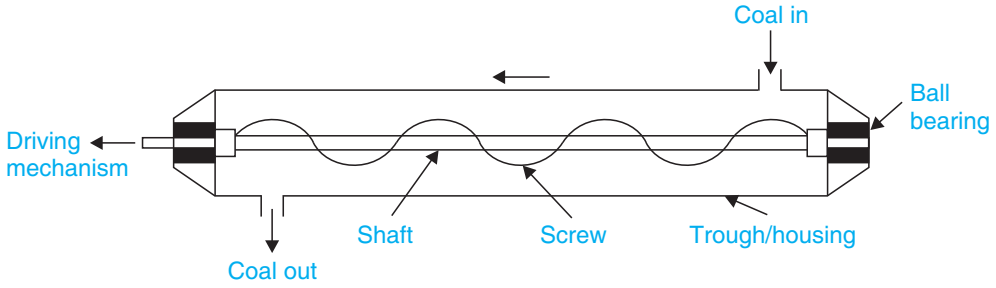


Fig. 3.12. Screw conveyor.

Diameter of the screw	.....15 to 50 cm
Speed	.....70 to 120 r.p.m.
Maximum capacity	.....125 tonnes/hour.

***(iii)* Vee bucket elevator.** In this type of elevator, steel V-shaped buckets are rigidly fastened to an endless chain going round sprockets. The buckets are equally spaced on the chain, and receive their load by dipping into coal pocket at the lower end of the system. The material elevated in V-buckets is discharged either by centrifugal force at the top of the elevator or by drawing back the buckets on the discharged side.

Advantages :

1. Less power is required for operating the equipment (as the coal is carried not dragged).

2. Coal can be discharged at elevated places.

3. Less floor area is required.

Disadvantages :

Its capacity is limited and hence *not suitable for large capacity stations.*

Fig. 3.13 shows a **'bucket elevator'** which is used for moderate lifts. The material is continuously handled and can be both hoisted and conveyed.

***(iv)* Pivoted bucket conveyor.** This conveyor consists of malleable iron buckets suspended by pivots midway between the joints of two endless chains, which are driven by a motor located at some convenient point, usually at the top of a vertical rise. While travelling horizontally, buckets maintain their position due to gravity and support the joints. The conveyor is loaded by passing below a crusher. The coal is charged into the bunker by a tripping device.

Advantages :

1. Low operational cost.

2. High capacity.

3. Less floor area requirement.

Disadvantages :

High initial cost of the equipment.

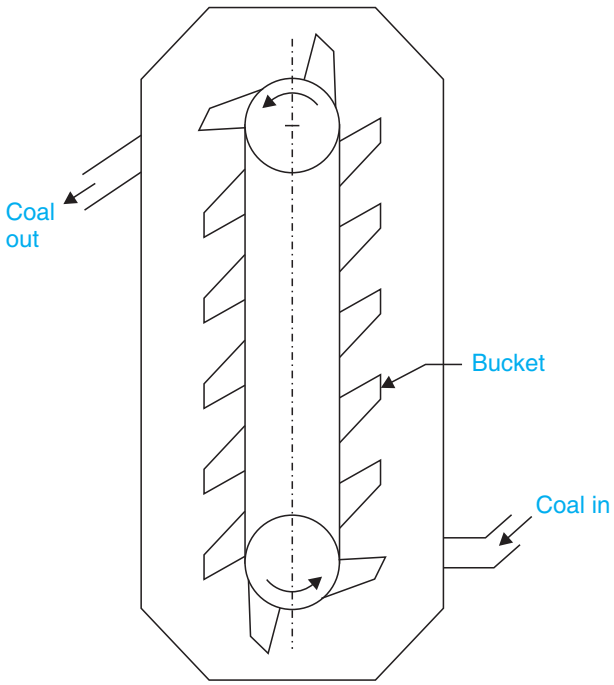


Fig. 3.13. Bucket elevator.

(*v*) Grab bucket conveyor. Refer to Fig. 3.14. It is a form of hoist which lifts and transfers the load on a single rail or track from one point to another. This is a costly machine and is justified only when other arrangements are not possible. Capacity of a grab bucket may be about 50 tonnes per hour.

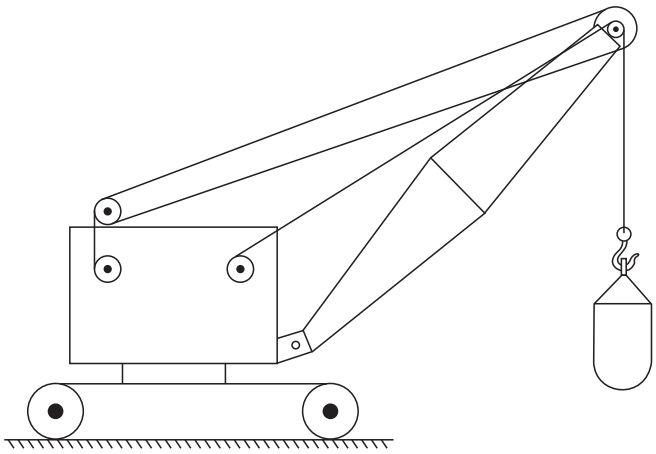


Fig. 3.14. Grab bucket conveyor.

(*vi*) Flight conveyor (or Scraper). It is generally used for transfer of coal when filling of number of storage bins situated under the conveyor is required. It consists of one or two strands of chain, to which steel scrapers are attached. The scraper scraps the coal through a trough and the coal is discharged in the bottom of the trough as shown in Fig. 3.15. Capacity of a conveyor of this type may range from 10 to 100 tonnes per hour. It is used extensively for conveying coal horizontally and for inclinations up to 35°.

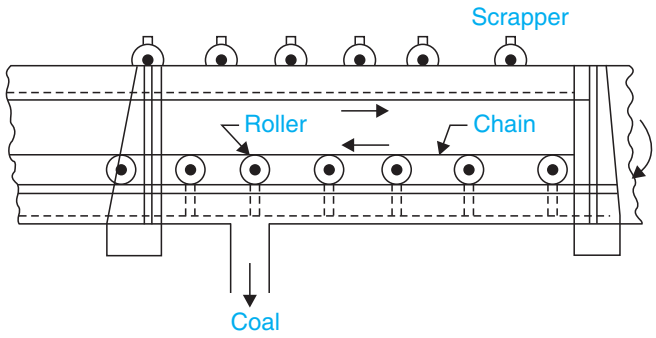


Fig. 3.15. Flight conveyor.

Advantages :

1. It has a rugged construction.
2. Requires little operational care.
3. It can be used for transfer of coal as well as ash.
4. Its speed can be easily regulated.
5. It needs small headroom.

Disadvantages :

1. Excessive wear due to dragging action.
2. High maintenance cost.
3. The speed is limited to 30 m/min. to reduce the abrasive action of material handled.
4. Power consumption is more (due to dragging action).

(*vii*) Skip hoist. Refer to Fig. 3.15 (*a*). It is used for high lifts and handling is non-continuous. This arrangement is simple and cheap and operation costs including labour and maintenance are low. The skip hoist is the oldest and simplest means of elevating coal or ash and is favourite of engineers particularly in ash handling.

5. Storage of coal. It is very essential that adequate quantity of coal should be stored. Storage of coal gives protection against the interruption of coal supplies when there is delay in transportation of coal or due to strikes in coal mines. In regard to storage of coal the following points should be considered :

(*i*) There should be no standing water near the storage area.

(*ii*) At a place where a well-drained area is not available, drainage ditches should be installed.

(*iii*) Storage area should be solid and not loose or porous.

(*iv*) Piles should be built up in successive layers and as far as possible compact.

(*v*) Conical piling should be avoided.

(*vi*) In order to protect against wind erosion, piles should be sealed.

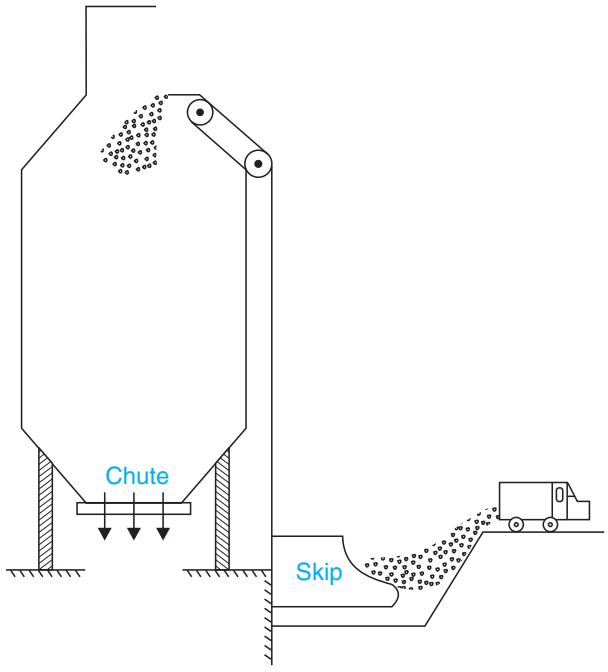


Fig. 3.15. (*a*) Skip hoist.

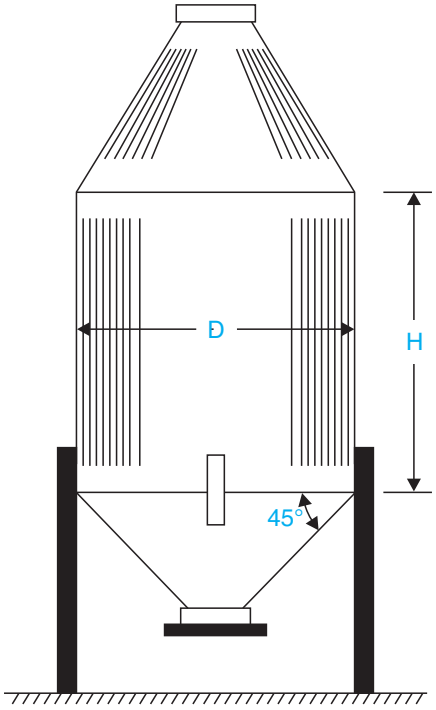


Fig. 3.16. Cylindrical bunker.

(*vii*) Storage should be done in such a way that the handling cost is minimum.

(*viii*) At storage site fire fighting equipment should be easily available.

'Live storage' is a covered storage provided in plants, sufficient to meet one day requirement of the boiler. Bunkers (Fig. 3.16) made of steel or reinforced concrete are used to store the coal ; from here the coal is transferred to the boiler grates.

6. Inplant handling. It may refer to any one of the following :

(*i*) Coal handling between the final storage and the firing equipment.

(*ii*) A conveying system to feed coal from any bunker section to any firing unit and to move coal from one bunker section to another.

(*iii*) Inplant handling may mean no more than chutes to direct flow into individual firing units and gates or valves to control the flow.

Inplant handling may include the equipment such as belt conveyors, screw conveyors, bucket elevators etc. to transfer the coal. Weigh lorries, hoppers and automatic scales are used to record the quantity of coal delivered to the furnace.

7. Weighing and measuring. To weigh the quantity of coal the following equipment is used :

(*i*) Weigh bridge (*ii*) Belt scale
(*iii*) Weigh lorry (*iv*) Automatic scale.

8. Furnace firing. Refer to Articles 3.9 and 3.10.

3.8.5. Layout of a Fuel Handling Equipment

Fig. 3.17 shows a schematic layout of a fuel handling equipment of a modern steam power plant where coal (a solid fuel) is used. Brief description is given below :

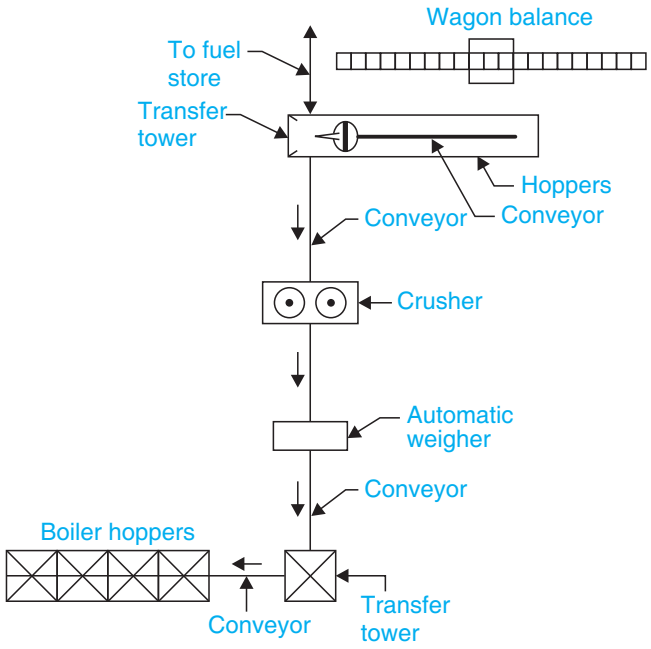


Fig. 3.17. Layout of a fuel handling equipment.

— Coal is supplied to the power plant in railway wagons.

— After weighing on wagon balance the coal is then unloaded into underground hoppers or bunkers. The wagon can be unloaded either manually or through rotary wagon tipplers.

— From the bunkers, the coal is lifted by conveyor to the transfer tower from where it can be delivered either to the fuel store or by a conveyor to a crusher.

— The coal is then passed through the magnetic separators and screens and crushed in crushers into pieces 25 to 30 mm in size for stoker firing and 10 to 20 mm when pulverished fuel is fired in boiler furnaces. The crushed coal in the later case is *milled to a fine powder* and then it is carried through automatic weigher to a transfer tower where fuel is lifted and distributed between boiler hoppers by a conveyor.

3.9. COMBUSTION EQUIPMENT FOR STEAM BOILERS

3.9.1. General Aspects

The combustion equipment is a component of the steam generator. Since the source of heat is the combustion of a fuel, a working unit must have, whatever, equipment is

necessary to receive the fuel and air, proportioned to each other and to the boiler steam demand, mix, ignite, and perform any other special combustion duties, such as distillation of volatile from coal prior to ignition.

— *Fluid fuels are handled by burners ; solid lump fuels* by *stokers*.

— In boiler plants hand firing on grates is *practically unheard* of now-a-days in new plants, although there are many small industrial plants still in service with hand firing.

— The fuels are mainly bituminous coal, fuel oil and natural gas mentioned in order of importance. All are composed of hydrocarbons, and coal has, as well, much fixed carbon and little sulphur. To burn these fuels to the desired end products, CO_2 and H_2O, requires (*i*) *air in sufficient proportions*, (*ii*) *a good mixing of the fuel and air, (iii) a turbulence* or *relative motion between fuel and air*. The combustion equipment *must fulfil these requirements and, in addition, be capable of close regulation of rate of firing the fuel, for boilers which ordinarily operate on variable load*. Coal-firing equipment *must also have a means for holding and discharging the ash residue*.

The basic requirements of combustion equipment :

1. Thorough mixing of fuel and air.

2. Optimum fuel-air ratios leading to most complete combustion possible maintained over full load range.

3. Ready and accurate response of rate of fuel feed to load demand (usually as reflected in boiler steam pressure).

4. Continuous and reliable ignition of fuel.

5. Practical distillation of volatile components of coal.

6. Adequate control over point of formation and accumulation of ash, when coal is the fuel.

Natural gas is used as a boiler fuel in gas well regions where fuel is relatively cheap and coal sources comparatively distant. The transportation of natural gas over land to supply cities with domestic and industrial heat has made the gas in the well more valuable and the gas-fired steam generator more difficult to justify in comparison with coal, or fuel cost alone. Cleanliness and convenience in use are other criteria of selection, but more decisive in small plants in central power stations.

Transportation costs add less to the delivery price of oil than gas ; also fuel oil may be stored in tanks at a reasonable cost, whereas, gas cannot. Hence although fuel oil is usually more costly than coal per kg of steam generated, many operators select fuel oil burners rather than stokers because of the simplicity and cleanliness of storing and transporting the fuel from storage to burner.

Depending on the type of combustion equipment, boilers may be classified as follows :

1. Solid fuels fired :

(*a*) Hand fired

(*b*) Stoker fired

(*i*) Overfeed stokers

(*ii*) Underfeed strokers.

(*c*) Pulverised fuel fired

(*i*) Unit system

(*ii*) Central system

(*iii*) Combination of (*i*) and (*ii*).

2. Liquid fuel fired :

(*a*) Injection system

(*b*) Evaporation system

(*c*) Combination of (*a*) and (*b*).

3. Gaseous fuel fired :

(*a*) Atmospheric pressure system

(*b*) High pressure system.

3.9.2. Combustion Equipment for Solid Fuels—Selection Considerations

While selecting combustion equipment for solid fuels the following considerations should be taken into account :

1. Initial cost of the equipment.

2. Sufficient combustion space and its ability to withstand high flame temperature.

3. Area of the grate (over which fuel burns).

4. Operating cost.

5. Minimum smoke nuisance.

6. Flexibility of operation.

7. Arrangements for thorough mixing of air with fuel for efficient combustion.

3.9.3. Burning of Coal

The two most commonly used methods for the burning of coal are :

1. Stroker firing

2. Pulverised fuel firing.

The selection of one of the above methods depends upon the following factors :

(*i*) Characteristics of the coal available.

(*ii*) Capacity of the boiler unit.

(*iii*) Load fluctuations.

(*iv*) Station load factor.

(*v*) Reliability and efficiency of the various types of combustion equipment available.

3.9.3.1. Stoker firing

*A **"stoker"** is a power operated fuel feeding mechanism and grate.*

Advantages of stoker firing :

1. A cheaper grade of fuel can be used.
2. A higher efficiency attained.
3. A greater flexibility of operations assured.
4. Less smoke produced.
5. Generally less building space is necessary.
6. Can be used for small or large boiler units.
7. Very reliable, maintenance charges are reasonably low.
8. Practically immune from explosions.
9. Reduction in auxiliary plant.
10. Capital investment as compared to pulverised fuel system is less.
11. Some reserve is gained by the large amount of coal stored on the grate in the event of coal handling plant failure.

Disadvantages :

1. Construction is complicated.
2. In case of very large units the initial cost may be rather higher than with pulverised fuel.
3. There is always a certain amount of loss of coal in the form of riddling through the grates.
4. Sudden variations in the steam demand cannot be met to the same degree.
5. Troubles due to slagging and clinkering of combustion chamber walls are experienced.
6. Banking and stand by losses are always present.
7. Structural arrangements are not so simple and surrounding floors have to be designed for heavy loadings.
8. There is excessive wear of moving parts due to abrasive action of coal.

Classification of stoker firing :

Automatic stokers are *classified* as follows :

1. Overfeed stokers
2. Underfeed stokers.

In case of overfeed stokers, the coal is fed into the grate *above* the point of air admission and in case of underfeed stokers, the coal is admitted into the furnace *below* the point of air admission.

1. Overfeed stokers

Principle of operation. Refer to Fig. 3.18. The principle of an overfeed stoker is discussed below :

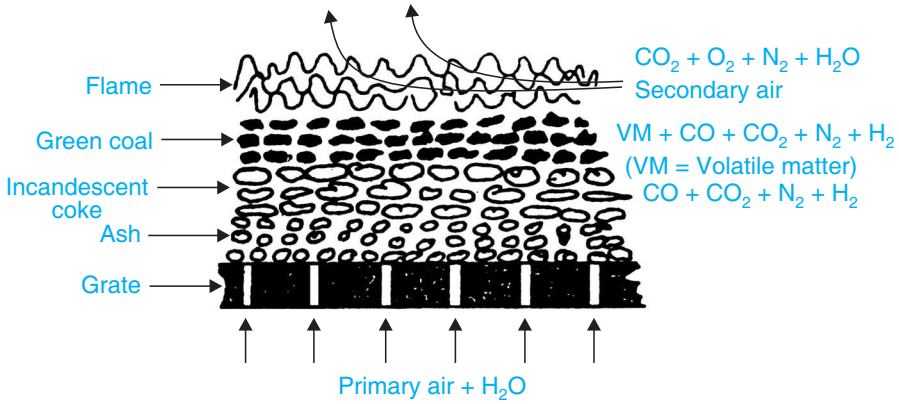


Fig. 3.18. Principle of overfeed stoker.

The fuel bed section receives fresh coal on top surface. The ignition plane lies between green coal and incandescent coke.

The air (with its water vapour content from atmosphere) enters the bottom of the grate under pressure. In flowing through the grate opening the air is heated while it cools the grate. The warm air then passes through a layer of hot ashes and picks up the heat energy.

The region immediately above the ashes contains a mixture of incandescent coke and ash, coke content increasing in upward direction. As the air comes in contact with incandescent coke, the oxygen reacts with carbon to form carbon dioxide. Water vapour entering with the air reacts with coke to form CO_2, CO and free H_2. Upon further travel through the incandescent region some of the CO_2 reacts with coke to form CO. Hence no free O_2 will be present in the gases leaving the incandescent region.

Fresh fuel undergoing distillation of its volatile matter forms the top-most layer of the fuel bed. Heat for distillation and eventually ignition comes from the following *four sources* :

(*i*) By conduction from the incandescent coke below.

(*ii*) From high temperature gases diffusing through the surface of the bed.

(*iii*) By radiation from flames and hot gases in the furnace.

(*iv*) From the hot furnace walls.

The ignition zone lies directly below the raw fuel undergoing distillation.

To burn the combustible gases, additional secondary air must be fed into the furnace to supply the needed oxygen. The secondary air must be injected at considerable speed to create turbulence and to penetrate to all parts of

the area above the fuel bed. The combustible gases then completely burn in the furnace.

Fuel, coke and ash in the fuel bed move in direction opposite to that of air and gases. Raw fuel continually drops on the surface of the bed. The rising air feed cools the ash until it finally rests in a plane immediately adjacent to the grate.

Types of overfeed stokers

The "overfeed stokers" are used for large capacity boiler installation where the coal is burnt with pulverisation.

These stokers are mainly of following two types :

1. Travelling grate stoker
   (*a*) Chain grate type (*b*) Bar grate type
2. Spreader stoker.

1. Travelling grate stoker

These stokers may be *chain grate type or bar grate type*. These two differ only in the details of grate construction.

Fig. 3.19 shows a "**Chain grate stoker**".

A chain grate stoker consists of flexible endless chain which forms a support for the fuel bed. The chain travels over two sprocket wheels one at the front and one at the rear of furnace. The front sprocket is connected to a variable speed drive mechanism. The speed of the stroker is 15 cm to 50 cm per minute.

The coal bed thickness is shown for all times by an index plate. This can be regulated either by adjusting the opening of fuel grate or by the speed control of the stoker driving motor.

The air is admitted from the underside of the grate which is divided into several compartments each connected to an air duct. The grate should be saved from being overheated. For this, coal should have sufficient ash content which will form a layer on the grate.

Since there is practically no agitation of the fuel bed, non-coking coals are best suited for chain grate stokers.

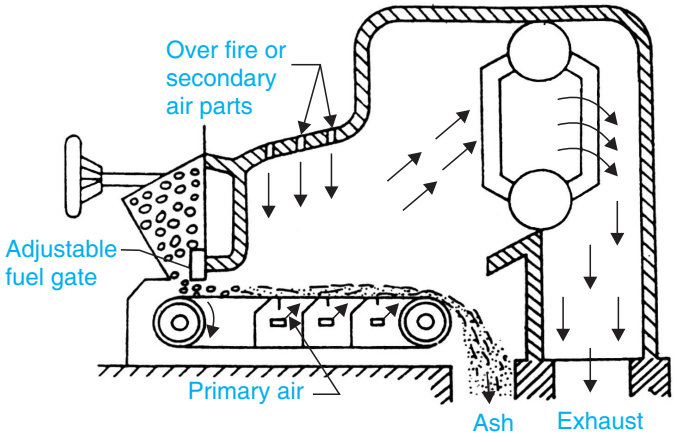


Fig. 3.19. Chain grate stoker.

The rate of burning with this stoker is 200 to 300 kg per m^2 per hour when forced draught is used.

Advantages of chain grate stoker :

1. Simple in construction.
2. Initial cost low.
3. Maintenance charges low.
4. Self-cleaning stoker.
5. Gives high release rates per unit volume of the furnace.
6. Heat release rates can be controlled just by controlling the speed of chain.

Disadvantages :

1. Preheated air temperatures are limited to 180°C maximum.
2. The clinker troubles are very common.
3. There is always some loss of coal in the form of fine particles through riddlings.
4. Ignition arches are required (to suit specific furnace conditions).
5. This cannot be used for high capacity boilers (200 tonnes/hr or more).

2. Spreader stoker. Refer to Fig. 3.20.

— In this type of stoker the coal is not fed into furnace by means of grate. The function of the grate is only to support a bed of ash and move it out of the furnace.

— From the coal hopper, coal is fed into the path of a rotor by means of a conveyer, and is thrown into the furnace by the rotor and is *burnt in suspension*. The *air for combustion* is supplied through the holes in the grate.

— The *secondary air* (or overfire *air*) to *create turbulence and supply oxygen for thorough combustion of coal* is supplied through *nozzles* located directly above the ignition arch.

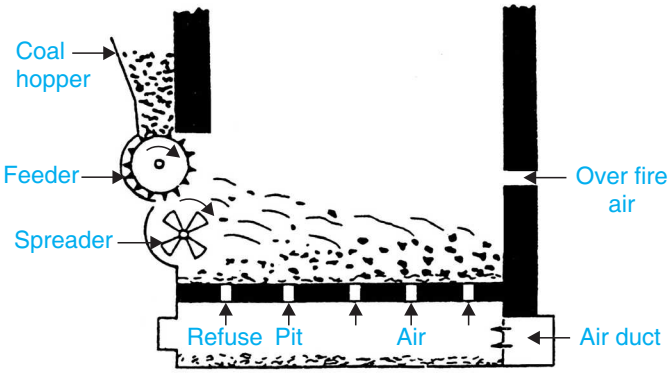


Fig. 3.20. Spreader stoker.

— Unburnt coal and ash are deposited on the grate which can be moved periodically to remove ash out of the furnace.

— Spreader stokers *can burn any type of coal.*

— This type of stoker can be used for boiler capacities from 70000 kg to 140000 kg of steam per hour. The heat release rate of 10×10^6 kcal/m^2-hr is possible with *stationary grate* and of 20×10^6 kcal/m^2-hr is possible with *travelling grate.*

Advantages :

1. A wide variety of coal can be burnt.

2. This stoker is simple to operate, easy to light up and bring into commission.

3. The use of high temperature preheated air is possible.

4. Operation cost is considerably low.

5. The clinking difficulties are reduced even with coals which have high clinkering tendencies.

6. Volatile matter is easily burnt.

7. Fire arches etc. are generally not required with this type of stokers.

8. As the depth of coal bed on the grate is usually limited to 10 to 15 cm only, fluctuating loads can be easily met with.

Disadvantages :

1. It is difficult to operate spreader with varying sizes of coal with varying moisture content.

2. Fly-ash is much more.

3. No remedy for clinker troubles.

4. There is a possibility of some fuel loss in the cinders up the stack because of the thin fuel bed and suspension burning.

2. Underfeed stokers

Principle of operation. Refer to Fig. 3.21 (*a*).

— *The underfeed principle is suitable for burning the semi-bituminous and bituminous coals.*

— Air entering through the holes in the grate comes in contact with the raw coal (green coal). Then it passes through the incandescent coke where reactions similar to overfeed system take place. The gases produced then pass through a layer of ash. The secondary air is supplied to burn the combustible gases.

The underfeed stokers fall into two main groups, the *single retort* and *multi-retort stokers*.

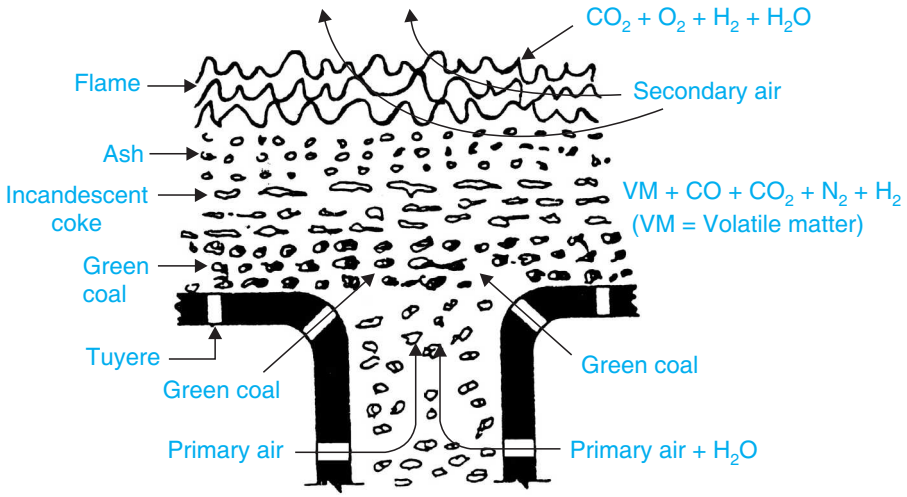


Fig. 3.21 (*a*) Principle of underfeed feeders.

Multi-retort underfeed stokers :

Refer to Fig. 3.21 (*b*).

— The stoker consists of a series of sloping parallel troughs formed by tuyere stacks. These troughs are called *retorts*. Under the coal hopper at the head end of the retorts, *feeding rams* reciprocate back and forth. With the ram in the outer position coal from the hopper falls into space vacated by the rain. On the inward stroke the ram forces the coal into the retort.

— The height and profile of the fuel bed is controlled by *secondary*, or *distributing rams*. These rams oscillate parallel to the retort axes, the length of their stokes can be varied as needed. They slowly move the entire fuel bed down the length of the stoker.

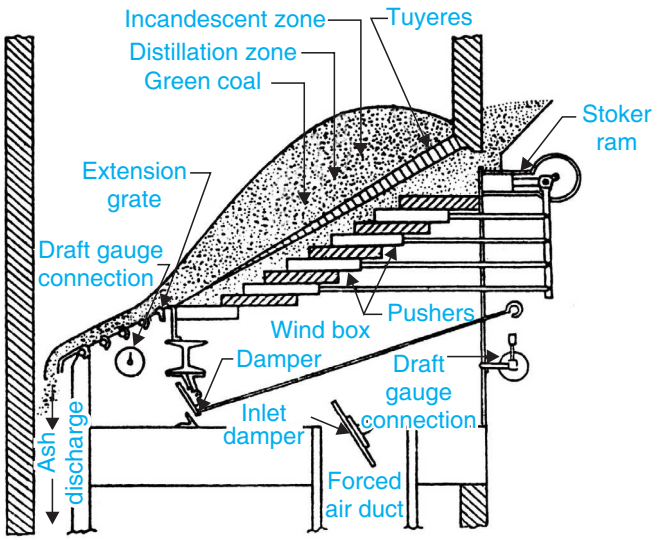


Fig. 3.21 (*b*) Multi-retort underfeed stokers.

— At the rear of the stoker the partly burned fuel bed moves onto an *extension grate* arranged in sections. These sections also oscillate parallel to the fuel-bed movement. The sharp slope of the stoker aids in moving the fuel bed. Fuel-bed movement keeps it slightly agitated to break up clinker formation. From extension grate the ash moves onto ash dump plate. Tilting the dump plate at long intervals deposits the ash in the ashpit below.

— *Primary air* from the wind box underneath the stoker enters the fuel bed through holes in the vertical sides of the tuyeres. The extension grate carries a much thinner fuel bed and so must have a lower air pressure under it. The air entering from the main wind box into the extension-grate wind box is regulated by a *controlling air damper*.

In this stoker the number of retorts may vary from 2 to 20 with coal burning capacity ranging from 300 kg to 2000 kg per hour per retort.

Underfeed stokers are *suitable for non-clinkering, high voltatile coals having caking properties and low ash contents*.

Advantages :

1. High thermal efficiency (as compared to chain grate stokers).

2. Combustion rate is considerably higher.

3. The grate is self cleaning.

4. Part load efficiency is high particularly with multi-retort type.

5. Different varieties of coals can be used.

6. Much higher steaming rates are possible with this type of stoker.

7. Grate bars, tuyeres and retorts are not subjected to high temperature as they remain always in contact with fresh coal.

8. Overload capacity of the boiler is high as large amount of coal is carried on the grate.

9. Smokeless operation is possible even at very light load.

10. With the use of clinker grinder, more heat can be liberated out of fuel.

11. Substantial amount of coal always remains on the grate so that the boiler may remain in service in the event of temporary breakdown of the coal supply system.

12. It can be used with all refractory furnaces because of non-exposure of stoker mechanism to the furnace.

Disadvantages :

1. High initial cost.

2. Require large building space.

3. The clinker troubles are usually present.

4. Low grade fuels with high ash content cannot be burnt economically.

3.9.3.2. Pulverised fuel firing

In pulverised fuel firing system the *coal is reduced to a fine powder with the help of grinding mill and then projected into the combustion chamber with the help of hot air current*. The amount of air required (known as *secondary air*) to complete the combustion is supplied separately to the combustion chamber. The resulting turbulence in the combustion chamber helps for uniform mixing of fuel and air and thorough combustion. *The amount of air which is used to carry the coal and to dry it before entering into the combustion chamber is known as 'Primary air'* and the amount of air which is supplied separately for completing the combustion is known as '*Secondary air*'.

The *efficiency* of the pulverised fuel firing system mostly *depends upon the size of the powder*. The fineness of the coal should be such as 70% of it would pass through a 200 mesh sieve and 90% through 50 mesh sieve.

Fig. 3.22 shows elements of pulverised coal system.

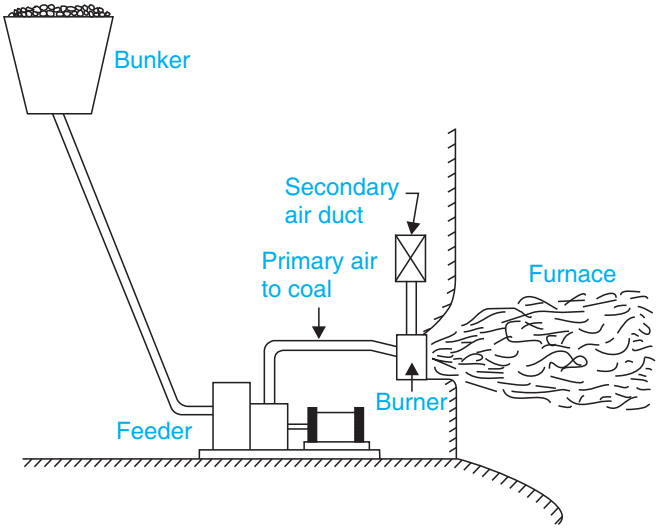


Fig. 3.22. Elements of pulverised coal system.

Advantages :

1. Any grade of coal can be used since coal is powdered before use.
2. The rate of feed of the fuel can be regulated properly resulting in fuel economy.
3. Since there is almost complete combustion of the fuel there is increased rate of evaporation and higher boiler efficiency.
4. Greater capacity to meet peak loads.
5. The system is practically free from sagging and clinkering troubles.
6. No standby losses due to banked fires.
7. Practically no ash handling problems.
8. No moving part in the furnace is subjected to high temperatures.
9. This system works successfully with or in combination with gas and oil.
10. Much smaller quantity of air is required as compared to that of stoker firing.
11. Practically free from clinker troubles.
12. The external heating surfaces are free from corrosion.
13. It is possible to use highly preheated secondary air (350°C) which helps for rapid flame propagation.
14. The furnace volume required is considerably less.

Disadvantages :

1. High capital cost.
2. Lot of fly-ash in the exhaust, which makes the removing of fine dust uneconomical.
3. The possibility of explosion is more as coal burns like gas.
4. The maintenance of furnace brickwork is costly.
5. Special equipment is needed to start this system.
6. The skilled operators are required.
7. A separate coal preparation plant is necessary.
8. High furnace temperatures cause rapid deterioration of the refractory surfaces of the furnace.
9. Nuisance is created by the emission of very fine particles of grit and dust.
10. Fine regular grinding of fuel and proper distribution to burners is usually difficult to achieve.

Pulverised Fuel Handling

Basically, pulverised fuel plants may be divided into the following *two systems* :

1. Unit system
2. Central system.

Unit system :

A unit system is shown in Fig. 3.23.

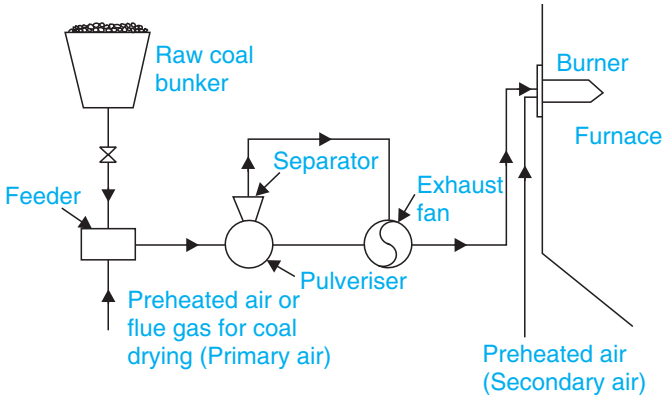


Fig. 3.23. Unit system.

Most pulverised coal plants are now being installed with unit pulveriser.

The *unit system* is so called from the fact that each burner or burner group and the pulveriser constitute a unit. Crushed coal is fed to the pulverising mill at a variable rate governed by the combustion requirements of the boiler and furnace. Primary air is admitted to the mill and becomes the transport air which carries the coal through the short delivery pipe to the burner. This air may be preheated if mill drying is desirable.

Advantages :

1. The layout is simple and permits easy operation.
2. It is cheaper than central system.
3. Less spaces are required.
4. It allows direct control of combustion from the pulveriser.
5. Maintenance charges are less.
6. There is no complex transportation system.

7. In a replacement of stokers, the old conveyor and bunker equipment may be used.

8. Coal which would require drying in order to function satisfactorily in the central system may usually be employed without drying in the unit system.

Disadvantages :

1. Firing aisle is obstructed with pulverising equipment, unless the latter is relegated to a basement.

2. The mills operate at variable load, a condition not especially conducive to best results.

3. With load factors in common practice, total mill capacity must be higher than for the central system.

4. Flexibility is less than central system.

Central system :

This system is illustrated in Fig. 3.24.

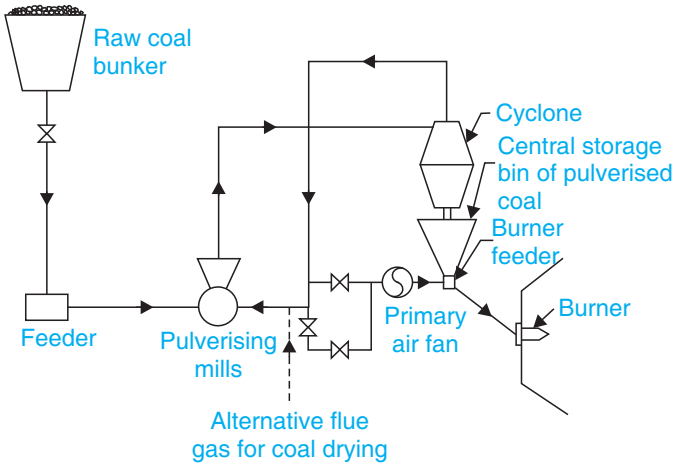


Fig. 3.24. Central system.

A central pulverising system employs a limited number of large capacity pulverisers at a central point to prepare coal for all the burners. Driers, if required, are conveniently installed at this point. From the pulverisers the coal is transported to a central storage bin where it is deposited and its transporting air vented from the bin through a "*cyclone*". This bin may contain from 12 to 24 hours supply of pulverised coal. From the bin the coal is metered to the burners by motor-driven feeders of varied design. Primary air, added at the feeders, floats the coal to the burners.

Advantages :

1. Offers good control of coal fineness.

2. The pulverising mill may work at constant load because of the storage capacity between it and the burners.

3. The boiler aisels are unobstructed.

4. More latitude in the arrangement and number of burners is allowed to the designers.

5. The large storage is protection against interruption of fuel supply to the burners.

6. Less labour is required.

7. Power consumption per tonne of coal handled is low.

8. Burners can be operated independent of the operation of coal preparation plant.

9. Fans handle only air, as such, there is no problem of excessive wear as in case of unit system, where air and coal both are handled by the fan.

Disadvantages :

1. Driers are usually necessary.

2. Fire hazard of quantities of stored pulverised coal.

3. Central preparation may require a separate building.

4. Additional cost and complexity of coal transportation system.

5. Power consumption of auxiliaries is high.

Pulveriser. Coal is pulverised in order to increase its surface exposure, thus promoting rapid combustion without using large quantities of excess air. A pulveriser is the most important part of a pulverised coal system. Pulverisers (sometimes called *mills*) are classified as follows:

1. Attrition mills
   (*i*) Ball and race mills.
   (*ii*) Bowl mills
2. Impact mills
   (*i*) Ball mills
   (*ii*) Hammer mills.

Pulverisers are driven by electric motors with the feeders either actuated by the main drive or by a small D.C. motor, depending upon the control used.

Ball and race mill. This a low speed unit in which grinding pressure is maintained by adjustable springs. The coal passes between the two rotating elements again and again until it has been pulverised to the desired degree of fineness. Fig. 3.25 shows a ball and race mill. Mill, feeder and fan require up to 14 kWh per tonne of coal pulverised.

Bowl mill. The bowl mill grinds the coal between a whirling bowl and rolls mounted on pivoted axes. Coal fed into the centre is thrown by centrifugal force against the sides of the bowl where it is pulverised between the sides of the bowl and the grinding ring. The fine and intermediate sizes are picked up from the top by an air current and carried into the separator above for classification. It consumes about 5 kWh of electricity per tonne of coal.

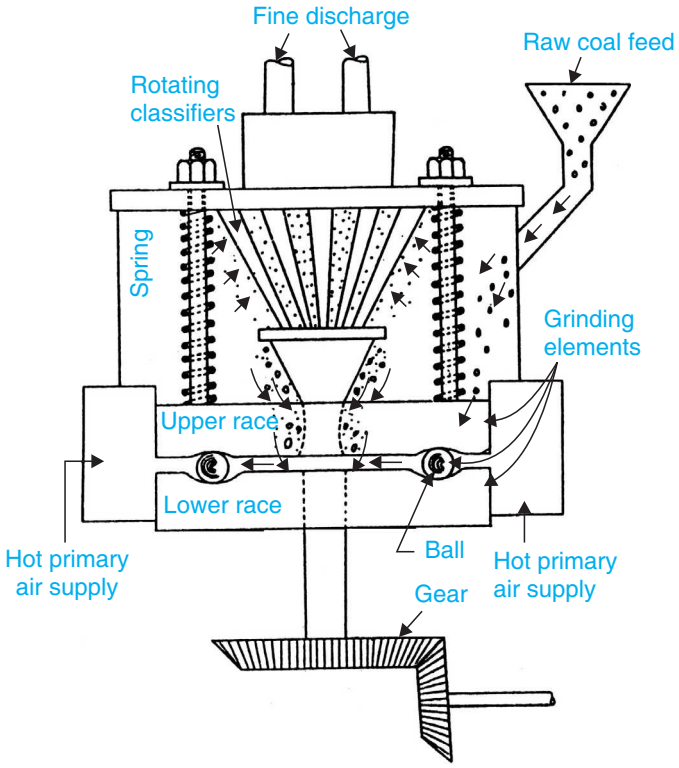


Fig. 3.25. Ball and race mill.

Ball mill. The ball mill operates something like a foundry tumbling barrel. The large rotating drum (100–200 r.p.m.) contains a quantity of iron balls mixed with the coal. As the drum turns balls are carried upward to be dropped on the coal while others, remaining in the agitated mixture, grind the coal at random between them. The coal is fed into one end and reduced in size by this action until it can be swept out of the mill by a current of air. Fig. 3.26 shows the principle of ball mill.

Hammer mills. These mills have swinging hammers or bars, into the path of which is fed the coal to be pulverised. Grinding is done by a combination of impact on the large particles and attrition on the smaller ones. Hot air is given to dry the coal. These mills are excellent dryers. It is *compact, low in cost* and *simple*. Its *maintenance is costly* and the *power consumption is high when fine powder is required*. *Its capacity is limited*.

Fig. 3.27 shows the *principle of impact mill*.

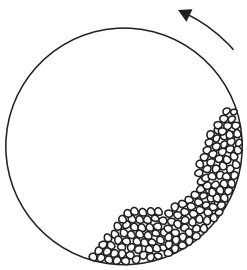


Fig. 3.26. Principle of ball mill.

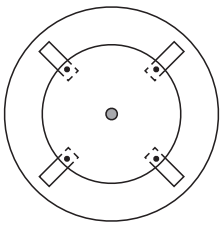


Fig. 3.27. Principle of impact mill.

3.9.4. Burners

Primary air that carries the powdered coal from the mill to the furnace is only about 20% of the total air needed for combustion. Before the coal enters the furnace, it must be mixed with additional air, known as *secondary air,* in burners mounted in the furnace wall. *In addition to the prime function of mixing, burners must also maintain stable ignition of fuel-air mix* and *control the flame shape and travel in the furnace*. Ignition depends on the rate of flame propagation. To prevent flash back into the burner, the coal-air mixture must move away from the burner at a rate equal to flame-front travel. *Too much secondary air can cool the mixture and prevent its heating to ignition temperature*.

The *requirements of a burner* can be summarised as follows :

(*i*) The coal and air should be so handled that there is stability of ignition.

(*ii*) The combustion is complete.

(*iii*) In the flame the heat is uniformly developed avoiding any superheat spots.

(*iv*) Adequate protection against overheating, internal fires and excessive abrasive wear.

3.9.4.1. Pulverised fuel burners

Pulverised fuel burners may be *classified* as follows :

1. Long flame burners
2. Turbulent burners
3. Tangential burners
4. Cyclone burners.

1. Long flame burners. These are also called U-flame or steamlined burners. In this type of burner coal is floated on a portion of air supply (primary air) and supplied to the burner in one stream. Secondary and tertiary air supplies are maintained as shown in Fig. 3.28. The length of flame is increased in the combustion chamber by downward initial flow of the flame. The flame produced is stable, long and intense but it can be made short and intense by adding much secondary air. Tertiary air enters through the burner and forms an envelope around the primary air and fuel and provides better mixing.

Furnaces for low volatile coal are equipped with such burners to give a long flame path for slower burning particles.

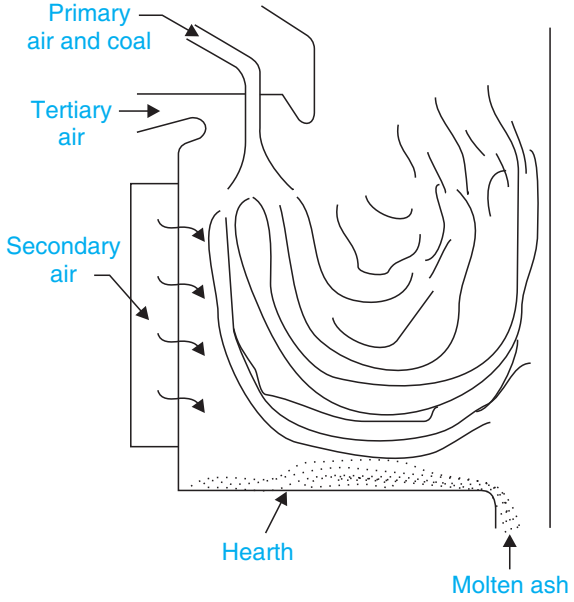


Fig. 3.28. Long flame burner.

2. Turbulent burners. Refer to Fig. 3.29. It is also called a *short flame burner*. These burners can fire horizontally or at some inclinations by adjustment. The fuel-air mixture and secondary hot air are arranged to pass through the burner in such a way that there is good mixing and the mixture is projected in highly turbulent form in the furnace. Due to high turbulence created before entering the furnace, the mixture burns intensely and combustion is completed in short distance.

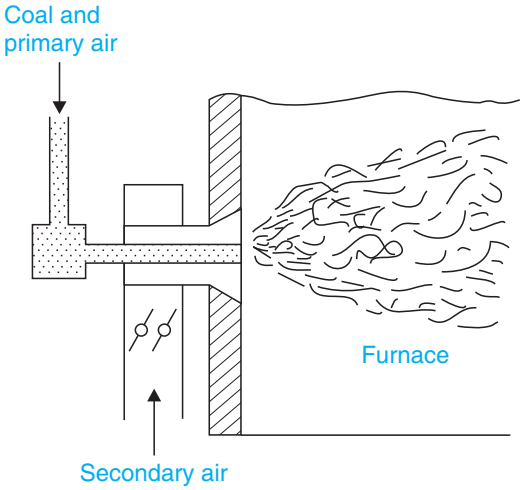


Fig. 3.29. Turbulent burner.

This burner gives *high rate of combustion compared with other types*. This is generally *preferred for high volatile coals*. All modern plants use this type of burner.

3. Tangential burners. These burners are set as shown in Fig. 3.30. In this case four burners are located in the four corners of the furnace and are fired in such a way that the four flames are tangential to an imaginary circle formed at the centre. The swirling action produces adequate turbulence in the furnace to complete the combustion in a short period and avoids the necessity of producing high turbulence at the burner itself.

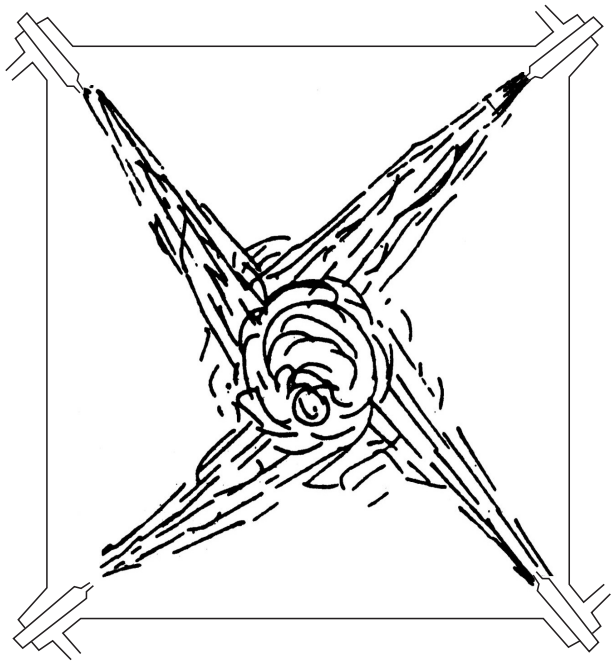


Fig. 3.30. Plan of furnace with tangential firing.

The tangential burners have the following *advantages* :

1. The parts of the burner are well-protected by furnace wall tubes.
2. The operation of these burners is very simple.
3. High heat release with complete and effective utilisation of furnace volume is possible.
4. The completeness of combustion is exceptionally good and a maximum degree of turbulence exists throughout the furnace.
5. Liquid, gaseous and pulverised fuels can be readily burned either separately or in combination.

4. Cyclone burners. Two main *disadvantages* associated with pulverised coal firing are :

(*i*) High cost.

(*ii*) 70% of the ash escapes as fly-ash which requires expensive dust collectors in the flue gas path.

These disadvantages are offset by a *cyclone burner*. In a cyclone burner coal is crushed to a maximum size of 6 mm and blows into a cylindrical cyclone furnace. The

fuel is quickly consumed and liberated ash forms a molten film flowing over the inner wall of the cylinder. Owing to *inclination of the furnace*, the molten ash flows to an appropriate disposal system.

The description of a cyclone burner (developed by M/s Babcock and Wilcox) is given below : Refer to Fig. 3.31.

It consists of a horizontal cylindrical drum having a diameter varying from 2 to 4 metres depending upon the capacity of the boiler. Depending upon the capacity of the burner the number of cyclone burners used may be one or more. If the number of cyclone burners used is more than one, the diameter of each burner is less. These burners are attached to the side of the furnace wall and have vents for primary air, *crushed coal* (6 mm diameter maximum size) and secondary air. It is *water-cooled*. The horizontal axis of the burner is slightly deflected towards the boiler.

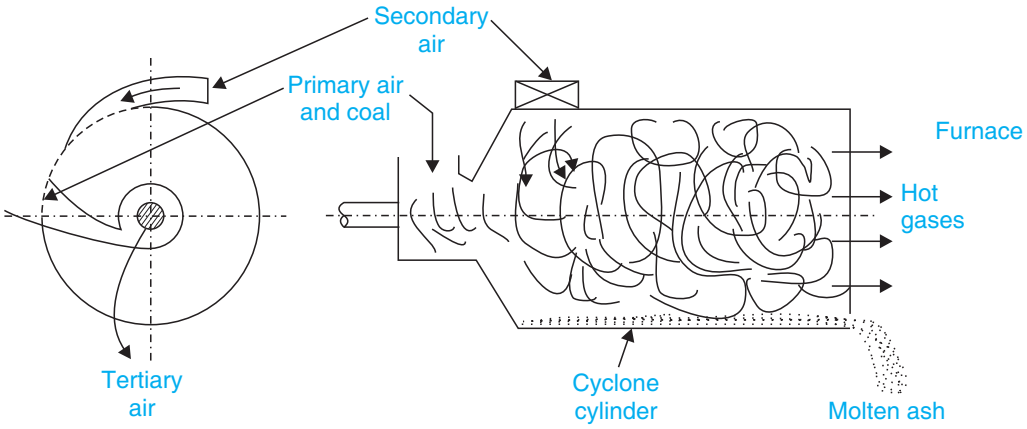


Fig. 3.31. Cyclone burner.

The cyclone burner receives crushed coal carried in primary air (at 80 cm water pressure) at the left end. Tangential entry of the coal throws it to the surface of the cylindrical furnace. Secondary air enters the furnace through tangential ports at the upper edge at high speed and creates a strong and highly turbulent vortex. Extremely high heat liberation rate and use of preheated air cause high temperatures to the tune of 2000°C in the cyclone. The fuel supplied is quickly consumed and liberated ash forms a molten film flowing over the inner wall of the cylinder. Due to horizontal axis of the burner being tilted the molten ash flows to an appropriate disposal system. The cyclone furnace gives best results with low grade fuels.

Advantages :

1. High furnace temperatures are obtained.
2. Simplified coal existing equipments can be used instead of costly pulverised mills.
3. The cyclone burners reduce the percentage of excess air used.
4. It can burn poorer and cheaper grades of coal.
5. As the swirling effect and consequently the mixing of air and crushed coal is better, it provides for a higher furnace capacity and efficiency.
6. Boiler efficiency is increased.
7. The cost of milling in cyclone fire is less as the finer particles are not required in this case.
8. Combustion rates can be controlled by simultaneous manual adjustment of fuel feed and air flow and response in firing rate changes is comparable to that of pulverised coal firing.

3.9.4.2. Oil burners

Principle of oil firing. *The functions of an oil burner are to mix the fuel and air in proper proportion and to prepare the fuel for combustion*. Figure 3.32 shows the principle of oil firing.

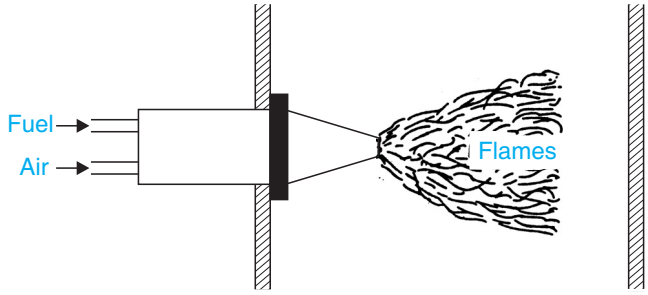


Fig. 3.32. Principle of oil burning.

Classification of oil burners. The oil burners may be *classified* as :

1. *Vapourising oil burners :*
   (*a*) Atmospheric pressure atomising burner
   (*b*) Rotating cup burner

(*c*) Recirculation burner

(*d*) Wick type burner

2. *Atomising fuel burners :*

(*a*) Mechanical or oil pressure atomising burner

(*b*) Steam or high pressure air atomising burner

(*c*) Low pressure air atomising burner.

1. Vapourising oil burners. Following are the requirements of a vapourising/evaporation oil burner :

(*i*) To vapourise the fuel before ignition.

(*ii*) To mix the vapourised fuel thoroughly with the air.

(*iii*) To minimise the soot formation.

(*iv*) To give high heat release by burning large quantity of oil per hour.

(*v*) To allow for efficient combustion of fuel at part load operation.

(a) Atmospheric pressure atomising burner. This burner makes use of highly volatile liquid fuels such as neptha, volatile gasoline etc. Here the *fuel at low pressure* is passed through a tube adjacent to the flame before being released through an orifice. While passing through the hot tube, most of the fuel is vapourised so that the fluid ejected from the orifice is more or less a vapour. The required quantity of primary air is supplied to burn the vapour stream in a cylindrical tube.

(b) Rotating cup burner. These burners are used on low as well as medium capacity boilers.

In this type of burner, the fuel oil flows through a tube in the hollow shaft of the burner and into the cup at the furnace end. An electric motor or an air turbine runs the shaft and the cup at high speeds (3000 to 10000 r.p.m.). As a result of centrifugal force fuel is split into small droplets. About 10 to 15 per cent of air is supplied as primary air. This air is supplied from a blower surrounding the cup. The shape of the flame is governed by the sharp edge of the cup and the position of air nozzle.

(c) Recirculating burner. The part of the combustion products may be recirculated in order to heat up the incoming stream of fuel and air. Low ratio of the mass of recirculated combustion products to the mass of unburnt fuel-air mixture results in less temperature rise of the mixture, whereas, high ratio may extinguish the flame due to increased proportions of circulated products. An optimum ratio may be determined for different fuels experimentally.

In recirculation burner (utilising the above principle) circulation system is separated from the combustion by a solid wall.

(d) ***Wick burners.*** In this type of a burner a cotton or asbestos wick is used which raises the liquid fuel by capillary action. The fuel from the uppermost part of the wick is evaporated due to radiant heat from the flame and the nearby heated surfaces. Air is admitted through holes in the surrounding walls.

A wick burner is suitable for models or domestic appliances.

2. Atomising fuel burners. Following are the *requirements of an automising fuel burner :*

(*i*) To automise the fuel into fine particles of equal size.

(*ii*) To supply air in required quantity at proper places in the combustion chamber.

(*iii*) To give high combustion intensity.

(*iv*) To give high thermal efficiency.

(*v*) To operate without difficulty at varying loads.

(*vi*) To create necessary turbulence inside the combustion chamber for proper combustion of fuel.

(*vii*) To minimise soot formation and carbon deposit, particularly on the burner nozzle.

(a) Mechanical atomising burners. A mechanical atomising oil burner consists of the following four principal parts :

(*i*) Atomiser (*ii*) Air register (*iii*) Diffuser (*iv*) Burner throat opening.

(*i*) *Atomiser.* It breaks up the oil mechanically into a fine uniform spray that will burn with minimum of excess air when projected into the furnace. The spray is produced by using relatively high pressure to force oil at high velocity through small tangential passages of sprayer plate into a chamber where it is rapidly rotated, centrifugal force in the rotating oil causes it to break up into a thin layered, mist like, hollow conical spray as it is released through the orifice plate.

(*ii*) *Air register.* An air register is an integral part of the oil-burner assembly. It consists of a number of overlapping vanes which deliver the air for combustion to the furnace throat with the correct degree of spin.

(*iii*) *Diffuser.* It is a shield in the form of a perforated hollow metal cone mounted near the furnace end of the atomiser assembly. *It stabilises the flame to prevent it from being blown away from the atomiser tip.*

(*iv*) *Burner throat opening.* It is circular and concentric with burner outlet. It is made of refractory. The atomiser and diffuser assembly should be so positioned that the flame clears the throat opening sufficiently to avoid striking. This burner has an insulated front and thus is designed to operate with preheated air.

(b) Steam atomising burners. Of various methods of oil atomisation, that which employs steam is usually the most convenient. This method may, however, absorbs some 4 to 5% of the total amount of steam generated. These burners may be divided into two categories :

(*i*) The outside mix

(*ii*) The inside mix.

In case of *outside mixing* [Fig. 3.33 (*a*)] *type burners,* oil is ejected through one side of the holes and is blasted by a high velocity jet of steam issuing from other holes. *Mixing*, however, occurs *outside the burner*.

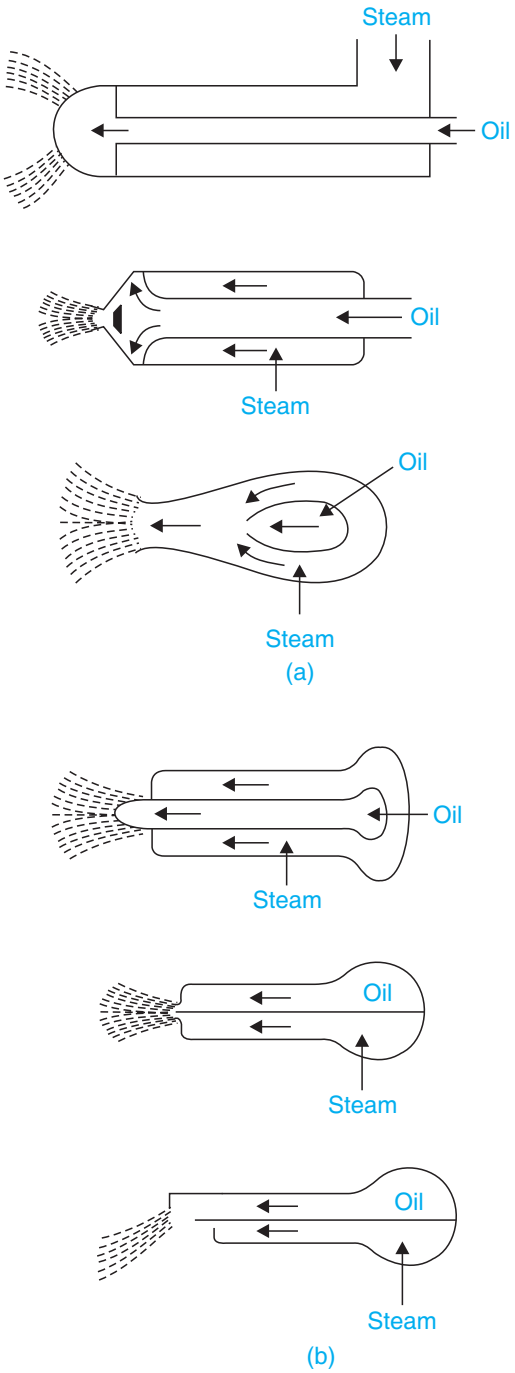


Fig. 3.33. (*a*) Inside mixing (*b*) Outside mixing.

In case of *inside mixing type burners* steam and oil are *mixed inside the burner* before the mixture is projected in the furnace in either a flat spray or in a hollow cone. *These burners provide high efficiency at the high firing rates and flexible flame shape*. In this type of burner instead of steam high pressure air can also be used.

(c) Low pressure air atomising burners. They operate on the same principle as for burners described earlier. In this case air pressure required ranges from 0.015 bar to 0.15 bar.

These are the simplest and most versatile atomising type of burners and usually give troublefree service for long interrupted periods.

3.9.4.3. Gas burners

Gas burning claims the following ***advantages*** :

(*i*) It is much simpler as the fuel is ready for combustion and requires no preparation.

(*ii*) Furnace temperature can be easily controlled.

(*iii*) A long slow burning flame with uniform and gradual heat liberation can be produced.

(*iv*) Cleanliness.

(*v*) High chimney is not required.

(*vi*) No ash removal is required.

For generation of steam, natural gas is invariably used in the following cases :

(*i*) Gas producing areas.

(*ii*) Areas served by gas transmission lines.

(*iii*) Where coal is costlier.

Typical gas burners used are shown in Figs. 3.34 to 3.36.

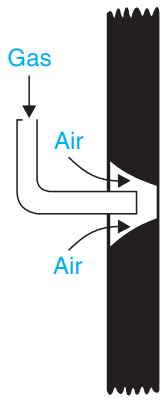


Fig. 3.34

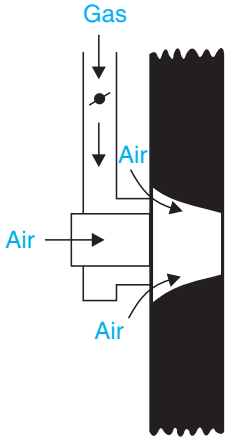


Fig. 3.35

Refer to Fig. 3.34. In this burner the mixing is poor and a fairly long flame results.

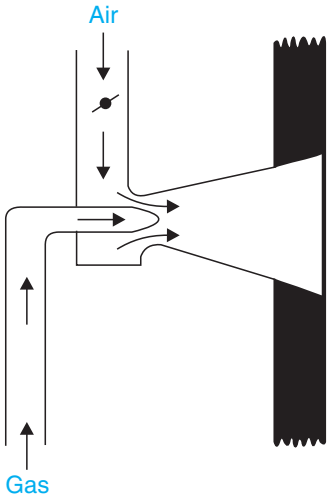


Fig. 3.36

Refer to Fig. 3.35. This is a *ring type burner* in which a short flame is obtained.

Refer to Fig. 3.36. This arrangement is used when both gas and air are under pressure.

In order to prevent the flame from turning back the velocity of the gas should be more than the "*rate of flame propagation*".

3.10. FLUIDISED BED COMBUSTION (FBC)

*A **fluidised bed** may be defined as the bed of solid particles behaving as a fluid.* The *principle of FBC-system* is given below :

When a gas is passed through a packed bed of finely divided solid particles, it experiences a pressure drop across the bed. At low gas velocities, this pressure drop is small and does not disturb the particles. But if the gas velocity is increased further, a stage is reached, *when particles are suspended in the gas stream and the packed bed becomes a 'fluidised bed'*. With further increase in gas velocity, the bed becomes turbulent and rapid mixing of particles occurs. In general, the behavior of this mixture of solid particles and gas is like a fluid. Burning of a fuel in such a state is known as a *fluidised bed combustion*.

Fig. 3.37 shows the arrangement of the FBC system.

On the distributor plate are fed the fuel and inert material *dolomite* and from its bottom air is supplied. The high velocity of air keeps the solid feed material in suspending condition during burning. The generated heat is rapidly transferred to the water passing through the tubes immersed in the bed and generated steam is taken out. During the burning sulphur dioxide formed is absorbed by the dolomite and prevents its escape with the exhaust gases. The molten slag is tapped from the top surface of the bed.

The primary object of using the *inert material* is to control the bed temperature, it accounts for 90% of the bed volume. It is very necessary that the selection of an inert material should be done judiciously as it remains with the fuel in continuous motion and at high temperature to the tune of 800°C. Moreover, the inert material should not disintegrate coal, the parent material of the bed.

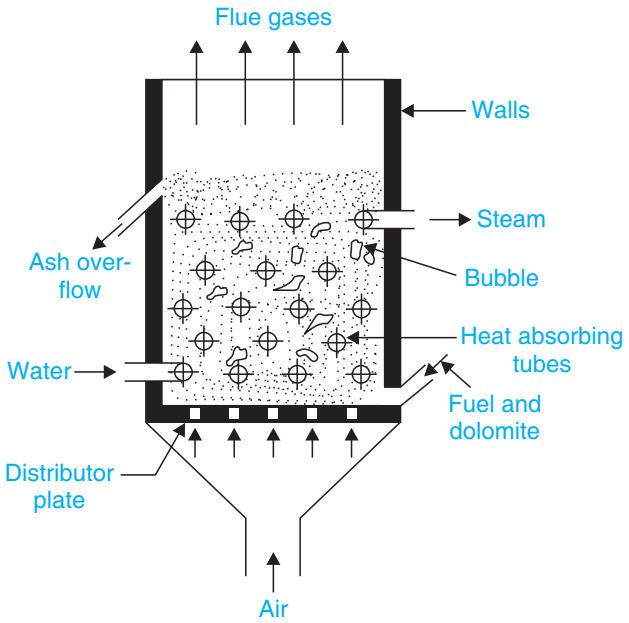


Fig. 3.37. Basic FBC system.

The cost economic shows that a saving of about 10% in operating cost and 15% capital cost could be achieved for a unit rating of 120 MW and it may be still higher for bigger units.

Advantages :

1. As a result of better heat transfer, the unit size and hence the *capital costs are reduced*.
2. It can respond rapidly to changes in load demand (since thermal equilibrium between air and coal particles in the bed is quickly established).
3. Low combustion temperatures (800 to 950°C) inhibits the formation of nitrogen oxides like nitric oxide and nitrogen dioxide.
4. Since combustion temperatures are low the fouling and corrosion of tubes is reduced considerably.
5. As it is not necessary to grind the coal very fine as is done in pulverised fuel firing, therefore, the cost of coal crushing is reduced.
6. Pollution is controlled and combustion of high-sulphur coal is possible.
7. FBC system can use solid, liquid or gaseous fuel or mix as well as domestic and industrial waste. Any variety of coal can be used successfully.

8. Combustion temperature can be controlled accurately.

9. The system can be readily designed for operation at raised combustion pressure, owing to the simplicity of arrangement, small size of the plant and reduced likelihood of corrosion or erosion of gas turbine blades.

10. The combustion in conventional system becomes unstable when the ash exceeds 48% but even 70% ash containing coal can be efficiently burned in FBC.

11. The large quantity of bed material acts as a thermal storage which reduces the effect of any fluctuation in fuel feed ratio.

3.11. ASH HANDLING

A huge quantity of ash is produced in central stations, sometimes being as much as 10 to 20% of the total quantity of coal burnt in a day. Hundreds of tonnes of ash may have to be handled every day in large power stations and mechanical devices become indispensable. A station using low grade fuel has to deal with large quantities of ash.

Handling of ash includes :

(*i*) Its removal from the furnace.

(*ii*) Loading on the conveyers and delivery to the fill or dump from where it can be disposed off by sale or otherwise.

Handling of ash is a problem because ash coming out of the furnace is too hot, it is dusty and irritating to handle and is accompanied by some poisonous gas. Ash needs to be *quenched* before handling due to following *reasons* :

(*i*) Quenching reduces corrosion action of the ash.

(*ii*) It reduces the dust accompanying the ash.

(*iii*) It reduces temperature of the ash.

(*iv*) Ash forms clinkers by fusing in large lumps and by quenching clinkers will disintegrate.

3.11.1. Ash Handling Equipment

A good **ash handling plant** should have the following *characteristics* :

1. It should have enough capacity to cope with the volume of ash that may be produced in a station.

2. It should be able to handle large clinkers, boiler refuse, soot etc. with little personal attention of the workmen.

3. It should be able to handle hot and wet ash effectively and with good speed.

4. It should be possible to minimise the corrosive or abrasive action of ashes and dust nuisance should not exist.

5. The plant should not cost much.

6. The operation charges should be minimum possible.

7. The operation of the plant should be noiseless as much as possible.

8. The plant should be able to operate effectively under all variable load conditions.

9. In case of addition of units, it should need minimum changes in original layout of plant.

10. The plant should have high rate of handling.

The commonly used equipment for ash handling in large and medium size plants may comprise of :

(*i*) Bucket elevator

(*ii*) Bucket conveyor

(*iii*) Belt conveyor

(*iv*) Pneumatic conveyor

(*v*) Hydraulic sluicing equipment

(*vi*) Trollies or rail cars etc.

Fig. 3.38 shows the outline of ash disposal equipment.

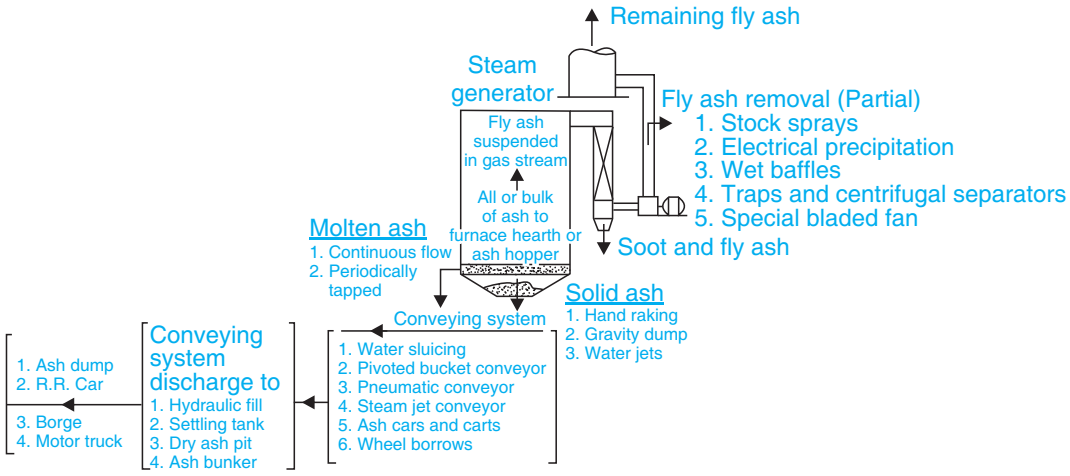


Fig. 3.38. Outline of ash disposal equipment.

3.11.2. Ash Handling Systems

The modern ash-handling systems are mainly classified into four groups :

1. Mechanical handling system
2. Hydraulic system
3. Pneumatic system
4. Steam jet system.

1. Mechanical handling system

Fig. 3.39 shows a mechanical handling system. This system is generally employed for *low capacity power plants* using coal as fuel.

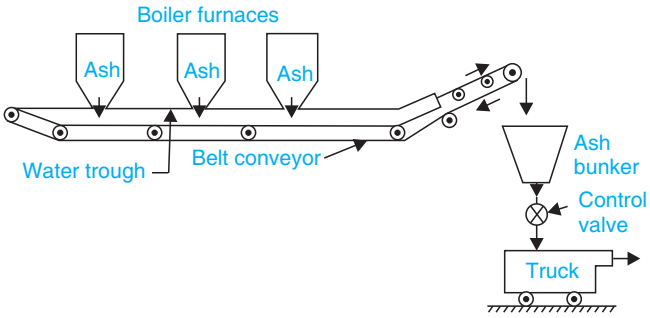


Fig. 3.39. Mechanical handling system.

The hot ash released from the boiler furnaces is made to fall over the belt conveyor after cooling it through water seal. This cooled ash is transported to an ash bunker through the belt conveyor. From ash bunker the ash is removed to the dumping site through trucks.

2. Hydraulic system

In this system ash is carried with the flow of water with high velocity through a channel and finally dumped in the sump. This system is subdivided as follows :

(*a*) Low pressure system

(*b*) High pressure system.

(a) Low pressure system. Refer to Fig. 3.40. In this system a trough or drain is provided below the boilers and the water is made to flow through the trough. The ash directly falls into the troughs and is carried by water to sumps. In the sump the ash and water are made to pass through a screen so that water is separated from ash ; this water is pumped back to the trough for reuse and ash is removed to the dumping yard.

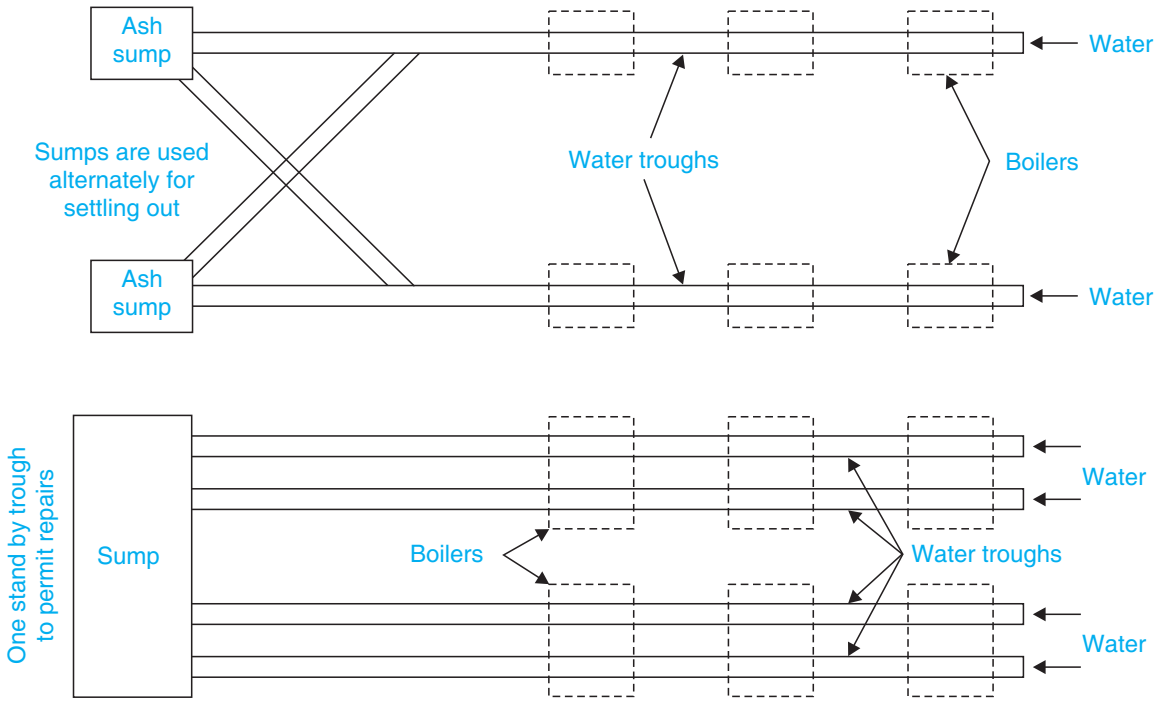


Fig. 3.40. Low pressure system.

The ash carrying capacity of this system is 50 tonnes/hour and distance covered is 500 metres.

(b) High pressure system. Refer to Fig. 3.41. The hoppers below the boilers are fitted with water nozzles at the top and on the sides. The top nozzles quench the ash while the side ones provide the driving force for the ash. The cooled ash is carried to the sump through the trough. The water is again separated from ash and recirculated.

The ash carrying capacity of this system is as large as 120 tonnes per hour and the distance covered is as large as 1000 metres.

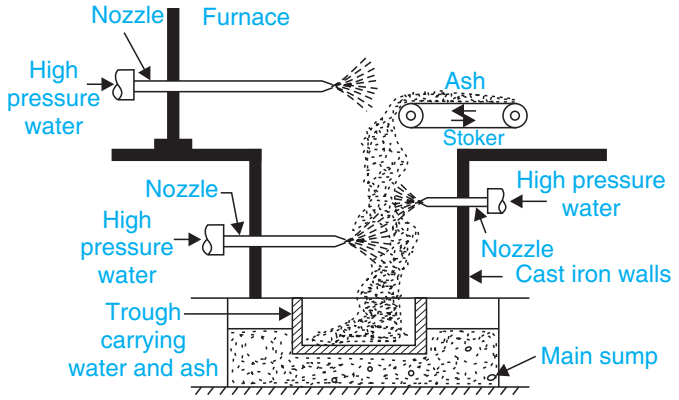


Fig. 3.41. High pressure system.

Advantages of hydraulic system :

1. The system is clean and healthy.
2. It can also be used to handle stream of molten ash.
3. Working parts do not come into contact with the ash.
4. It is dustless and totally closed.
5. It can discharge the ash at a considerable distance (1000 m) from the power plant.
6. The unhealthy aspects of ordinary ash basement work is eliminated.
7. Its ash carrying capacity is considerably large, hence suitable for large thermal power plants.

3. Pneumatic system

Fig. 3.42 shows the schematic of a pneumatic ash handling system. This system can handle abrasive ash as well as fine dusty materials such as fly-ash and soot. It is preferable for the boiler plants from which ash and soot must be transported some far off distance for final disposal.

The exhauster provided at the discharge end creates a high velocity stream which picks up ash and dust from all discharge points and then these are carried in the conveyor pipe to the point of delivery. Large ash particles are generally crushed to small sizes through mobile crushing units which are fed from the furnace ash hopper and discharge into the conveyor pipe which terminates into a separator at the delivery end.

The *separator* working on the *cyclone principle* removes dust and ash which pass out into the ash hopper at the bottom while clean air is discharged from the top.

The *exhauster* may be mechanical or it may use steam jet or water jet for its operation. When a *mechanical exhauster* is used it is usually essential to use a filter or washer to ensure that the exhauster handles clear air. Such type of exhauster may be used in a large station as the power requirements are less. *Steam exhauster* may be used in small and medium size stations. Where large quantities of water are easily and cheaply available *water exhauster* is preferred.

The ash carrying capacity of this system varies from 25 to 15 tonnes per hour.

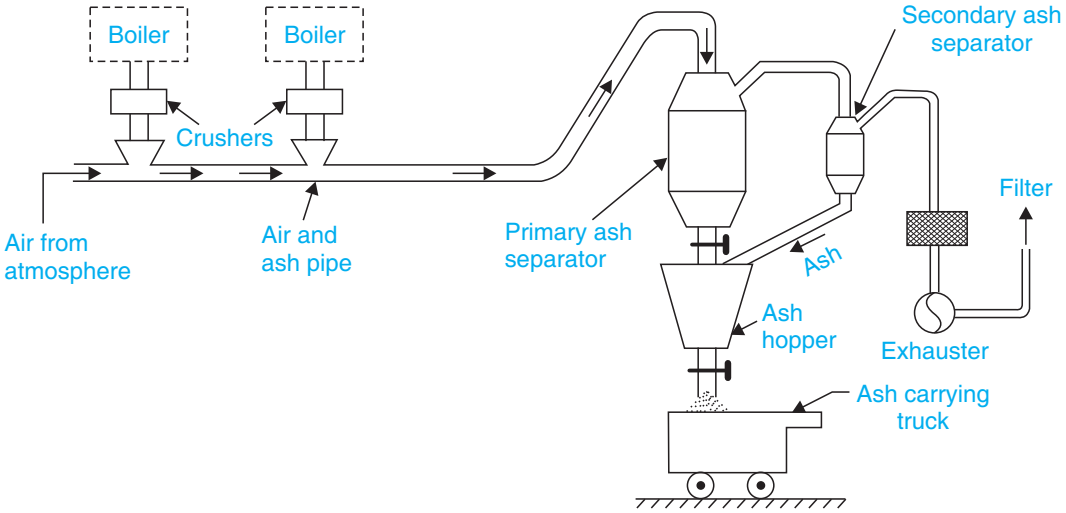


Fig. 3.42. Pneumatic or vacuum extraction ash handling system.

Advantages :

1. No spillage and rehandling.
2. High flexibility.
3. There is no chance of ash freezing or sticking in the storage bin and material can be discharged freely by gravity.

4. The dustless operation is possible as the materials are handled totally in an enclosed conduit.

5. The cost of plant per tonne of ash discharged is less in comparison to other systems.

Disadvantages :

1. There is a large amount of wear in the pipe work necessitating high maintenance charges.

2. More noisy than other systems.

4. Steam jet system

In this case steam at sufficiently high velocity is passed through a pipe and dry solid materials of considerable size are carried along with it. In a high *pressure steam jet system* a jet of high pressure steam is passed in the direction of ash travel through a conveying pipe in which the ash from the boiler ash hopper is fed. The ash is deposited in the ash hopper.

This system can remove economically the ash through a horizontal distance of 200 m and through a vertical distance of 30 m.

Advantages :

1. Less space requirement.

2. Less capital cost in comparison to other systems.

3. Auxiliary drive is not required.

4. It is possible to place the equipment in awkward position too.

Disadvantages :

1. Noisy operation.

2. This system necessitates continuous operation since its capacity is limited to about 7 tonnes per hour.

3. Due to abrasive action of ash the pipes undergo greater wear (and to reduce this wearing action the pipes are lined with nickel alloy).

3.12. DUST COLLECTION

3.12.1. Introduction

The products of combustion of coal-fed fires contain particles of solid matter floating in suspension. This may be smoke or dust. If *smoke*, the indication is that combustion conditions are faulty, and the proper remedy is in the design and management of the furnace. If *dust*, the particles are mainly fine ash particles called "*Fly-ash*" intermixed with some quantity of carbon-ash material called "*cinder*". *Pulverised coal and spreader stoker firing units are the principle types causing difficulty from this source.* Other stokers may produce minor quantities of dust but generally not enough to demand special gas cleaning equipment. The two mentioned are troublesome because coal is burned in suspension—in a turbulent furnace atmosphere and every opportunity is offered for the gas to pick up the smaller particles and sweep them along with it.

The size of the dust particles is measured in *microns*. The micron is one millionth of a metre. As an indication of the scale of this measure, the diameter of a human hair is approximately 80 microns. Typical classification of particles by name is given in Fig. 3.43, but the limits shown are, for the most part, arbitrary. A critical characteristic of dust is its "*Settling Velocity*" in still air. *This is proportional to the product of the square of micron size and mass density*.

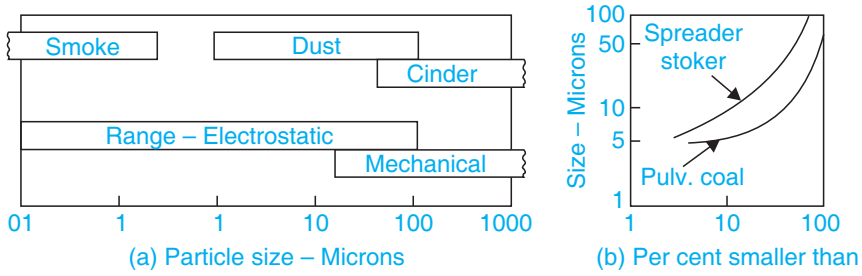


Fig. 3.43. Typical particle sizes : (*a*) Flue gas particles and ranges of collecting equipment. (*b*) Typical distribution of particle size in products of combustion.

3.12.2. Removal of Smoke

Smoke is produced due to the incomplete combustion of fuels. Smoke particles are less than 1 micron in size. The smoke disposal to the atmosphere is not desirable due to the following *reasons* :

(*i*) Smoke is produced due to incomplete combustion of coal. This will create a big economic loss due loss of heating value of coal.

(*ii*) A smoky atmosphere is unhealthy.

(*iii*) Smoke corrodes the metals, darkens the paints and gives lower standards of cleanliness.

In order to check the nuisance of smoke the coal should be completely burnt in the furnace. *The presence of dense smoke indicates poor furnace conditions and a loss in efficiency and capacity of a boiler plant.*

3.12.3. Removal of Dust and Dust Collectors

The removal of dust and cinders from flue gas can usually be effected to the required degree by commercial dust collectors.

The dust collectors may be *classified* as follows :

1. Mechanical dust collectors :

(i) Wet type (Scrubbers)

(a) Spray type

(b) Packed type

(c) Impingement type

(ii) Dry type

(a) Gravitational separators

(b) Cyclone separators

2. Electrical dust collectors :

(i) Rod type

(ii) Plate type.

1. Mechanical dust collectors

The basic principles of mechanical dust collectors is shown in Fig. 3.44.

Fig. 3.44 (a). Enlarging the duct cross-sectional area to slow down the gas gives the heavier particles a chance to settle out.

Fig. 3.44 (b). When a gas makes a sharp change in flow direction, the heavier particles tend to keep going in the original direction and so settle out.

Fig. 3.44 (c) Impingement baffles have more effect on the solid particles than the gas, helping them to settle out.

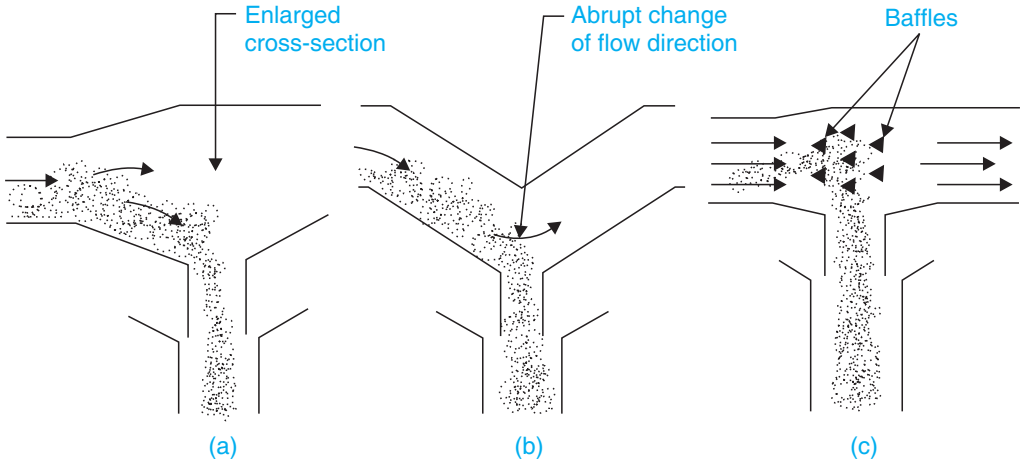


Fig. 3.44. Principles used in dust collection.

(i) Wet type dust collectors. Wet types, called *scrubbers*, operate with water sprays to wash dust from the air. Such large quantities of wash water are needed for central station gas washing that this system is *seldom* used. It also produces a waste water that may require chemical neutralization before it can be discharged into natural bodies of water.

(ii) Dry type dust collectors. It is a commonly used dust collector.

(a) Gravitational separators. These collectors act by slowing down gas flow so that particles remain in a chamber long enough to settle to the bottom. They are not very suitable because of large chamber volume needed.

(b) Cyclone separators. The cyclone is a separating chamber wherein high-speed gas rotation is generated for the purpose of "*centrifuging*" the particles from the carrying gases. Usually, there is an outer downward flowing vertex which turn into an inward flowing vertex. Involute inlets and sufficient velocity head pressure are used to produce the vortices. As multiple, small-diameter vortices with high pressure drops appear to have high cleaning efficiency, that type is now being exploited. Skimming cyclones shave off the dust at the periphery of the vortex along with a small portion of the gas flow. This concentrated flow is then led to a secondary chamber for final separation.

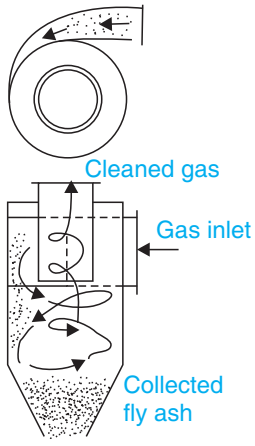


Fig. 3.45. Cyclone separator.

The factors which affect the performance of this collector are *gas volume, particulate loading, inlet velocity, temperature, diameter to height ratio of cyclone and dust characteristics*.

The advantages and disadvantages of cyclone collectors are given below :

Advantages :

1. Rugged in construction.
2. Maintenance costs are relatively low.
3. Efficiency increases with increase in load.
4. Easy to remove bigger size particles.

Disadvantages :

1. Requires more power than other collectors.
2. Incapable to remove dust and ash particles which remain in suspension with still air.
3. Less flexible (in terms of volume handled).
4. High pressure loss comparatively (from 2 cm to 15 cm of water).
5. Requires considerable head room and must be placed outside the boiler room.
6. As the fineness of the dust particle increases its collection efficiency decreases.

2. Electrical dust collector

Electrostatic precipitators. This type, also called "Cottrell precipitators", works effectively on the finer flue dusts. Fig. 3.46 shows the basic elements of an electrostatic precipitator. These are :

(*i*) Source of high voltage,
(*ii*) Ionizing and collecting electrodes,
(*iii*) Dust-removal mechanism, and
(*iv*) Shell to house the elements.

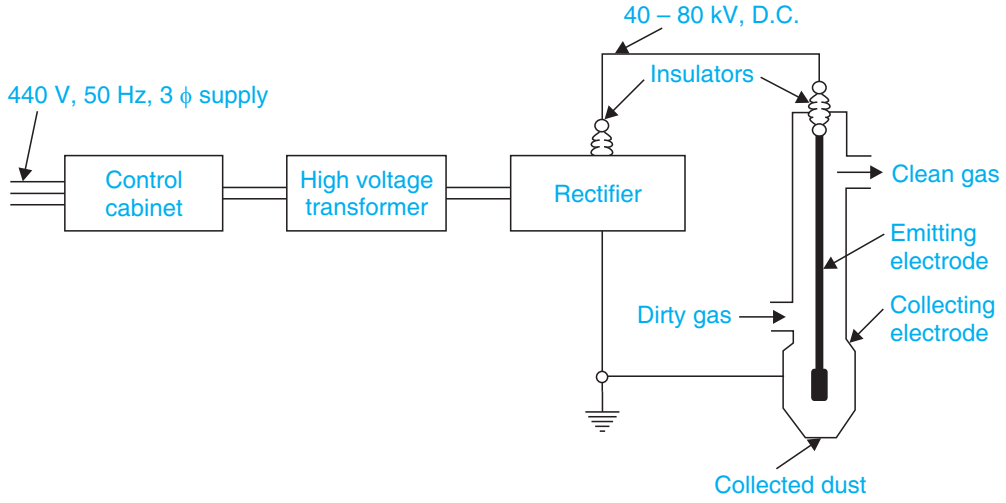


Fig. 3.46. Basic elements of electrostatic precipitators.

The precipitator has two sets of electrodes, insulated from each other, that maintain an electrostatic field between them at high voltage. The field ionizes dust particles that pass through it, attracting them to the electrode of opposite charge. The high voltage system maintains a negative potential of 30,000 to 60,000 volts with the collecting electrodes grounded. The collecting electrodes have a large contact surface. Accumulated dust falls of the electrode when it is rapped mechanically.

A wet type of this unit removes dust by a water film flowing down on the inner side of the collecting electrode. These units have collection efficiency of the order of 90%.

The advantages and disadvantages of an electrostatic precipitator are listed below :

Advantages :

1. Can effectively remove very small particles like smoke, mist and flyash.
2. Easy operation.
3. The draught loss is quite less (1 cm of water).
4. Most effective for high dust loaded gas.
5. As compared to other separators its maintenance charges are minimum.
6. The dust is collected in dry form and can be removed either dry or wet.

Disadvantages :

1. Space requirement is more (than wet system).
2. Necessary to protect the entire collector from sparking.
3. Running charges are considerably high.
4. Capital cost of equipment is high.
5. The collection efficiency is not maintained if the gas velocity exceeds that for which the plant is designed.

3.12.4. Efficiency of Dust Collectors

The '*collection efficiency*' of a dust separator is the amount of dust removed per unit weight of dust. *Though dust collectors remove contaminants, they increase draught losses and hence the fan power*.

The '*absolute efficiency*' of a dust collector is the percentage of entering solids that will be removed by the collector. Some manufactures prefer to rate their equipment on efficiency curves as illustrated in Fig. 3.47.

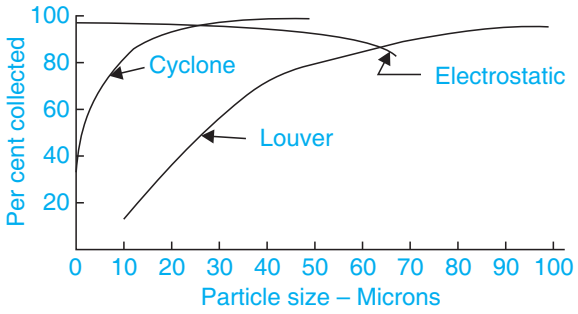


Fig. 3.47. Typical fractional efficiencies of dust collectors.

Bag test dust sampler. Refer to Fig. 3.48.

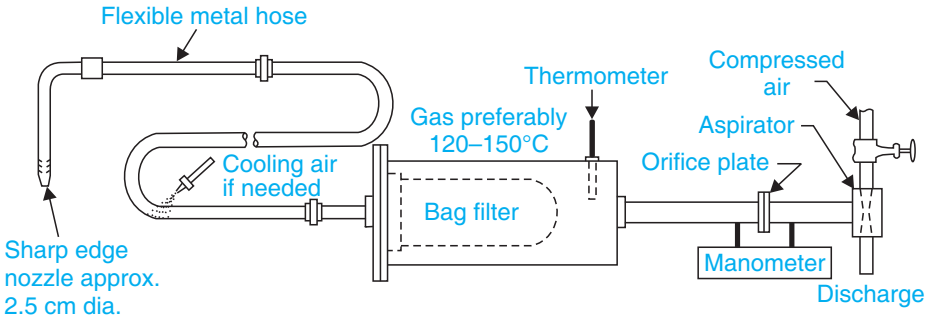


Fig. 3.48. Dust sampler.

This is an apparatus for *withdrawing a sample of dusty gas and filtering out the dust.* Weighing of the filter before and after a timed collection period, together with the data on relative area of sampling nozzle to flue gas passage, will suffice to establish the *collection efficiency* if the gas passage is traversed both at the inlet and discharge of the dust collector, load remaining steady meanwhile.

In order to obtain average samples the duct cross-sectional area must be subdivided into elements and a reading taken at the geometrical centre of each. Furthermore in a true sample the gas velocity into sampling tube must be the same as that of the surrounding gas flow. This considerably complicates the testing, for preliminary pitot-static traverse must be made and then the rate of flow into the sample nozzle adjusted for the same velocity. This explains the reason for some of the components shown on the sampler.

3.12.5. Installation of Dust Collectors

Dust collectors are installed *between the boiler and the chimney, usually on the chimney side of the air heater, if there is one*. There would be some advantages from the stand point of heater cleanliness were the collector to be put ahead of it, however, the practice seems to be to follow with the collector, and use blowers to keep the heater surfaces clean. Where there is more than one boiler, the practice is to use an individual collector for each boiler. In some cases a low resistance inertial and an electrostatic precipitator have been installed in series, again with *pros* and *cons* as to which should be ahead of the other. Generally, the mechanical type is placed first in the gas flow. Another characteristic of interest in a combination is the *variation of collection efficiency with the gas flow. As the flow increases, the electrostatic efficiency decreases, the cyclone efficiency increases*.

During the original power plant layout a dust collector should receive careful consideration.

3.12.6. Uses of Ash and Dust

The *uses of ash and dust* are listed below :

1. Ash is widely used in the production of cement.
2. Ash is used in the production of concrete. 20 per cent fly-ash and 30 per cent bottom ash are presently used constructively in U.S.A.
3. Because of their better alkali values, they are used for treating acidic soils. It has been found that if ash is used in limited quantity in soil, it increases the yield of corn, turnip etc.
4. From the ash, the metals such as Al, Fe, Si and titanium can be recovered.

3.12.7. General Layout of Ash Handling and Dust Collection System

Fig. 3.49 shows the general layout of ash handling and dust collection system which is self explanatory.

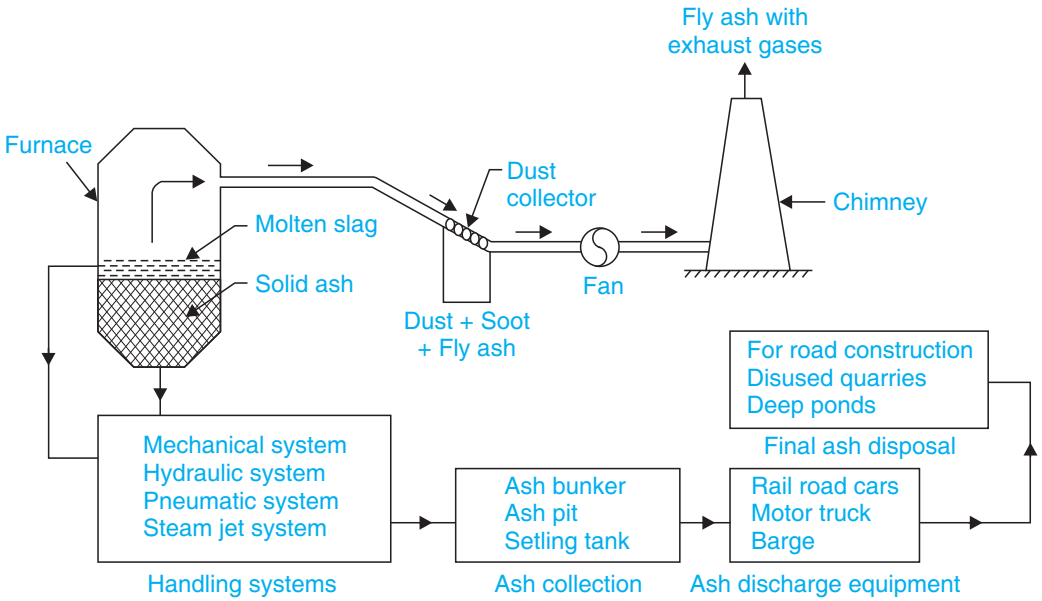


Fig. 3.49. General layout of ash handling and dust collection system.

3.12.8. Flyash—Its Composition, Disposal and Applications

3.12.8.1. Composition

- The **fly-ash** *is the residue from the combusion of pulverized coal collected by the mechanical or electrostatic separators from the flue gases of thermal power plants.* The fly-ash obtained from electrostatic precipitators is finer than portland cement, whereas that obtained from cyclone separators is comparatively coarser and may contain large amounts of unburnt fuel.
- It consists mainly of spherical glassy particles ranging from 1 to 150 μm in diameter, of which the bulk passes through a 45 μm sieve.
- The fly-ash, like portland cement, contains oxide of calcium, aluminium and silicon, but the amount of calcium oxide is considerably less.

The ***constituents*** of fly-ash are : *Silicon dioxide* (SiO_2) = 30 to 60% ;

Aluminium oxide (Al_2O_3) = 15 to 30% ; *Unburnt fuel* (carbon) = Up to 30% ;

Calcium oxide (CaO) = 1 to 7% ; *Magnesium oxide* (MgO) = Small amounts ;

Sulphur trioxide (SO_3) = Small amounts.

In fly-ash, the carbon content *should be as small as possible,* whereas *the silicon content should be as high as possible.*

The composition of fly-ash varies with the *type of fuel burnt, load on boiler* and *type of separator* etc.

3.12.8.2. Disposal of fly-ash

Presently, the fly-ash is disposed off in the following two ways :

1. ***Dry system.*** Here the fly-ash is transferred into an overhead silo or a bunker at the plant *penumatically*. The use of mechanical means (*e.g.,* screw conveyors etc.) for the removal of fly-ash is restored to only if the quantity of flash to be handled is small.

2. ***Wet system.*** In this system of disposal of fly-ash, the *fly-ash is mixed with water and sluiced to the settling ponds or dumping areas near the plant.* The system, however, will work satisfactorily if the following *conditions* are satisfied : (*i*) The water supply is available continuously, (*ii*) Large areas of wasteland for ponding are available, and (*iii*) The filled-up ponds are emptied regularly.

The present system of fly-ash disposal causes the following *problems :*

1. The region's ecology is disturbed.

2. Wastage of costly land (due to dumping of fly-ash) in the vicinity of thermal power stations.

3. The fly-ash causes health hazard to the people living near the thermal power stations.

4. The transport of fly-ash to the selected ash ponds entails heavy expenditure.

5. Soil, vegetation, under ground-water resources etc. get polluted.

3.12.8.3. Applications of fly-ash

The fly-ash may be *used* in the following ways :

1. The fly-ash may be used in ***concrete*** as an *admixture* or *in-part replacement of cement.* The fly-ash is generally used in the following three ways :

- As a *part replacement of cement.*
- As a *part replacement of fine aggregate.*
- As a *simultaneous replacement of cement and fine aggregate.*

2. Cellular concrete blocks :

These blocks are light in weight and are produced by *autoclaving a set mix of a fine silicons material such as fly-ash and binder in the form of lime.*

Advantages :

(*i*) Low thermal conductivity.

(*ii*) Stable against temperature and humidity variations.

(*iii*) Better sound insulation.

(*iv*) Better strength to weight ratio.

(*v*) Since the cellular concrete blocks are machine finished and uniform in size, therefore, less quantity of cement mortar is required. Further as the blocks are smooth and uniformly coloured, plaster can be avoided completely.

3. Fly-ash building bricks :

- To manufacture fly-ash building bricks, the *fly-ash*, *sand* and *lime* are mixed approximately in the ratio of 80 : 13 : 7. The bricks are made by using *hydraulic press and the semi-dried bricks are cured in a steam chamber at an appropriate temperature and pressure.*
- As compared to conventional bricks, these bricks are :

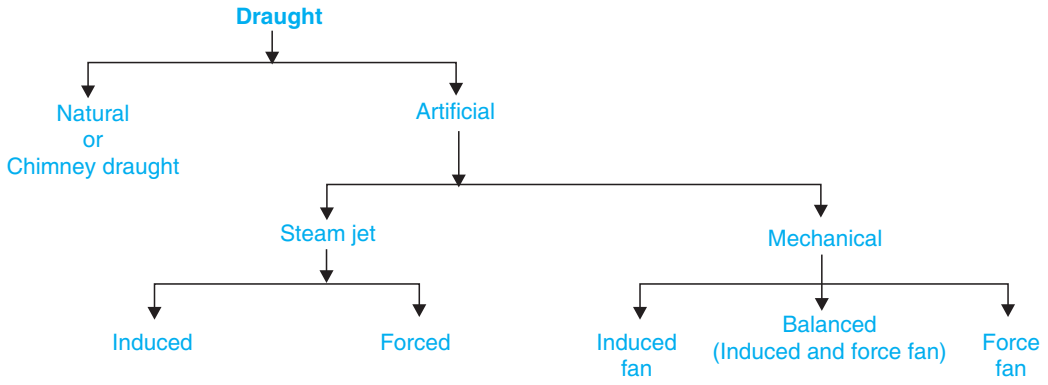
— *superior in shape, technical specifications, impermeability* and *compressive* strength ;
— *light in weight* (20 per cent) ; and
— *cheaper* (about 10 to 15 per cent).

3.13. CHIMNEY DRAUGHT

3.13.1. Definition and Classification of Draught

The small pressure difference which causes a flow of gas to take place is termed as a **draught.** The function of the draught, in case of a boiler, is to force air to the fire and to carry away the gaseous products of combustion. In a boiler furnace proper combustion takes place only when sufficient quantity of air is supplied to the burning fuel.

The draught may be classified as :



3.13.2. Natural Draught

Natural draught is obtained by the use of a chimney. The chimney in a boiler installation performs one or more of the following functions : (*i*) *It produces the draught whereby the air and gas are forced through the fuel bed, furnace, boiler passes and settings ; (ii) It carries the* products of combustion to such a height before discharging them that they will not be objectionable or injurious to surroundings. A *chimney* is vertical tubular structure built either of masonry, concrete or steel. *The draught produced by the chimney is due to the density difference between the column of hot gases inside the chimney and the cold air outside.*

Fig. 3.50 shows a schematic arrangement of a chimney of height '*H*' metres above the grate.

We have : $p_1 = p_a + \rho_g \cdot gH$

where, p_1 = Pressure at the grate level (Chimney side),

p_a = Atmospheric pressure at chimney top,

$\rho_g \cdot gH$ = Pressure due to the column of hot gas of height H metres, and

ρ_g = Average mass density of hot gas.

Similarly, $p_2 = p_a + \rho_a \cdot gH$

where, p_2 = Pressure acting on the grate on the *open side*.

$\rho_a \cdot gH$ = Pressure exerted by the column of cold air outside the chimney of height H metres.

ρ_a = Mass density of air outside the chimney.

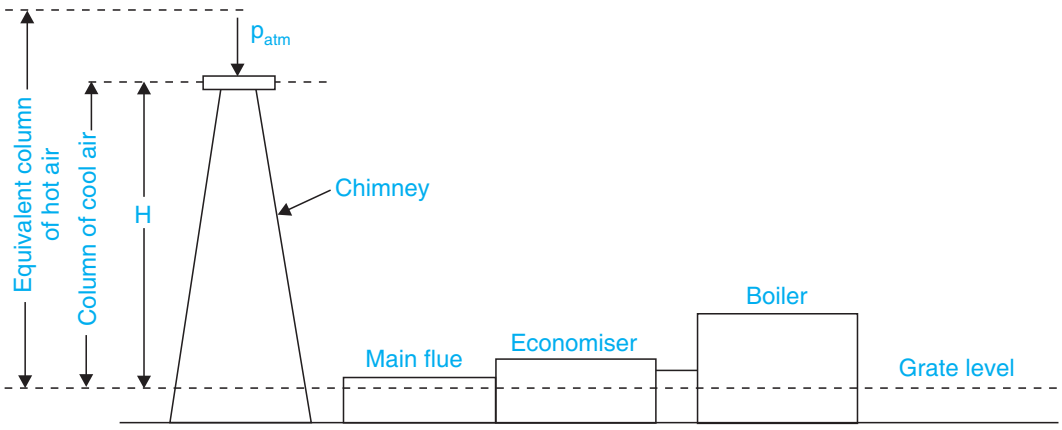


Fig. 3.50

∴ Net pressure difference causing the flow through the combustion chamber,

$$\Delta p = p_2 - p_1 = (\rho_a - \rho_g)\, gH \qquad ...(3.1)$$

This *difference of pressure causing the flow of gases is known as* **'static draught'.** Its value is small and is generally *measured by a water manometer*.

It may be noted that this pressure difference in chimney is generally *less* than 12 mm of water.

3.13.3. Chimney Height and Diameter

Let us assume that the volume of products of combustion is equal to the volume of air supplied both reduced to the same temperature and pressure conditions.

Let, m_a = Mass of air supplied per kg of fuel,

T_a = Absolute temperature of atmospheric air, and

T_g = Average absolute temperature of chimney gases.

Also, $\dfrac{\text{Mass of hot gases}}{\text{Mass of air}} = \dfrac{m_a + 1}{m_a}$, temperature and pressure being same.

The mass density of air at atmospheric conditions is given by (using gas equation) :

$$\rho_a = \frac{p}{RT_a} = \frac{1.01325 \times 10^5}{287} \cdot \frac{1}{T_a} = 353 \cdot \frac{1}{T_a} \qquad ...(3.2)$$

The mass density of hot gases at temperature T_g is given by

$$\rho_g = \frac{p}{RT_g} \cdot \left(\frac{m_a + 1}{m_a}\right)$$

$$= \frac{1.01325 \times 10^5}{287} \cdot \frac{1}{T_g} \cdot \left(\frac{m_a + 1}{m_a}\right)$$

$$= 353 \cdot \frac{1}{T_g} \cdot \left(\frac{m_a + 1}{m_a}\right) \qquad ...(3.3)$$

Inserting the values of ρ_a and ρ_g into eqn. (3.1), we get :

$$\Delta p = 353\, gH \left[\frac{1}{T_a} - \frac{1}{T_g} \cdot \left(\frac{m_a + 1}{m_a}\right)\right] \qquad ...(3.4)$$

Assuming that the draught pressure Δp produced is equivalent to H_1 metre height of burnt gases, we have

$$\Delta p = \rho_g \cdot gH_1 = 353 \left(\frac{m_a + 1}{m_a}\right) \cdot \frac{1}{T_g}\, g\, H_1 \qquad ...(3.5)$$

Equations (3.4) and (3.5), we get :

$$353 \left(\frac{m_a + 1}{m_a}\right) \frac{1}{T_a}\, g \cdot H_1$$

$$= 353\, g\, H \left[\frac{1}{T_a} - \frac{1}{T_g}\left(\frac{m_a + 1}{m_a}\right)\right]$$

$$\frac{353}{T_a}\left(\frac{m_a + 1}{m_a}\right) g H_1 = \frac{353}{T_g}\, gH - \frac{353}{T_g}\, gH \left(\frac{m_a + 1}{m_a}\right)$$

$$\frac{353}{T_a}\left(\frac{m_a + 1}{m_a}\right) g\, H_1$$

$$= \frac{353}{T_g}\left(\frac{m_a + 1}{m_a}\right) g\, H \left[\left(\frac{m_a}{m_a + 1}\right)\frac{T_g}{T_a} - 1\right]$$

$$\therefore \quad H_1 = H \left[\left(\frac{m_a}{m_a + 1}\right)\frac{T_g}{T_a} - 1\right] \qquad ...(3.6)$$

Due to losses at various sections along the path of the flue gas, the actual draught available is *always less* than that given by the eqn. (3.4).

If h_w is the height, in mm of a column of water which will produce the pressure Δp, then

$$h_w = 353\, H \left[\frac{1}{T_a} - \frac{1}{T_g}\left(\frac{m_a + 1}{m_a}\right)\right] \qquad ...(3.7)$$

(1 mm of water = 9.81 *Pa*)

The height h_w would be shown by the use of a U-tube manometer.

Note. The formula as expressed by eqn. (3.7) is used for numerical calculation work only.

Chimney diameter :

Assuming no loss, the velocity of the gases passing through the chimney is given by

$$C = \sqrt{2gH_1}$$

If the pressure loss in the chimney is equivalent to a hot-gas column of h' metres, then :

$$C = \sqrt{2g\,(H_1 - h')} = 4.43\sqrt{H_1 - h'} \quad ...(3.8)$$

$$= 4.43\sqrt{H_1}\ \sqrt{1 - \frac{h'}{H_1}} = K\sqrt{H_1} \quad ...(3.9)$$

where $K = 4.43\sqrt{1 - \frac{h'}{H_1}}$

The value of K : 0.825 ..... For *brick chimneys*, and
1.1 ..... For *steel chimneys*.

The mass of the gases flowing through any cross-section of the chimney is given by :

$$\dot{m}_g = \rho_g \cdot A \cdot C \text{ kg/s}$$

or, $$\dot{m}_g = \rho_g \cdot \frac{\pi}{4} D^2 . C$$

$$\therefore \quad D^2 = \frac{\dot{m}_g}{\rho_g C} \times \frac{4}{\pi}$$

or, $$D = 1.128\sqrt{\frac{\dot{m}_g}{\rho_g \cdot C}} \quad ...(3.10)$$

3.13.4. Condition for Maximum Discharge Through a Chimney

The chimney draught is most effective when the maximum weight of hot gases is discharged in a given time, and it will be shown that this occurs when the absolute temperature of the chimney gases bears a certain relation to the absolute temperature of the outside air.

We know that the velocity of gas through the chimney, assuming the losses to be negligible, is given by

$$C = \sqrt{2gH_1}, \quad \text{where } h' = 0$$

Inserting the value of H_1 from eqn. (3.6)

$$C = \sqrt{2gH\left[\left(\frac{m_a}{m_a + 1}\right)\frac{T_g}{T_a} - 1\right]} \quad ...(3.11)$$

The density of the hot gas is given by

$$\rho_g = \frac{p}{RT_g} \quad ...(3.12)$$

The mass of gas discharged per second,

$$m_g = A \times C \times \rho_g$$

Inserting the values of C and ρ_g from eqns. (3.11) and (3.12), we get

$$m_g = A\sqrt{2gH\left[\left(\frac{m_a}{m_a + 1}\right)\frac{T_g}{T_a} - 1\right]}\ \frac{p}{RT_g}$$

$$m_g = \frac{K}{T_g}\sqrt{\left(\frac{m_a}{m_a + 1}\right)\frac{T_g}{T_a} - 1} \quad ...(3.13)$$

where constant $K = \dfrac{A \times p \times \sqrt{2gH}}{R}$

The value of m_g will be *maximum*, if

$$\frac{dm_g}{dT_g} = 0 \text{ as } T_a \text{ and } m_a \text{ are fixed quantities}$$

$$\therefore \quad \frac{d}{dT_g}\left[\frac{K}{T_g}\sqrt{\left(\frac{m_a}{m_a + 1}\right)\frac{T_g}{T_a} - 1}\right] = 0$$

or, $$\frac{d}{dT_g}\left[\frac{1}{T_g}\sqrt{\left(\frac{m_a}{m_a + 1}\right)\frac{T_g}{T_a} - 1}\right] = 0$$

or, $$\frac{d}{dT_g}\left[\frac{(ZT_g - 1)^{1/2}}{T_g}\right] = 0$$

where $Z = \dfrac{m_a}{m_a + 1} \cdot \dfrac{1}{T_a}$

or, $$\frac{d}{dT_g}\left[(ZT_g - 1)^{1/2} \times T_g^{-1}\right] = 0$$

or, $$(Z \cdot T_g - 1)^{1/2} \cdot (-1)(T_g)^{-2} + T_g^{-1} \times \frac{1}{2}(ZT_g - 1)^{-1/2} \times Z = 0$$

or, $$\frac{-(ZT_g - 1)^{1/2}}{T_g^{\,2}} + \frac{Z}{2T_g(ZT_g - 1)^{1/2}} = 0$$

or, $$\frac{-2\,(ZT_g - 1) + ZT_g}{2\,(T_g)^2\,(ZT_g - 1)^{1/2}} = 0$$

or, $$-2(ZT_g - 1) + ZT_g = 0$$

or, $$-2ZT_g + 2 + ZT_g = 0$$

or , $$ZT_g = 2$$

or , $$\frac{m_a}{m_a + 1} \cdot \frac{T_g}{T_a} = 2$$

i.e., $$\frac{T_g}{T_a} = 2\left(\frac{m_a + 1}{m_a}\right) \quad ...(3.14)$$

Thus we see that the *absolute temperature of the chimney gases bears a certain ratio to the absolute temperature of the outside air.*

Putting the value of $\frac{T_g}{T_a}$ in eqn. (3.6), we get :

$$(H_1)_{max} = H\left[\left(\frac{m_a}{m_a+1}\right)\times 2\left(\frac{m_a+1}{m_a}\right)-1\right]$$

$$= H\,(2-1) = H$$

i.e., $(H_1)_{max} = H$ ...(3.15)

The draught in mm of water column for maximum discharge can be evaluated by inserting the value of T_g/T_a in eqn. (3.7)

$$\therefore \quad (h_w)_{max} = 353\,H\left(\frac{1}{T_a}-\frac{1}{2\,T_a}\right)$$

$$= \frac{176.5\,H}{T_a} \text{ mm of water} \qquad ...(3.16)$$

3.13.5. Efficiency of a Chimney

The temperature of the flue gases leaving a chimney, in case of *natural draught,* is higher than that of flue gases leaving it in case of *artificial draught* system because a certain minimum temperature is needed to produce a given draught with the given height of a chimney. As far as steam generation is concerned, in case of a natural draught system the heat carried away by flue gases is more due to *higher* flue gas temperature. This indicates that the draught is created at the cost of thermal efficiency of the boiler plant installation since a portion of the heat carried away by the flue gases to produce the required draught could have been used either in heating the air going to furnace or in heating the feed water going to boiler ; thereby improving the thermal efficiency of the installation. Let,

T' = Absolute temperature of flue gases leaving the chimney to create the draught of h_w mm of water,

T'' = Absolute temperature of flue gases leaving the chimney in case of artificial draught of h_w mm of water, and

c_p = Mean specific heat of flue gases.

The extra heat carried away by 1 kg of flue gas due to higher temperature required to produce the natural draught

$= c_p\,(T' - T'')$, since T' is greater than T''.

The draught pressure produced by the natural draught system in height of hot gases column,

$$H_1 = H\left[\left(\frac{m_a}{m_a+1}\right)\times\frac{T_g}{T_a}-1\right] \text{ metre}$$

The maximum energy this head would give to 1 kg of flue gas which is at the expense of extra heat carried away from the boiler plant

$$= H\left[\left(\frac{m_a}{m_a+1}\right)\times\frac{T_g}{T_a}-1\right] \quad \text{...Energy units}$$

$$= \frac{H}{J}\left[\left(\frac{m_a}{m_a+1}\right)\times\frac{T_g}{T_a}-1\right] \quad \text{...Heat units}$$

$\therefore$ Efficiency of chimney,

$$\eta_{ch} = \frac{\frac{H}{J}\left[\left(\frac{m_a}{m_a+1}\right)\times\frac{T_g}{T_a}-1\right]}{c_p\,(T'-T'')} \qquad ...(3.17)$$

In the equation, $T' = T_g$.

(In SI units J = 1)

- The efficiency of a chimney is proportional to the height but even for a very tall chimney the efficiency will be *less than 1%* and thus we see that chimney is *very inefficient as an instrument for creating draught*.

3.13.6. Draught Losses

The loss in a draught may be due to the *reasons* mentioned below :

(*i*) The frictional resistance offered by the flues and gas passages to the flow of flue gases.

(*ii*) Loss near the bends in the gas flow circuit.

(*iii*) Loss due to friction head in equipments like grate, economiser, superheater etc.

(*iv*) Loss due to imparting velocity to the flue gases.

The loss in draught in a chimney is 20 per cent of the total draught produced by it.

3.13.7. Artificial Draught

In the boiler installations of today the total static draught required may vary from 30 to 350 mm of water column.

It may not be possible to build a chimney high enough to produce draught of such a large magnitude. To meet this requirement artificial draught system should be used. It may be a *mechanical draught* or a *steam jet draught.* The former is used for central power stations and many other boiler installations while the latter is employed for small installations and in locomotives.

3.13.8. Forced Draught

In a mechanical draught system, the draught is produced by a fan. In a forced draught system, a blower or a fan is installed *near or at the base of the boiler* to force the air through the cool bed and other passages through the furnace, flues, air preheater, economiser etc. It is a *positive pressure draught. The enclosure for the furnace etc. has to be very highly sealed so that gases from the furnace do not leak out in the boiler house.*

3.13.9. Induced Draught

In this system a fan or blower is located *at or near the base of the chimney*. The pressure over the fuel bed is reduced below that of the atmosphere. By creating a partial vacuum in the furnace and flues, the products of combustion are drawn from the main flue and they pass up the chimney. *This draught is used usually when economisers and air preheaters are incorporated in the system.* The draught is similar in action to the natural draught.

3.13.10. Balanced Draught

It is a *combination of the forced and induced draught systems.* In this system, the *forced draught fan overcomes the resistance in the air preheater and chain grate stoker while the induced draught fan overcomes draught losses through boiler, economiser, air preheater and connecting flues.*

The *forced draught* entails following *advantages over induced draught* :

1. Forced draught fan does not require water-cooled bearings.
2. Tendency to air leak into the boiler furnace is reduced.
3. No loss due to inrush of cold air through the furnace doors when they are opened for fire and cleaning fires.
4. Fan size and power required for the same draught are 1/5 to 1/2 of that required for an induced draught fan installation because forced draught fan handles cold air.

3.13.11. Advantages of Mechanical Draught

The mechanical draught possesses the following *advantages* :

1. Easy control of combustion and evaporation.
2. Increase in evaporative power of a boiler.
3. Improvement in the efficiency of the plant.
4. Reduced chimney height.
5. Prevention of smoke.
6. Capability of consuming low grade fuel.
7. Low grade fuel can be used as the intensity of artificial draught is high.
8. The fuel consumption per kW due to artificial draught is 15% less than that for natural draught.
9. The fuel burning capacity of grate is 200 to 300 kg/m^2-hr with mechanical draught, whereas, it is hardly 50 to 100 kg/m^2-hr with natural draught.

3.13.12. Steam Jet Draught

Steam jet draught is a simple and easy method of producing artificial draught. It may be of forced or induced type depending upon where the steam jet to produce draught is located. If the steam jet is *directed into the smoke box* near the stack, the air is *induced* through the flues, the grate and ash pit to the smoke box. If the jet is *located before the grate,* air is *forced* through the fuel bed, furnace and flues to the chimney.

The steam jet draught entails the following *advantages* :

(*i*) Very simple and economical.

(*ii*) Occupies minimum space.

(*iii*) Requires very little attention.

(*iv*) In forced type steam jet draught, the steam keeps the fire bars cool and prevents the adhering of clinker to the fire bars.

(*v*) Several classes of low grade fuels can be used with this system.

WORKED EXAMPLES

Example 3.1. *Calculate the mass of flue gases flowing through the chimney when the draught produced is equal to 1.9 cm of water. Temperature of flue gases is 290°C and ambient temperature is 20°C. The flue gases formed per kg of fuel burnt are 23 kg. Neglect the losses and take the diameter of the chimney as 1.8 m.*

Solution. Draught in mm of water,

$$h_w = 1.9 \text{ cm} = 19 \text{ mm}$$

Temperature of flue gases,

$$T_g = 290 + 273 = 563 \text{ K}$$

Ambient temperature,

$$T_a = 20 + 273 = 293 \text{ K}$$

Flue gases formed per kg of fuel burnt,

$$(m_a + 1) = 23 \text{ kg}$$

Diameter of the chimney, $D = 1.8$ m

Mass of flue gases, m_g :

Using the relation,

$$H_1 = H\left[\left\{\frac{m_a}{m_a + 1} \times \frac{T_g}{T_a}\right\} - 1\right]$$

where H_1 is the head in terms of gas column.

$$\text{Also,} \quad h_w = 353\, H\left[\frac{1}{T_a} - \frac{1}{T_g} \times \left(\frac{m_a + 1}{m_a}\right)\right]$$

$$19 = 353\,H\left(\frac{1}{293} - \frac{1}{563}\times\frac{23}{22}\right)$$

$$\left(\because\ m_a + 1 = 23 \text{ kg (given)}\right.$$
$$\left.i.e.\quad m_a = 22 \text{ kg}\right)$$

$$19 = 353\,H\,(0.00341 - 0.00185) = 0.548\,H$$

or, $H = 34.67$ m

$$\therefore\quad H_1 = 34.67\left(\frac{22}{23}\times\frac{563}{293} - 1\right) = 29.05 \text{ m of air.}$$

Velocity of gases,

$$C = \sqrt{2gH_1} = \sqrt{2\times 9.81\times 29.05} = 23.87 \text{ m/s.}$$

Now, mass of flue gases, $m_g = A \times C \times \rho_g$

where, $\rho_g = 353\left(\frac{m_a + 1}{m_a}\right)\cdot\frac{1}{T_g} = 353\times\frac{23}{22}\times\frac{1}{563}$

$= 0.655$ kg/m^3

$\therefore\quad m_g = \pi/4 \times (1.8^2) \times 23.87 \times 0.655$

$= \mathbf{39.8\ kg/s.}$ **(Ans.)**

Hence *mass of flue gases passing through the chimney* = **39.8 kg/s.** **(Ans.)**

Example 3.2. *A chimney of height 32 m is used for producing a draught of 16 mm of water. The temperatures of ambient air and flue gases are 27°C and 300°C respectively. The coal burned in the combustion chamber contains 81% carbon, 5% moisture and remaining ash. Neglecting losses and assuming the value of burnt products equivalent to the volume of air supplied and complete combustion of fuel find the percentage of excess air supplied.*

Solution. Height of the chimney,

$H = 32$ m

Draught in mm of water

= 16 mm

Ambient air temperature,

$T_a = 27 + 273 = 300$ K

Temperature of flue gases,

$T_g = 300 + 273 = 573$ K

Percentage of carbon in the fuel = 81%

Percentage of excess air supplied :

Using the relation,

$$h_w = 353\,H\left[\frac{1}{T_a} - \frac{1}{T_g}\left(\frac{m_a + 1}{m_a}\right)\right] \text{ mm of water}$$

$$16 = 353\times 32\left[\frac{1}{300} - \frac{1}{573}\left(\frac{m_a + 1}{m_a}\right)\right]$$

$$\frac{16}{353\times 32} = \frac{1}{300} - \frac{1}{573}\left(\frac{m_a + 1}{m_a}\right)$$

$$\frac{m_a + 1}{m_a} = 573\left(\frac{1}{300} - \frac{16}{353\times 32}\right)$$

$$= 573\,(0.003333 - 0.001416)$$

$$= 1.0984$$

$$\therefore\quad m_a = 10.16 \text{ kg/kg of fuel}$$

Again, $C + O_2 = CO_2$

$12 + 32 = 44$

Thus 1 kg of carbon requires $\frac{32}{12} = \frac{8}{3}$ kg of oxygen and $\frac{8}{3}\times\frac{100}{23} = 11.6$ kg of air. One kg of fuel contains only 0.81 carbon.

$\therefore$ Air required for complete combustion

$= 11.6 \times 0.81 = 9.396$ kg/kg of fuel.

Hence, *percentage excess air supplied*

$$= \frac{10.16 - 9.396}{9.396}\times 100 = \mathbf{8.13\%.}\quad \textbf{(Ans.)}$$

Example 3.3. *Determine the height and diameter of the chimney used to produce a draught for a boiler which has an average coal consumption of 1800 kg/h and flue gases formed per kg of coal fired are 14 kg. The pressure losses through the system are given below :*

Pressure loss in fuel bed = 7 mm of water, pressure loss in boiler flues = 7 mm of water, pressure loss in bends = 3 mm of water, pressure loss in chimney = 3 mm of water.

Pressure head equivalent to velocity of flue gases passing through the chimney = 1.3 mm of water.

The temperatures of ambient air and flue gases are 35°C and 310°C respectively.

Assume actual draught is 80% of theoretical.

Solution. Average coal consumption

= 1800 kg/h

Flue gases formed per kg of coal fired

= 14 kg

Temperature of ambient air,

$T_a = 35 + 273 = 308$ K

Temperature of flue gases,

$T_g = 310 + 273 = 583$ K.

Height of chimney, H :

Draught required is equivalent to overcome the losses and velocity head

$= 7 + 7 + 3 + 3 + 1.3 = 21.3$ mm of water.

Actual draught to be produced,

$$h_w = \frac{21.3}{0.8} = 26.62 \text{ mm of water}$$

$$h_w = 353\,H\left(\frac{1}{T_a} - \frac{1}{T_g}\cdot\frac{m_a + 1}{m_a}\right)$$

$$26.62 = 353\ H\left(\frac{1}{308} - \frac{1}{583} \times \frac{14}{13}\right)$$

$$= H\ (1.146 - 0.652) = 0.494\ H$$

$$H = 53.88 \text{ m}$$

$$\rho_g = \frac{353}{T_g}\left(\frac{m_a + 1}{m_a}\right) = \frac{353}{583} \times \frac{14}{13}$$

$$= 0.652 \text{ kg/m}^3$$

Flue gases formed per second

$$= \frac{1800 \times 14}{3600} = 7 \text{ kg}$$

$$m_g = A \times C \times \rho_g \qquad ...(i)$$

But $C = \sqrt{2gH_1}$

where H_1 is the equivalent velocity expressed in m of gas

$$H_1\rho_g = h_w\rho_w$$

where h_w is the water head equivalent to velocity head responsible for giving velocity to the gas,

$$\therefore \quad H_1 = \frac{h_w\rho_w}{\rho_g} = \frac{1.3 \times 1000}{1000 \times 0.652} = 1.993 \text{ m}$$

$$\therefore \quad C = \sqrt{2 \times 9.81 \times 1.993} = 6.25 \text{ m/s}$$

Substituting this value in eqn. (*i*), we get

$$7 = \frac{\pi}{4} D^2 \times 6.25 \times 0.625$$

or $$D^2 = \frac{7 \times 4}{\pi \times 6.25 \times 0.652}$$

$$\therefore \quad D = \mathbf{1.478\ m.} \quad \textbf{(Ans.)}$$

Example 3.4. *Calculate power of a motor required to drive a fan which maintains a draught of 54 mm of water under the following conditions for (i) induced draught fan, (ii) forced draught fan :*

Temperature of flue gases leaving the boiler in each case = 240°C

Temperature of air in the boiler house = 20°C

Air supplied per kg of fuel in each case = 18.5 kg

Mass of coal burnt per hour = 1820 kg

Efficiency of the fan = 82 per cent

Drive formulae, for forced draft and induced draft fans.

Solution. Temperature of gases,

$T_g = 240 + 273 = 513$ K

Temperature of air,

$T_a = 20 + 273 = 293$ K

Mass of air used,

$m_a = 18.5$ kg

Mass of coal used,

$M = 1820$ kg

Draught produce by the fan,

$h_w = 54$ mm of water

Efficiency of each fan,

$\eta_f = 82$ per cent.

(*i*) Power of motor required to drive induced draught fan, P_{ID} :

Using the relation :

$$P_{ID} = \frac{0.998 \times 10^{-8} h V_0 m_a M T_g}{\eta_f} \text{ kW}$$

$$= \frac{0.998 \times 10^{-8} \times 54 \times 0.7734 \times 18.5 \times 1820 \times 513}{0.82}$$

(where $V_0 = 0.7734$ m^3 at 0°C and 760 mm of Hg)

$$= \mathbf{8.78\ kW}. \quad \textbf{(Ans.)}$$

(*ii*) Power of a motor required to drive forced draught fan, P_{FD} :

$$P_{FD} = \frac{0.998 \times 10^{-8} h V_0 m_a M T_a}{\eta_f} \text{ kW}$$

$$= \frac{0.998 \times 10^{-8} \times 54 \times 0.7734 \times 18.5 \times 1820 \times 293}{0.82}$$

$$= \mathbf{5.014\ kW.} \quad \textbf{(Ans.)}$$

Power required to drive fan :

Let, p = Draught, ρ_a,

h_f = Draught produced by the fan, mm

V = Volumetric flow rate of combustion air at fan conditions, m^3/h, and

η_f = Fan efficiency.

Power required

$$= \frac{pV}{\eta_f} = \frac{\rho g h_f V}{\eta_f} = \frac{1000 \times g \times h_f V}{1000 \times \eta_f \times 3600} \text{ W}$$

$$= \frac{g h_f V}{\eta_f \times 1000 \times 3600} \text{ kW}$$

$$= 2.725 \times 10^{-6} \frac{hV}{\eta_f} \text{ kW} \qquad ...(3.18)$$

(i) Forced draught (F.D.) fan power, P_{FD} :

Let, M = Quantity of fuel burnt per hour,

m_a = Mass of air supplied, kg/kg of fuel,

T_a = Temperature of atmospheric air, and

T_0 = Temperature at N.T.P.

Volume of air at T_0,

$$V_0 = \frac{m_a M}{\rho}$$

$$\therefore \quad V = \frac{T_a V_0 m_a M}{273} \text{ m}^3\text{/h}$$

Substituting in eqn. (3.18), we get :
Power of F.D. fan,

$$P_{FD} = \frac{2.725 \times 10^{-6}}{273} \left(\frac{hV_0 m_a M T_a}{\eta_f} \right) \text{kW}$$

$$= 0.998 \times 10^{-8} \left(\frac{hV_0 m_a M T_a}{\eta_f} \right) \text{kW}$$

(ii) Induced draught (I.D.) fan power, P_{ID} :

Let, m = Mass of air supplied per kg of fuel,
Then, $m_a + 1$ = Mass of the products of combustion.
At the same temperature

$$\frac{\rho_g}{\rho_a} = \frac{m_a + 1}{m_a}$$

But $$\rho_a = \frac{273}{T_g} \times \frac{1}{V_0}$$

$$\therefore \quad \rho_g = \frac{273}{T_g} \times \frac{1}{V_0}$$

Volume handled by I.D. fan

$$= \frac{\text{Total mass handled by I.D. fan}}{\text{Density of gases}}$$

$$= \frac{M(m_a + 1)}{\rho_g} = \frac{M(m_a + 1) T_g V_0 m_a}{273 (m_a + 1)}$$

$$= \frac{M m_a T_g V_0}{273}$$

Substituting in eqn. (3.18), we get
Power of I.D. fan,

$$P_{ID} = \frac{2.725 \times 10^{-6} \times hM m_a T_g V_0}{273 \times \eta_f}$$

$$= 0.998 \times 10^{-8} \frac{hV_0 m_a M T_g}{\eta_f}$$

Assuming *same efficiency*, for the *same draught* (neglecting leakage), we have

$$\frac{\text{Power of I.D. fan}}{\text{Power of F.D. fan}} = \frac{T_g}{T_a}.$$

3.14. BOILERS

3.14.1. Introduction

In simple a ***boiler*** *may be defined as a closed vessel in which steam is produced from water by combustion of fuel*.

According to American Society of Mechanical Engineers (A.S.M.E.) a *'steam generating unit'* is defined as :

"A combination of apparatus for producing, furnishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated and vapourised."

The steam generated is employed for the following *purposes* :

(*i*) For generating power in steam engines or steam turbines.
(*ii*) In the textile industries for sizing and bleaching etc. and many other industries like sugar mills ; chemical industries.
(*iii*) For heating the buildings in cold weather and for producing hot water for hot water supply.

The *Primary requirements* of steam generators or boilers are :

(*i*) The water must be contained safely.
(*ii*) The steam must be safely delivered in desired condition (as regards its pressure, temperature, quality and required rate).

3.14.2. Classification of Boilers

The boilers may be classified as follows :

1. Horizontal, vertical or inclined

If the axis of the boiler is horizontal, the boiler is called as horizontal, if the axis is vertical, it is called vertical boiler and if the axis is inclined it is known as inclined boiler. *The parts of a horizontal boiler can be inspected and repaired easily but it occupies more space. The vertical boiler occupies less floor area.*

2. Fire tube and water tube

In the fire tube boilers, the hot gases are inside the tubes and the water surrounds the tubes. Examples : *Cochran, Lancashire* and *Locomotive boilers*.

In the water tube boilers, the water is inside the tubes and hot gases surround them. Examples : *Babcock* and *Wilcox, Stirling, Yarrow boiler* etc.

3. Externally fired and internally fired

The boiler is known as externally fired if the fire is outside the shell. Examples : *Babcock and Wilcox boiler, Stirling boiler* etc.

In case of internally fired boilers, the furnace is located inside the boiler shell. Examples : *Cochran, Lancashire boiler* etc.

4. Forced circulation and natural circulation

In *forced circulation* type of boilers, the circulation of water is done *by a forced pump*. Examples : *Velox, Lamont, Benson boiler* etc.

In *natural circulation* type of boilers, circulation of water in the boiler takes place due to *natural convention* currents produced by the application of heat. Examples : *Lancashire, Babcock* and *Wilcox boiler* etc.

5. High pressure and low pressure boilers

The boilers which produce steam at *pressures of 80 bar and above* are called *high* pressure boilers. Examples : *Babcock* and *Wilcox, Velox, Lamont, Benson boilers.*

The boilers which produce steam at pressure *below 80 bar* are called low pressure boilers. Examples : *Cochran, Cornish, Lancashire and Locomotive boilers.*

6. Stationary and portable

Primarily, the boilers are classified as either stationary (*land*) or mobile (*marine* and *locomotive*).

- Stationary boilers are used for power plant-steam, for central station utility power plants, for plant process steam etc.
- Mobile boilers or portable boilers include locomotive type, and other small units for temporary use at sites (just as in small coalfield pits).

7. Single-tube and multi-tube boilers

The fire tube boilers are classified as single-tube and multi-tube boilers, depending upon whether the fire tube is one or more than one. The examples of the former type are cornish, simple vertical boiler and rest of the boilers are multi-tube boilers.

3.14.3. Comparison between 'Fire-tube and Water-tube' Boilers

S. No.	*Particulars*	*Fire-tube boilers*	*Water-tube boilers*
1.	*Position of water and hot gases*	Hot gases inside the tubes and water outside the tubes.	Water inside the tubes and hot gases outside the tubes.
2.	*Mode of firing*	Generally internally fired.	Externally fired.
3.	*Operating pressure*	Operating pressure limited to 16 bar.	Can work under as high pressure as 100 bar.
4.	*Rate of steam production*	Lower	Higher.
5.	*Suitability*	Not suitable for large power plants.	Suitable for large power plants.
6.	*Risk on bursting*	Involves lesser risk on explosion due to lower pressure.	Involves more risk on bursting due to high pressure.
7.	*Floor area*	For a given power it occupies more floor area.	For a given power it occupies less floor-area.
8.	*Construction*	Difficult	Simple
9.	*Transportation*	Difficult	Simple
10.	*Shell diameter*	Large for same power	Small for same power
11.	*Chances of explosion*	Less	More
12.	*Treatment of water*	Not so necessary	More necessary
13.	*Accessibility of various parts*	Various parts not so easily accessible for cleaning, repair and inspection.	Various parts are more accessible.
14.	*Requirement of skill*	Require less skill for efficient and economic working.	Require more skill and careful attention.

3.14.4. Selection of a Boiler

While selecting a boiler the following *factors* should be considered :

1. The working pressure and quality of steam required (*i.e.*, whether wet or dry or superheated).
2. Steam generation rate.
3. Floor-area available.
4. Accessibility for repair and inspection.
5. Comparative initial cost.
6. Erection facilities.
7. The probable load factor.
8. The fuel and water available.
9. Operating and maintenance costs.

3.14.5. Essentials of a Good Steam Boiler

A good boiler should possess the following *features* :

1. The boiler should produce the maximum weight of steam of the required quality at minimum expenses.
2. Steam production rate should be as per requirements.
3. It should be absolutely reliable.
4. It should occupy minimum space.
5. It should be light in weight.
6. It should be capable of quick starting.
7. There should be an easy access to the various parts of the boiler for repairs and inspection.
8. The boiler components should be transportable without difficulty.
9. The installation of the boiler should be simple.

10. The tubes of the boiler should not accumulate soot or water deposits and should be sufficiently strong to allow for wear and corrosion.

11. The water and gas circuits should be such as to allow minimum fluid velocity (for low frictional losses).

3.14.6. Boiler Terms

Shell. The shell of a boiler consists of one or more steel plates bent into a cylindrical form and riveted or welded together. The shell ends are closed with the end plates.

Setting. The primary function of setting is to confine heat to the boiler and form a passage for gases. It is made of brickwork and may form the wall of the furnace and the combustion chamber. It also provides support in some types of boilers (*e.g.*, Lancashire boilers).

Grate. It is the platform in the furnace upon which fuel is burnt and it is made of cast iron bars. The bars are so arranged that air may pass on to the fuel for combustion. The area of the grate on which the fire rests in a coal or wood fired boiler is called grate surface.

Furnace. It is a chamber formed by the space above the grate and below the boiler shell, in which combustion takes place. It is also called a fire box.

Water space and steam space. The volume of the shell that is occupied by the water is termed *water space* while the entire shell volume less the water and tubes (if any) space is called *steam space.*

Mountings. The items such as stop valve, safety valves, water level gauges, fusible plug, blow-off cock, pressure gauges, water level indicator etc. are termed as mountings and a *boiler cannot work safely without them*.

Accessories. The items such as superheaters, economisers, feed pumps etc. are termed as accessories and they form integral part of the boiler. They *increase the efficiency of the boiler.*

Water level. The level at which water stands in the boiler is called *water level*. The space above the water level is called *steam space*.

Foaming. Formation of steam bubbles on the surface of boiler water due to high surface tension of the water.

Scale. A deposit of medium to extreme hardness occurring on water heating surfaces of a boiler because of an undesirable condition in the boiler water.

Blowing off. The removal of the mud and other impurities of water from the lowest part of the boiler (where they usually settle) is termed as *'blowing off'*. This is accomplished with the help of a blow off cock or valve.

Lagging. Blocks of asbestos or magnesia insulation wrapped on the outside of a boiler shell or steam piping.

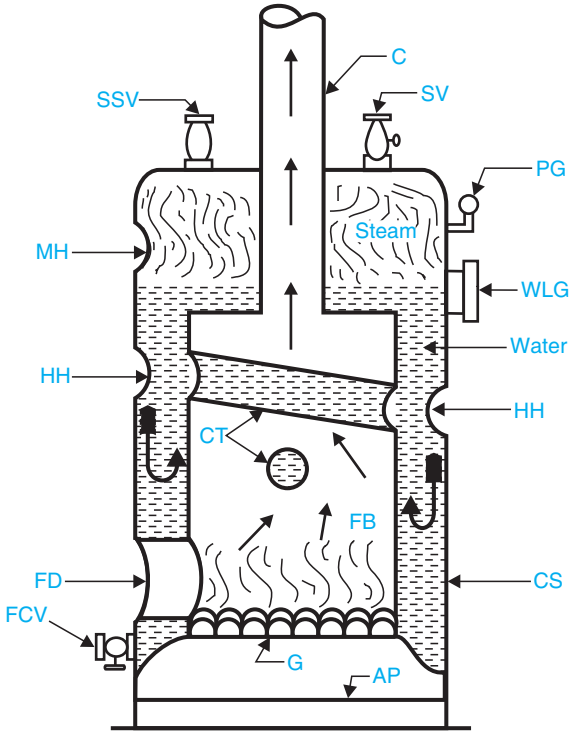
Refractory. A heat insulation material, such as fire brick or plastic fire clay, used for such purposes as lining combustion chambers.

3.14.7. Fire Tube Boilers

The various fire tube boilers are described as follows :

3.14.7.1. Simple vertical boiler

Refer to Fig. 3.51. It consists of a cylindrical shell, the greater portion of which is full of water (which surrounds the fire box also) and remaining is the steam space. At the bottom of the fire box is grate on which fuel is burnt and the ash from it falls in the ash pit.



CS = Cylindrical shell — *WLG* = Water level gauge
MH = Manhole — *C* = Chimney
CT = Cross tubes — *HH* = Hand hole
FB = Fire box — *FD* = Fire door
AP = Ash pit — *G* = Grate
PG = Pressure gauge — *SSV* = Steam stop valve
SV = Safety valve — *FCV* = Feed check valve

Fig. 3.51. Simple vertical boiler.

The fire box is provided with two cross tubes. This increases the heating surface and the circulation of water. The cross tubes are fitted inclined. This ensures efficient circulation of water. At the ends of each cross tube are provided hand holes to give access for cleaning these tubes. The combustion gases after heating the water and thus converting it into steam escape to the atmosphere through the chimney. Man hole, is provided to clean the interior of the boiler and exterior of the combustion chamber and chimney. The various mountings shown in Fig. 3.51 are (*i*) Pressure gauge, (*ii*) Water level gauge or indicator, (*iii*) safety valve, (*iv*) steam stop valve, (*v*) feed check valve, and (*vi*) water level gauge.

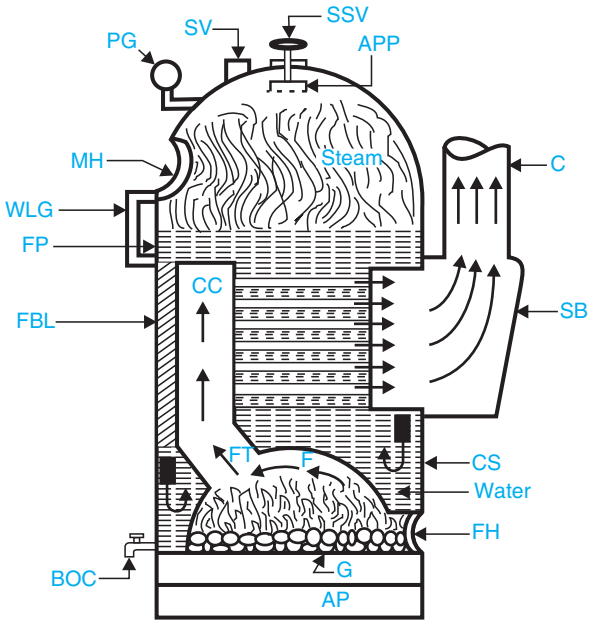
Flow of combustion gases and circulation of water in water jackets are indicated by arrows in Fig. 3.51.

The rate of production in such a boiler normally does not exceed 2500 kg/h and pressure is normally limited to 7.5 to 10 bar.

A simple vertical boiler is self-contained and can be transported easily.

3.14.7.2. Cochran boiler

It is *one of the best* types of vertical multi-tubular boiler, and has a number of horizontal fire tubes.



CS = Cylindrical shell
CC = Combustion chamber
FBL = Fir brick lining
F = Furnace (dome shaped)
G = Grate
AP = Ash pit
SV = Safety valve
MH = Man hole
WLG = Water level gauge
FT = Flue tube
SB = Smoke box
C = Chimney
FH = Fire hole
BOC = Blow-off cock
SSV = Steam stop valve
APP = Antipriming pipe
PG = Pressure gauge

Fig. 3.52. Cochran boiler.

Dimensions, working pressure, capacity, heating surface and efficiency are given below :

Shell diameter ..... 2.75 m
Height ..... 5.79 m
Working pressure ..... 6.5 bar (max. pressure = 15 bar)
Steam capacity ..... 3500 kg/h (max. capacity = 4000 kg/h)
Heating surface ..... 120 m^2
Efficiency ..... 70 to 75% (depending on the fuel used)

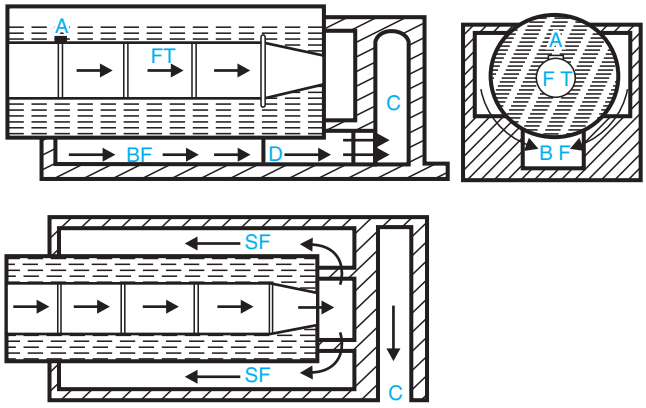
Cochran boiler consists of a cylindrical shell with a dome shaped top where the space is provided for steam. The furnace is one piece construction and is seamless. Its crown has a hemispherical shape and thus provides maximum volume of space. The fuel is burnt on the grate and ash is collected and disposed of from ash pit. The gases of combustion produced by burning of fuel enter the combustion chamber through the flue tube and strike against fire brick lining which directs them to pass through number of horizontal tubes, being surrounded by water. After which the gases escape to the atmosphere through smoke box and chimney. A number of hand-holes are provided around the outer shell for cleaning purposes.

The various boiler mountings shown in Fig. 3.52 are : (*i*) Water level gauge, (*ii*) Safety valve, (*iii*) Steam stop valve, (*iv*) Blow off cock, (*v*) Manhole, and (*vi*) Pressure gauge.

The path of combustion of gases and circulation of water are shown by arrows in Fig. 3.52.

3.14.7.3. Cornish boiler

This form of boiler was first adopted by Trevithick, the Cornish Engineer, at the time of introduction of high-pressure steam to the early Cornish engine, and is still used.



A = Fusible plug
BF = Bottom flue
D = Damper
FT = Flue tube
SF = Side flue
C = Passage to chimney

Fig. 3.53. Cornish boiler.

The specifications of Cornish Boiler are given below :

No. of flue tubes ..... One
Diameter of the shell ..... 1.25 to 1.75 m
Length of the shell ..... 4 to 7 m
Pressure of the steam ..... 10.5 bar
Steam capacity ..... 6500 kg/h.

Refer to Fig. 3.53. It consists of a cylindrical shell with flat ends through which passes a smaller flue tube containing the furnace. The products of combustion pass from the fire grate forward over the brickwork bridge to the end of the furnace tube ; they then return by the two side flues to the front end of the boiler, and again pass to the back end of a flue along the bottom of the boiler to the chimney.

The various boiler mountings which are used on this boiler are : (*i*) Steam stop valve, (*ii*) Pressure gauge, (*iii*) Water gauge, (*iv*) Fusible plug, (*v*) Blow off cock,

(*vi*) High steam low water safety valve, (*vii*) Feed check valve, and (*viii*) Manhole.

The advantage possessed by this type of boiler is that the sediment contained in the water falls to the bottom, where the plates are not brought into contact with the hottest portion of the furnace gases. The reason for carrying the product of combustion first through the side flues, and lastly through the bottom flue, is because the gases, having parted with much of their heat by the time they reach the bottom flue, are less liable to unduly heat the plates in the bottom of the boiler, where the sediment may have collected.

3.14.7.4. Lancashire boiler

This boiler is *reliable,* has *simplicity of design, ease of operation* and *less operating and maintenance costs.* It is commonly used in *sugar-mills* and *textile industries* where alongwith the power steam and steam for the process work is also needed. In addition this boiler is used where larger reserve of water and steam are needed.

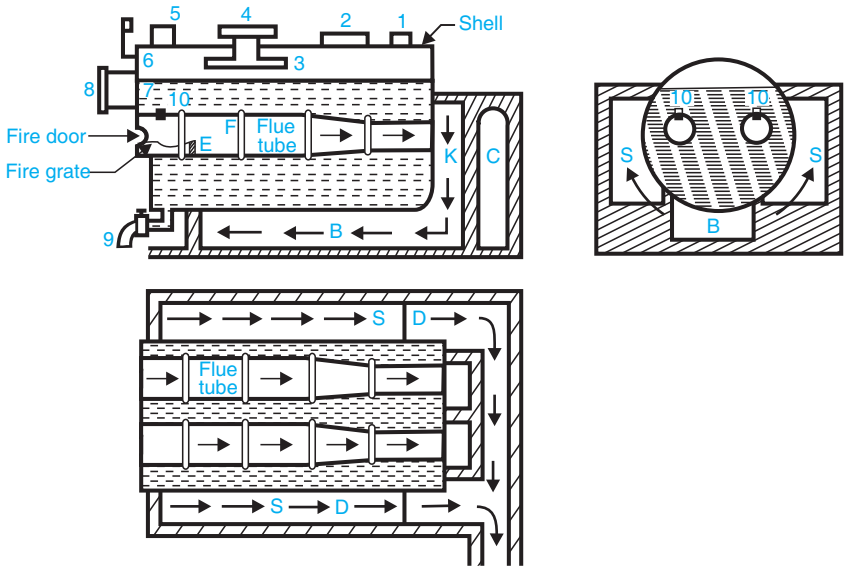
The *specifications* of Lancashire boiler are given below :

Diameter of the shell	..... 2 to 3 m
Diameter of the shell	..... 7 to 9 m
Maximum working pressure	..... 16 bar
Steam capacity	..... 9000 kg/h
Efficiency	..... 50 to 70%

Refer to Fig. 3.54. The Lancashire boiler consists of a cylindrical shell inside which two large tubes are placed. The shell is constructed with several *rings* of cylindrical from and it is placed horizontally over a brickwork which forms several channels for the flow of hot gases. These two tubes are also constructed with several rings of cylindrical form. They pass from one end of the shell to the other and are covered with water. The furnace is placed at the front end of each tube and they are known as furnace tubes. The coal is introduced through the fire hole into the grate. There is low brickwork fire bridge at the back of the gate to prevent the entry of the burning coal and ashes into the interior of the furnace tubes.

The combustion products from the grate pass up to the back end of the furnace tubes and then in downward direction. Thereafter they move through the bottom channel or bottom flue up to the front end of the boiler where they are divided and pass up to the side flues. Now they move along the two side flues and come to the chimney flue from where they lead to the chimney. To control the flow of hot gases to the chimney, dampers (in the form of sliding doors) are provided. As a result the flow of air to the grate can be controlled. The various mountings used on the boiler are shown in Fig. 3.54.

Note. In Cornish and Lancashire boilers, conical shaped cross tubes known as galloway tubes (not shown) may be fitted inside the furnace tubes to increase their heating surfaces and circulation of water. But these tubes have now become absolute for their considerable cost of fitting. Moreover, they cool the furnace gases and retard combustion.



B = Bottom flue
C = Chimney
D = Dampers
E = Fire-bridge
F = Flue tube
K = Main flue
S = Side flue

1. High steam low water safety valve
2. Manhole
3. Antipriming pipe
4. Steam stope valve
5. Safety valve
6. Pressure gauge
7. Feed check valve
8. Water gauge
9. Blow down cock
10. Fusible plug

Fig. 3.54. Lancashire boiler.

3.14.7.5. Locomotive boilers

It is mainly employed in locomotives though it may also be used as a stationary boiler. It is compact and its capacity for steam production is quite high for its size as it can raise large quantity of steam rapidly.

Dimensions and the specifications of the locomotives boilers (made at Chitranjan works in India) are given below :

Barrel diameter	..... 2.095 m
Length of the barrel	..... 5.206 m
Size of the tubes (superheater)	..... 14 cm
No. of superheater tubes	 38
Size of ordinary tubes	..... 5.72 cm
No. of ordinary tubes	 116
Steam capacity	..... 9000 kg/h
Working pressure	..... 14 bar
Grate area	..... 4.27 m^2
Coal burnt/h	..... 1600 kg
Heating surface	..... 271 m^2
Efficiency	..... 70%

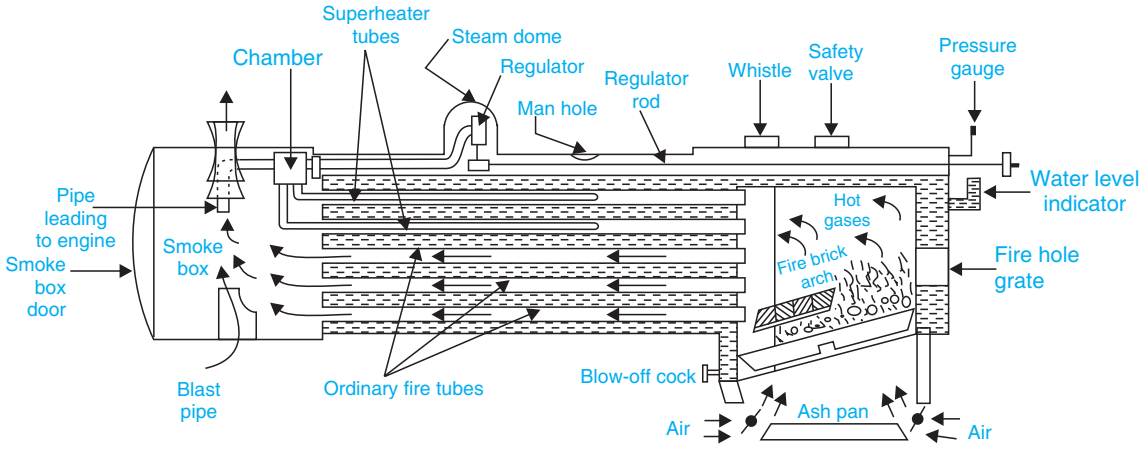


Fig. 3.55. Locomotive boiler.

Refer to Fig. 3.55. The locomotive boiler consists of a cylindrical barrel with a rectangular fire box at one end and a smoke box at the other end. The coal is introduced through the fire hole into the grate which is placed at the bottom of the fire box. The hot gases which are generated due to burning of the coal are deflected by an arch of fire bricks, so that walls of the fire box may be heated properly. The fire box is entirely surrounded by water except for the fire hole and the ash pit which is situated below the fire box is fitted with dampers at its front and back ends. The dampers control the flow of air to the grate. The hot gases pass from the fire box to the smoke box through a series of fire tubes and then they are discharged into the atmosphere through the chimney. The fire tubes are placed inside the barrel. Some of these tube are of larger diameter and the others of smaller diameter. The superheater tubes are placed inside the fire tubes of larger diameter. The heat of the hot gases is transmitted into the water through the heating surface of the fire tubes. The steam generated is collected over the water surface.

A dome shaped chamber known as *steam dome* is fitted on the upper part of the barrel, from where the steam flows through a steam pipe into the chamber. The flow of steam is regulated by means of a regulator. From the chamber it passes through the superheater tubes and returns to the superheated steam chamber (not shown) from which it is led to the cylinders through the pipes, one to each cylinder.

In this boiler natural draught cannot be obtained because it requires a very high chimney which cannot be provided on a locomotive boiler since it has to run on rails. Thus some artificial arrangement has to be used to produce a correct draught. As such the draught here is *produced by exhaust steam* from the cylinders which is discharged through the blast pipe to the chimney. When the locomotive is *standing* and no exhaust steam is available from the engine *fresh steam* from the boiler is used for the purpose.

The various boiler mountings include :

Safety valves, pressure gauge, water level indicator, fusible plug, man hole, blow-off cock and feed check valve.

A locomotive boiler entails the following *merits* and *demerits* :

Merits :

1. High steam capacity.
2. Low cost of construction.
3. Portability.
4. Low installation cost.
5. Compact.

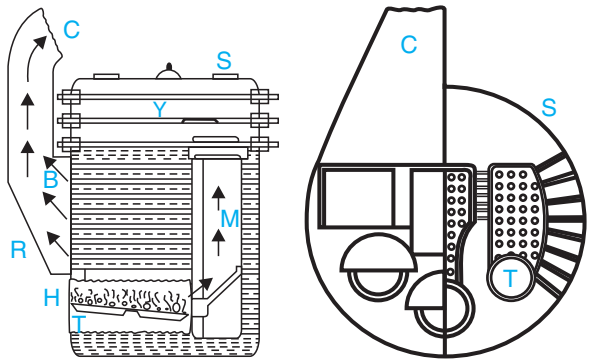
Demerits :

1. There are chances to corrosion and scale formation in the water legs due to the accumulation of sediments and the mud particles.
2. It is difficult to clean some water spaces.
3. Large flat surfaces need bracing.
4. It cannot carry high overloads without being damaged by overheating.
5. There are practical constructional limits for pressure and capacity which do not meet requirements.

3.14.7.6. Scotch boiler

The scotch type marine boiler is probably the *most popular* boiler for steaming capacities up to about 1000 kg/h and pressure of about 17 bar. It is of compact size and occupies small floor space.

Fig. 3.56 shows a single ended scotch type marine boiler. It consists of a cylindrical shell in which are incorporated one to four cylindrical, corrugated steel furnaces. The furnaces are internally fired and surrounded by water. A combustion chamber is located at the back end of the furnace and is also surrounded by water. Usually, each furnace has its own combustion chamber. A nest of fire tubes run from the front tube plate to the back tube plate.



T =	Furnace tube	*R* =	Smoke box door
H =	Fire hole	*C* =	Chimney
M =	Combustion chamber	*S* =	Shell
B =	Smoke box	*Y* =	Bar stays.

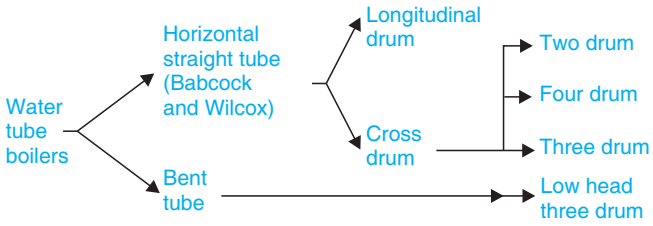
Fig. 3.56. Scotch boiler.

The hot gases produced due to burning of fuel move to the combustion chambers (by means of the draught). Then they travel to the smoke box through the fire tubes and finally leave the boiler *via* uptake and the chimney.

In a double-ended scotch boiler furnaces are provided at each end. They look like single-ended boilers placed back to back. A double-ended boiler for same evaporation capacity, is cheaper and occupies less space as compared to single-ended boiler.

3.14.8. Water Tube Boilers

The types of water tube boilers are given below :



3.14.8.1. Babcock and wilcox water tube boiler

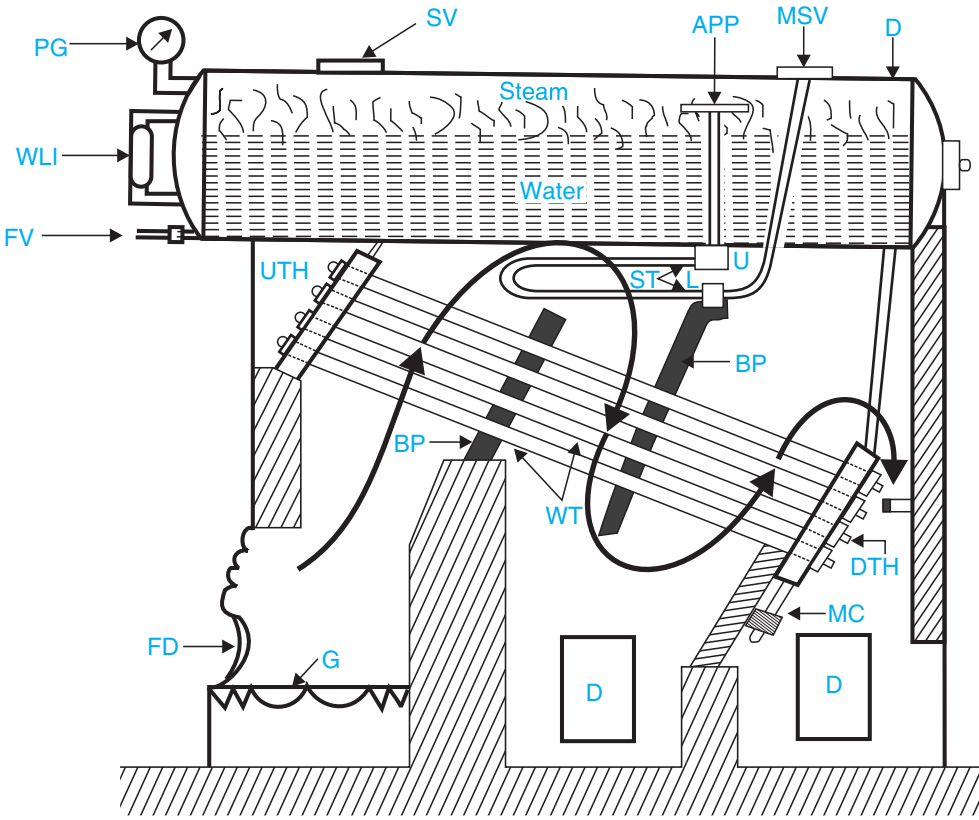
The water tube boilers are used exclusively, when pressure above 10 bar and capacity in excess of 7000 kg of steam per hour is required. Babcock and Wilcox water tube boiler is an example of horizontal straight tube boiler and may be designed for stationary or marine purposes.

The particulars (dimensions, capacity etc.) relating to this boiler are given below :

Diameter of the drum	.....	1.22 to 1.83 m
Length	.....	6.096 to 9.144 m
Size of the water tubes	.....	7.62 to 10.16 cm
Size of superheater tubes	.....	3.84 to 5.71 cm
Working pressure	.....	40 bar (max.)
Steaming capacity	.....	40000 kg/h (max.)
Efficiency	.....	60 to 80%

Fig. 3.57 shows a Babcock and Wilcox boiler with longitudinal drum. It consists of a drum connected to a series of front end and rear end headers by short riser tubes. To these headers are connected a series of inclined water tubes of solid drawn mild steel.

The angle of inclination of the water tubes to the horizontal is about 15° or more. A hand hole is provided in the header in front of each tube for cleaning and inspection of tubes. A feed valve is provided to fill the drum and inclined tubes with water the level of which is indicated by the water level indicator. Through the fire door the fuel is supplied to grate where it is burnt. The hot gases are forced to move upwards between the tubes by baffle plates provided. The water from the drum flows through the inclined tubes *via* downtake header and goes back into the shell in the form of water and steam *via* uptake header. The steam gets collected in the steam space of the drum. The steam then enters through the antipriming pipe and flows in the superheater tubes where it is further heated and is finally taken out through the main stop valve and supplied to the engine when needed.



D = Drum
DTH = Down take header
WT = Water tubes
BP = Baffle plates
D = Doors
G = Grate
FD = Fire door
MC = Mud collector
WLI = Water level indicator
PG = Pressure gauge
ST = Superheater tubes
SV = Safety valve
MSV = Main stop valve
APP = Antipriming pipe
L = Lower junction box
U = Upper junction box
FV = Feed valve.

Fig. 3.57. Babcock and Wilcox boiler.

At the lowest point of the boiler is provided a mud collector to remove the mud particles through a blow-down-cock.

The entire boiler except the furnace are hung by means of metallic slings or straps or wrought iron girders supported on pillars. This arrangement enables the drum and the tubes to expand or contract freely. The brickwork around the boiler encloses the furnace and the hot gases.

The various mountings used on the boiler are shown in Fig. 3.57.

A Babcock Wilcox water tube boiler with cross drum differs from longitudinal drum boiler in a way that how drum is placed with reference to the axis of the water tubes of the boiler. The longitudinal drum restricts number of tubes that can be connected to one drum circumferentially and limits the capacity of the boiler. In the cross drum there is no limitation of the number of connecting tubes.

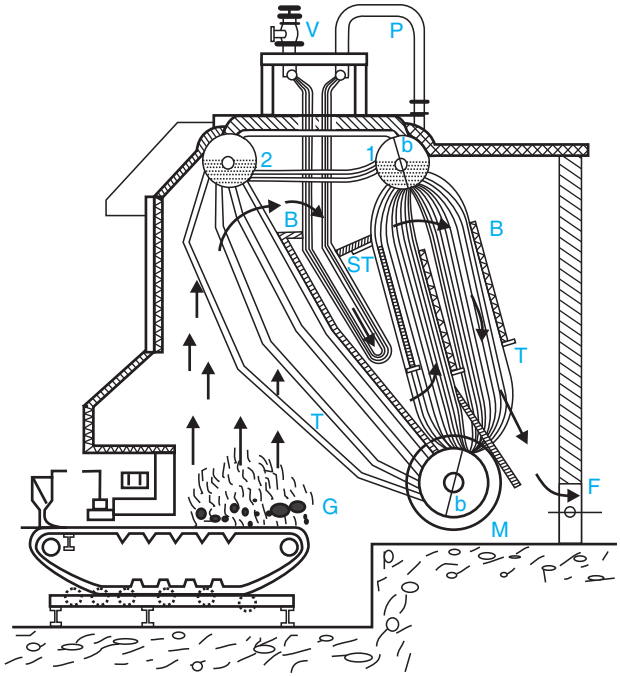
The pressure of steam in case of cross drum boiler may be as high as 100 bar and steaming capacity upto 27,000 kg/h.

3.14.8.2. Striling boiler

Stirling water tube boiler is an example of *bent tube* boiler. The main elements of a bent type water tube boiler are essentially drum or drums and headers connected by bent tubes. For large central power stations these boilers are very popular. They have steaming capacities as high as 50,000 kg/h and pressure as high as 60 bar.

Fig. 3.58 shows a small-sized stirling water tube boiler. It consists of two upper drums known as steam drums and a lower drum known as mud or water drum.

The steam drums are connected to mud drum by bank of bent tubes. The steam and water space of the steam drums are interconnected with each other, so that balance of water and steam may be obtained. For carrying out cleaning operation manhole at one end of each drum is provided. The feed water from the economiser (not shown) is delivered to the steam drum 1 which is fitted with a baffle. The baffle deflects the water to move downwards into the drum. The water flows from the drum 1 to the mud drum through the rearmost water tubes at the backside. So the mud particles and other impurities will move to the mud drum, where these particles may be deposited. As this drum is not subjected to high temperature, so the impurities may not cause harm to the drum. The blow off cock blows off the impurities. The baffle provided at the mud drum deflects the pure water to move upwards to the drum 1 through the remaining half of the water tubes at the back. The water also flows from it to the drum 2 through the water tubes which are just over the furnace. So they attain a higher temperature than the remaining portion of the boiler and a major portion of evaporation takes place in these tubes. The steam is taken from the drum 1 through a steam pipe and then it passes through the superheater tubes where the steam is superheated. Finally, the steam moves to the stop valve from where it can be supplied for further use.



V = Stop valve
P = Steam pipe
b = Water baffle
B = Baffle wall
ST = Superheater tubes
T = Water tubes
G = Grate
M = Mud drum

Fig. 3.58. Stirling boiler.

The combustion products ensuing from the grate move in the upward and downward directions due to the brickwall baffles and are finally discharged through the chimney into the atmosphere. Fire brick arch gets incandescent hot and helps in combustion and preventing the chilling of the furnace when fire door is opened and cold air rushes in.

The steam drums and mud drum are supported on steel beams independent of the brick-work.

It is lighter and more flexible than the straight tube boilers. But it is comparatively more difficult to clean and inspect the bent tubes.

3.14.9. High Pressure Boilers

3.14.9.1. Introduction

In applications where steam is needed at pressure, 30 bar, and individual boilers are required to raise less than about 30000 kg of steam per hour, *shell boilers are considerably cheaper than the water tube boilers.* Above these limits, shell boilers (generally factory built) are difficult to transport if not impossible. There are no such limits to water tube boilers. These can be site erected from easily transportable parts, and moreover the pressure parts are of smaller diameter and therefore can be thinner. The geometry can be varied to suit a wide range of situations and furnace is not limited to cylindrical form. Therefore, *water tube boilers are generally preferred for high pressure and high output, whereas, shell boilers for low pressure and low output.*

The modern high pressure boilers employed for power generation are for steam capacities 30 to 650 tonnes/h and above with a pressure up to 160 bar and maximum steam temperature of about 540°C.

3.14.9.2. Unique features of the high pressure boilers

Following are the *unique features* of high pressure boilers :

1. Method of water circulation
2. Type of tubing
3. Improved method of heating.

1. *Method of water circulation.* The circulation of water through the boiler may be *natural circulation* due to density difference or *forced circulation.* In all modern high pressure boiler plants, the water circulation is maintained with the help of pump which forces the water through the boiler plant. The use of natural circulation is limited to sub-critical boilers due to its limitations.

2. *Type of tubing.* In most of the high pressure boilers, the water circulated through the tubes and their external surfaces are exposed to the flue gases. In water tube boilers, if the flow takes place through one continuous tube, the large pressure drop takes place due to friction. This is *considerably reduced by arranging the flow to pass through parallel system of tubing.* In most of the cases, several sets of the tubings are used. This type of arrangement helps to *reduce the pressure loss,* and better control over the quality of the steam.

3. *Improved method of heating.* The following improved methods of heating may be used to increase the heat transfer :

(*i*) The saving of heat by *evaporation of water* above critical pressure of the steam.

(*ii*) The heating of water can be made by *mixing the superheated steam.* The mixing phenomenon *gives highest heat transfer co-efficient*.

(*iii*) The overall heat transfer coefficient can be increased by *increasing the water velocity inside the tube and increasing the gas velocity above sonic velocity*.

3.14.9.3. Advantages of high pressure boilers

The following are the *advantages* of high pressure boilers :

1. In high pressure boilers pumps are used to maintain forced circulation of water through the tubes of the boiler. This *ensures positive circulation of water and increases evaporative capacity of the boiler and less number of steam drums will be required.*
2. The *heat of combustion is utilised more efficiently* by the use of small diameter tubes in large number and in multiple circuits.
3. *Pressurised combustion* is used which *increases rate of firing of fuel* thus increasing the rate of heat release.
4. Due to compactness less floor space is required.
5. The tendency of scale formation is eliminated due to high velocity of water through the tubes.
6. All the parts are uniformly heated, therefore, the danger of overheating is reduced and thermal stress problem is simplified.
7. The differential expansion is reduced due to uniform temperature and this reduces the possibility of gas and air leakages.
8. The components can be arranged horizontally as high head required for natural circulation is eliminated using forced circulation. There is a greater flexibility in the components arrangement.
9. The steam can be raised quickly to meet the variable load requirements without the use of complicated control devices.
10. The *efficiency of plant is increased up to 40 to 42 per cent* by using high pressure and high temperature steam.
11. A very rapid start from cold is possible if an external supply of power is available. Hence, the boiler can be used for carrying peak loads or standby purposes with hydraulic station.
12. Use of high pressure and high temperature steam is economical.

3.14.9.4. LaMont boiler

This boiler works on a forced circulation and the circulation is maintained by a centrifugal pump, driven by a steam turbine using steam from the boiler. For emergency an electrically driven pump is also fitted.

Fig. 3.59 shows a LaMont steam boiler. The feed water passes through the economiser to the drum from which it is drawn to the circulation pump. The pump delivers the feed water to the tube evaporating section which in turn sends a mixture of steam and water to the drum. The steam in the drum is then drawn through the superheater. The superheated steam so obtained is then supplied to the prime mover.

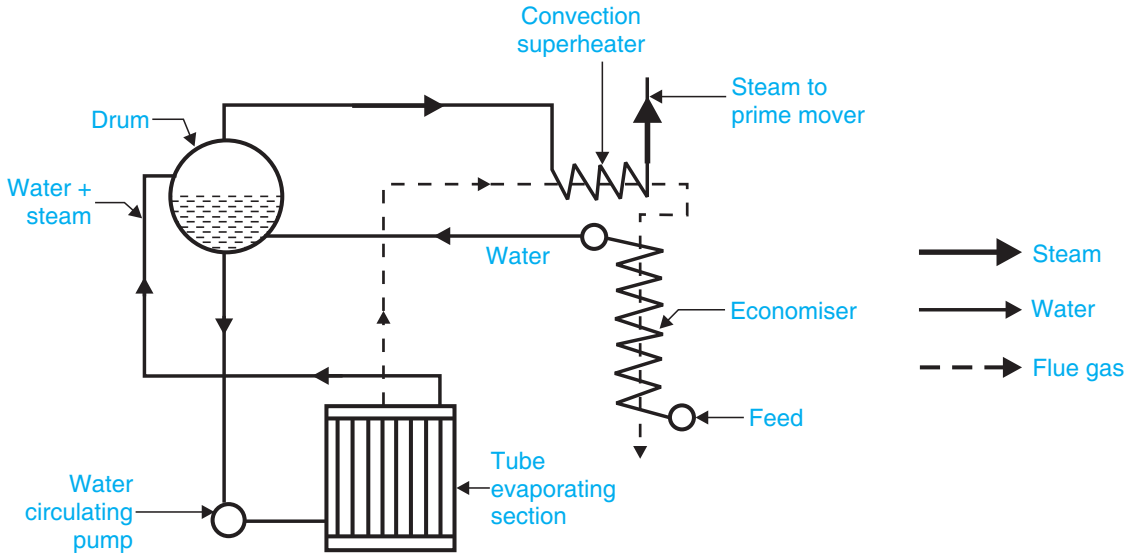


Fig. 3.59. LaMont boiler.

These boilers have been built to generate of 45 to 50 tonnes of superheated steam at a pressure of 130 bar and at a temperature of 500°C.

3.14.9.5. Loeffler boiler

In a LaMont boiler the major difficulty experienced is the deposition of salt and sediment on the inner surfaces of the water tubes. The deposition reduces the heat transfer and ultimately the generating capacity. This further increases the danger of overheating the tubes due to salt deposition as it has high thermal resistance. This difficulty was solved in Loeffler boiler by *preventing the flow of water into the boiler tubes.*

This boiler also makes use of forced circulation. Its novel principle is *the evaporating of the feed water by means of superheated steam from the superheater, the hot gases from the furnace being primarily used for superheating purposes.*

Fig. 3.60 shows a diagrammatic view of a Loeffler boiler. The high pressure feed pump draws water through the economiser (or feed water heater) and delivers it into the evaporating drum. The steam circulating pump draws saturated steam from the evaporating drum and passes it through radiant and convective superheaters where steam is heated to required temperature. *From the superheater about one-third of the superheated steam passes to the prime mover (turbine) the remaining two-thirds passing through the water in the evaporating drum in order to evaporate feed water.*

This boiler can carry higher salt concentrations than any other type and is more compact than indirectly heated boilers having natural circulation. These qualities fit it for land or sea transport power generation.

Loeffler boilers with generating capacity of 100 tonnes/h and operating at 140 bar are already commissioned.

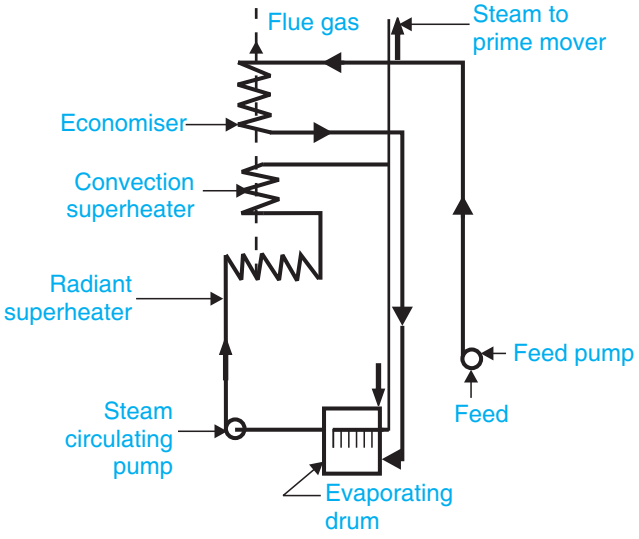


Fig. 3.60. Loeffler boiler.

Once Through Boilers :

Owing to the sharply increasing costs of construction and fuel it becomes essential for the designers to economise on the installation cost and to increase fuel efficiency in the new stations by using modern sophisticated technology. Higher size units with higher steam parameters seem a natural choice for economical installation and operation of thermal power plants. The 800 MW units would be designed on supercritical steam pressure with a drumless boiler on *once through principle*.

As the steam pressure increases, the *differential* between the specific weight of saturated water in down-comers and specific weight of steam-water mixture in furnace wall tubes, which *causes natural circulation* in boiler, goes on *decreasing. Sluggish circulation causes film boiling*. In film boiling, the tube metal remains in contact with steam bubbles which provide high thermal resistance for heat flow and therefore tube metal sharply deteriorates due to high metal temperature leading to failure of the boiler tubes.

It is *not possible to prevent "film boiling"* in the upper furnace tubes for pressures above *180 bar* with *natural circulation*. Therefore, generally above 160 bar pressure, *controlled circulation* in water walls is used by providing *boiler circulating pump* between down-comers and lower water distributing heaters and the water walls. In such controlled circulation boilers, it is possible to utilize high steam pressure up to 200 bar but beyond this, the effectiveness of Boiler drum in separating the saturated steam from water is reduced. Therefore, *beyond 200 bar, drumless boiler is envisaged*. In *sub-critical range* (< 225.65 bar), a **separator vessel** is utilized to separate out salts from steam water mixture, but in *supercritical range* (> 225.65 bar), the separate vessel cannot function and only **once through** (monotube) is adopted.

- Fig. 3.61 shows a *once through or monotype boiler* (a design adopted by Sulzers Brothers Ltd). In this design there is a separator vessel with sub-critical pressures ; the *once through circulation is provided by a "feed pump"*.

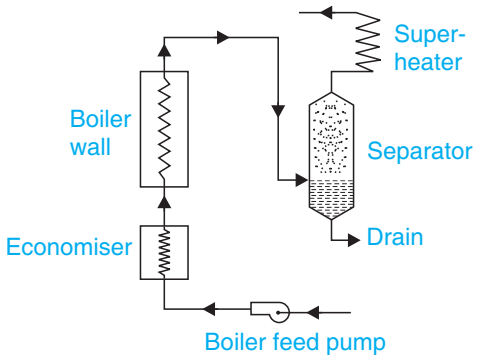


Fig. 3.61. Once through (or Monotype) boiler.

- Fig. 3.62 shows a combined circulatory boiler (a design adopted by M/s Combustion Engineering Co.). In this design a "*Mixing vessel*" provides suction to boiler circulating pumps at sub-critical pressures and inlet saturated steam to superheater and serves as a receiving header for steam-water mixture from evaporator suction. The boiler circulating pumps are required to function in the start-up or low pressure conditions but when the pressure goes above critical pressure then these are stopped and once through circulation is provided by boiler feed pump.

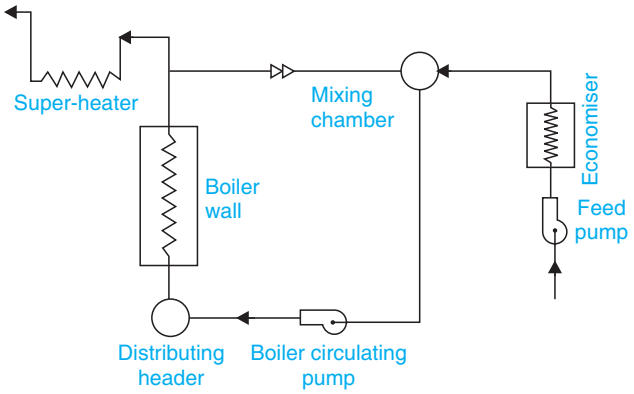


Fig. 3.62. Combined circulatory pump.

Advantages of Once through boilers :

The following are the *advantages of once through boilers for large thermal units :*

1. No higher limit for the higher steam pressure.
2. Full steam temperature can be maintained over a wider range of load.
3. Starting and cooling down of the boiler is fast.
4. No circulation disturbance due to rapid pressure fluctuations.
5. A once through boiler is smaller in size and weighs less in comparison to a natural circulation boiler.
6. Easy control of steam temperature during start-up and shut-down (which is very advantageous for start-up of boiler and turbine)
7. Greater freedom in arrangement and location of heating surfaces.
8. Easy to adopt variable pressure operation for better performance at part load operation.
9. Elimination of heavy walled drum decreases the metallurgical sensitivity of boiler against changes in pressure.

Flash Steam Generator :

- A flash steam generator is a special form of boiler having basically a *helix tube fired by down jet combustion of gas or oil*. Water is pumped into the helix and at exit 90 per cent of it is in the form of steam, the remaining water fraction being collected in the separator. The *tube helix principle, which eliminates the need for a water space, gives an extremely high heat output in a small area.*
- The *combustion efficiency* is about 80 per cent on oil, and 73 per cent on gas.
- The *advantages* are *very rapid response* (full steam production within about five minutes) and output ranges up to an evaporation rate of about 1 kg/s with operating steam pressure ranging from 3 to 70 bar.
- This type of boiler is more suitable when the plant is designed to take peak loads.

3.14.9.6. Benson boiler

In the LaMont boiler, the main difficult experienced *is the formation and attachment of bubbles on the inner surfaces of the heating tubes. The attached bubbles to the tube surfaces reduce the heat flow and steam generation as it offers high thermal resistance than water film. Benson in 1922 argued that if the boiler pressure was raised to critical pressure (225 atm.), the steam and water have the same density and therefore, the danger of bubble formation can be easily eliminated.* The first high pressure Benson boiler was put into operation in 1927 in West Germany.

This boiler too makes use of forced circulation and uses oil as fuel. It chief novel *principle is that it eliminates the latent heat of water by first compressing the feed to a pressure of 235 bar, it is then above the critical pressure and its latent heat is zero.*

Fig. 3.63 shows a schematic diagram of a Benson boiler. This boiler does not use any drum. The feed water after circulation through the economic tubes flows through the radiant parallel tube section to evaporate partly. The steam water mixture produced then moves to the transit section where this mixture is converted into steam. The steam is now passed through the convection superheater and finally supplied to the prime mover.

Boilers having as high as 650°C temperature of steam had been put into service. The maximum working pressure obtained so far from commercial Benson boiler is 500 atm. The Benson boilers of 150 tonnes/h generating capacity are in use.

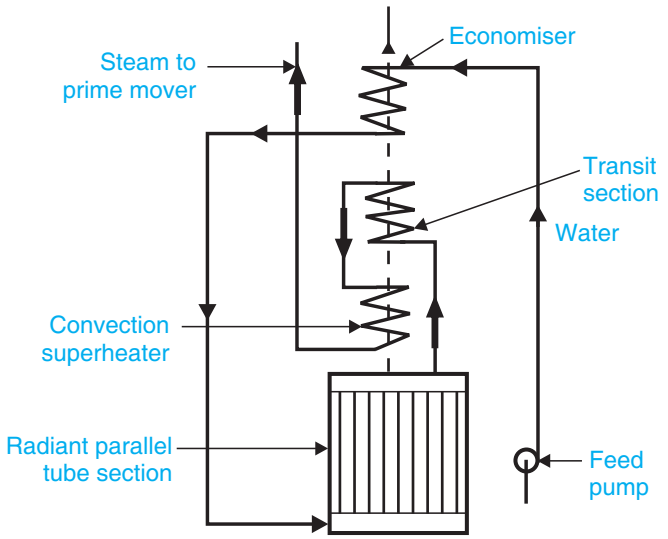


Fig. 3.63. Benson boiler.

Advantages of a Benson Boiler :

The Benson boiler possesses the following *advantages* :

1. It can be erected in a comparatively smaller floor area.

2. The total weight of a Benson boiler is 20% less than other boilers, since there are no drums. This also reduces the cost of the boiler.

3. It can be started very quickly because of welded joints.

4. Natural convection boilers require expansion joints but these are not required for Benson boiler as the pipes are welded.

5. The furnace walls of the boiler can be more efficiently protected by using smaller diameter and closed pitched tubes.

6. The transfer of parts of the boiler is easy as no drums are required and majority of the parts are carried to the site without pre-assembly.

7. It can be operated most economically by varying the temperature and pressure at part loads and overloads. The desired temperature can also be maintained constant at any pressure.

8. The blow-down losses of the boiler are hardly 4% of natural circulation boiler of the same capacity.

9. Explosion hazards are not severe as it consists of only tubes of small diameter and has very little storage capacity.

10. The superheater in a Benson boiler is an integral part of forced circulation system, therefore, no special starting arrangement for superheater is required.

3.14.9.7. Velox boiler

It is a well known fact that when the gas velocity exceeds the sound-velocity, the heat is transferred from the gas at a much higher rate than rates achieved with sub-sonic flow. The advantage of this theory is taken to effect the large heat transfer from a smaller surface area in this boiler.

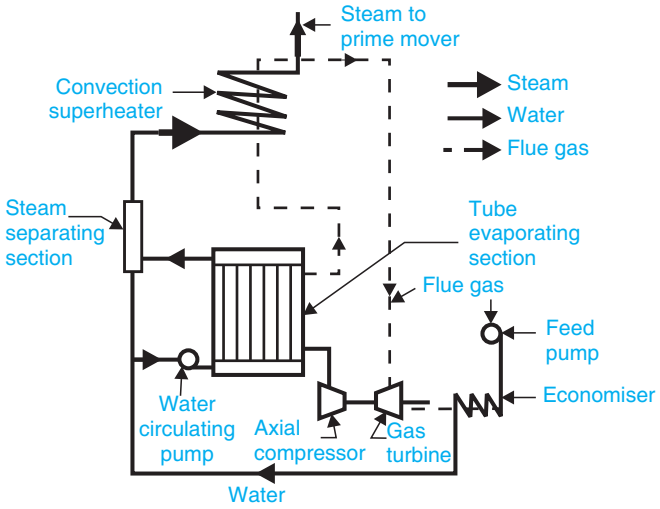


Fig. 3.64. Velox boiler.

This boiler makes use of ***pressurised combustion.***

The gas turbine drives the axial flow compressor which raises the incoming air from atmosphere pressure to furnace pressure. The combustion gases after heating the water and steam flow through the gas turbine to the atmosphere. The feed water after passing through the economiser is pumped by a water circulating pump to the tube evaporating section. Steam separated in steam separating section flows to the superheater, from there it moves to the prime mover.

The size of the Velox boiler is limited to 100 tonnes/h because 600 B.H.P. is required to run the air compressor at this output. The power developed by the gas turbine is not sufficient to run the compressor and therefore, some power from external source power must be supplied.

Advantages :

1. The boiler is very compact and has greater flexibility.

2. Very high combustion rates are possible.

3. It can be quickly started.

4. Low excess air is required as the pressurised air is used and the problem of draught is simplified.

3.14.9.8. Supercritical boilers

A large number of steam generating plants are designed between working ranges of 125 atm. and 510°C to 300 atm. and 660°C ; these are basically characterised as *subcritical and supercritical.*

Usually, *a sub-critical boiler* consists of three distinct section as *preheater* (economiser), *evaporator* and *superheater*.

A *super-critical boiler* requires only *preheater* and *superheater*.

The constructional layout of both the above types of boilers is, however, practically identical.

These days it has become a rule to use *super-critical boilers above 300 MW capacity units.*

The super-critical boilers claim the following *advantages* over critical type :

1. Large heat transfer rates.

2. Owing to less heat capacity of the generator the pressure level is more stable and therefore gives better response.

3. Because of absence of two phase mixture the problems of erosion and corrosion are minimised.

4. More adaptable to load fluctuations (because of great ease of operation, simplicity and flexibility).

5. The turbo-generators connected to super-critical boilers can generate peak loads by changing the pressure of operation.

6. Higher thermal efficiency.

Presently, 246 atm. and 538°C are used for unit size above 500 MW capacity plants.

3.14.9.9. Supercharged boiler

In a supercharged boiler, the combustion is carried out under pressure in the combustion chamber by supplying the compressed air. The exhaust gases from the combustion chamber are used to run the gas turbine as they are exhausted to high pressure. The gas turbine runs the air compressor to supply the compressed air to the combustion chamber.

Advantages :

1. Owing to very high overall heat transfer co-efficient the heat transfer surface required is hardly 20 to 25% of the heat transfer surface of a conventional boiler.

2. The part of the gas turbine output can be used to drive other auxiliaries.

3. Small heat storage capacity of the boiler plant gives better response to control.

4. Rapid start of the boiler is possible.

5. Comparatively less number of operators are required.

Corrosion in boilers and its prevention

For the safety and performance of fossil fired boilers proper selection of tube material is very essential.

It is of paramount importance to keep the tubes clean internally and externally free of deposits that could impair heat transfer and lead to corrosion, ultimately causing tube failures. Corrosion damage is always experienced inside tubes of the boiler, economiser and superheater when water chemistry is not maintained within limit as recommended by the manufacturers.

Materials commonly used for various parts/sections of the boilers are given below :

Parts/Sections	Materials
1. *Furnace walls and economisers*	Carbon steels and ferric alloys with small percentages of chromium (5–10%).
2. *Superheater and reheater tubes*	— Carbon steels... up to 500°C temp. — Alloy steels ... temp. > 500°C. — Carbon-molybdenum steel is used at *inlet section.* — Ferritic alloy steel with high percentage of chromium is used for downstream section of superheater. — Stainless steel and high chromium steels are recommended for *hotter sections* (560–600°C).

Composite tubes (consisting of an outer layer of 50% Cr, 15% Ni steel, metallurgically bonded to inner layer of 800 H) are used when coal-ash attack is severe.

Following are the few important phenomena which contribute to corrosion :

(*i*) Hydrogen induced brittle fracture.	Water-side problems
(*ii*) Bulk deposit corrosion.	
(*iii*) Corrosion fatigue.	
(*iv*) Stress corrosion cracking.	
(*v*) Oxidation.	
(*vi*) Fouling.	Fireside problems
(*vii*) Slagging.	

If inspite of design efforts high temperature corrosion occurs then the problem can be solved by using any one of the following methods :

1. Using the fuels having more favourable characteristics.

2. Replacing the damaged tubes with tubes containing high chromium content.

3. Providing stainless steel tube shields at the cost of reduced efficiency.

3.15. ACCESSORIES

Accessories *are the auxiliary plants required for steam boilers for their proper operation and for the increase of their efficiency.*

Commonly used accessories are discussed as follows :

3.15.1. Feed Pumps

The feed pump is a pump which is used to *deliver feed water to the boiler.* It is desirable that the quantity of water supplied should be at least equal to that evaporated and supplied to the engine. Two types of pumps which are commonly used as feed pumps are : (*i*) *Reciprocating pump*, and (*ii*) *Rotary pump*.

The reciprocating pump consists of a pump cylinder and a piston. Inside the cylinder reciprocates a piston which displaces water. The reciprocating pump may be of two types :

1. Single-acting pump
2. Double-acting pump.

In a single-acting pump the water is displaced by one side of the piston only and so the water is discharged in alternate strokes.

In a double-acting pump, the water is discharged in each stroke of the piston since the water is displaced by both the sides of the piston.

The reciprocating feed pumps are continuously run by steam from the same boiler to which water is to be fed.

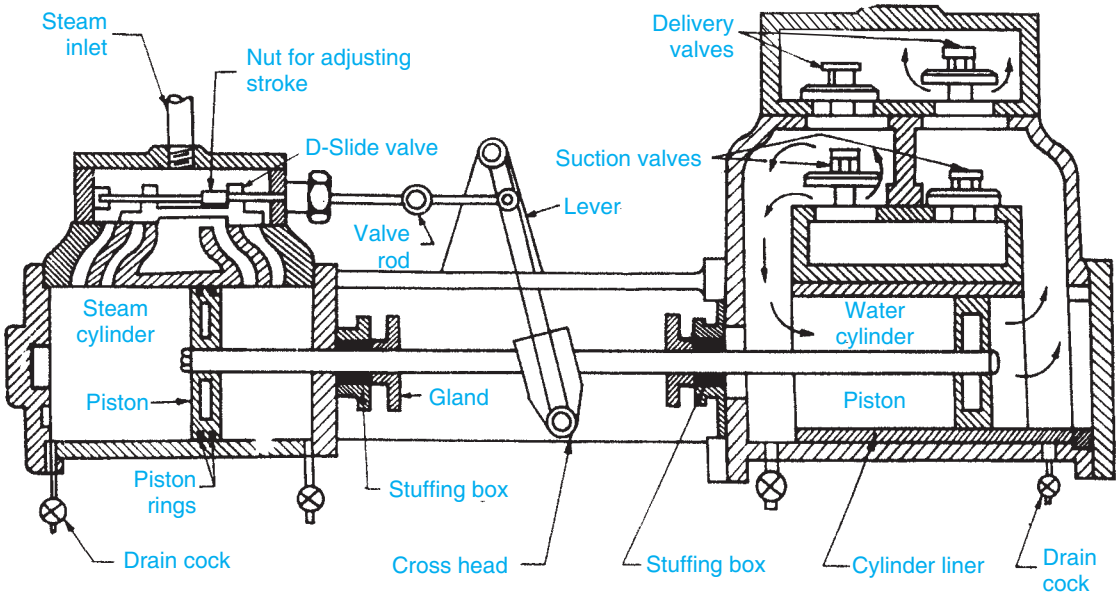


Fig. 3.65. Feed pump.

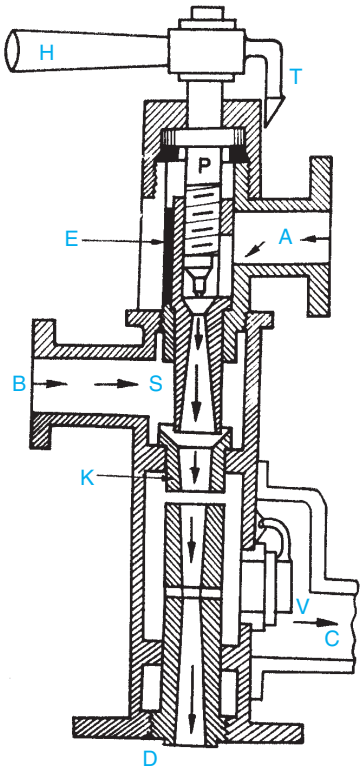
Fig. 3.65 shows a duplex direct acting steam pump. Here there are two single steam cylinders placed side by side. Slide valves distribute the steam in each cylinder. The slide valve in each cylinder steam chest is operated by the crosshead on the piston rod of the opposite cylinder, through an arrangement of rods and rocker arms. The feed pump is generally double-acting. On each side of the pump plunger there are suction and discharge valves. The pumps work alternately and consequently continuous flow of water is maintained. *Double feed pump is commonly employed for medium size boilers.*

Rotary feed pumps are of centrifugal type and are commonly run either by a small steam turbine or by an electric motor. A rotary pump consists of a casing and a rotating element known as impeller which is fitted over a shaft. It utilises the centrifugal force of the rotating impeller for pumping the liquid from one place to the other.

3.15.2. Injector

The function of an injector is to feed water into the boiler. It is commonly employed for vertical and locomotive boilers and does not find its application in large capacity high pressure boilers. It is also used where the space is not available for the installation of a feed pump.

In an injector the water is delivered to the boiler by steam pressure ; the *kinetic energy of steam is used to increase the pressure and velocity of the feed water.*



S = Steam cone
K = Combining cone
D = Delivery cone
P = Spindle
A = Steam pipe
B = Water pipe
E = Key
H = Handle
T = Pointer
V = Valve
C = Overflow pipe

Fig. 3.66. Injector.

Fig. 3.66 shows an injector. It consists of a spindle P, a steam cone S, a combining cone K, a delivery cone D, and a handle H, with a pointer T. The spindle's upper end is provided with a handle while the lower end serves the purpose of a valve. The pointer on the handle indicates the 'shut' and 'open' position of the valve. The lower part of the spindle has a screw which works in a nut which is integral part of the steam cone. The key E checks the rotation of steam cone. With the rotation of the handle steam cone moves up or down and consequently the valve controls the steam flow through the steam cone. The steam enters through the steam pipe A, while the feed water enters through the water pipe B. The flow of water is also regulated due to sliding motion of the steam cone by its lower end. The water mixes with the steam at the combining cone where it is condensed. The mixture then passes through the delivery cone and there its kinetic energy is converted into pressure energy. The final pressure must be greater than the steam pressure of boiler otherwise water will not enter into the boiler. The excess water finds its way through the overflow pipe.

Advantages of an injector :

1. Low initial cost.
2. Simplicity.
3. Compactness.
4. Absence of dynamic parts.
5. Thermal efficiency very high (about 99%).
6. Ease of operation.

Disadvantages :

1. Pumping efficiency is low.
2. It cannot force very hot water.
3. Irregularity of operation under extreme variation in steam pressure.

Note. An injector is more efficient than a feed pump because all the heat in the operating steam is returned to boiler and in addition to performing the work of a pump, the injector acts as a feed water heater. But when a large quantity of feed water is involved (*e.g.* marine and large installations) feed pumps are employed because they have greater reliability and require lesser amount of attention.

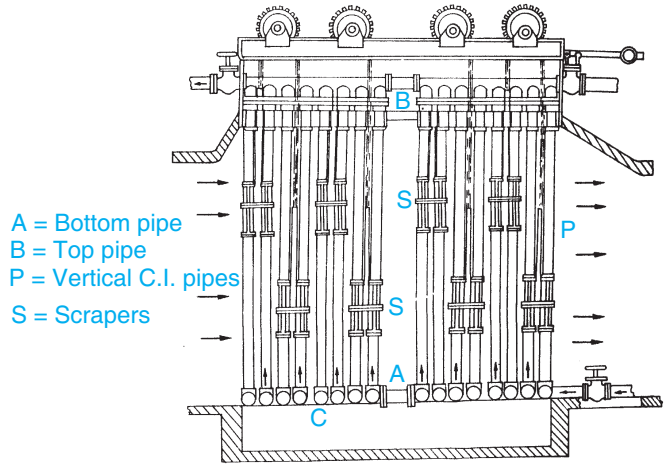
3.15.3. Economiser

An economiser is a device in which the waste heat of the flue gases is utilised for heating the feed water.

Economiser are of the two types : (*i*) *Independent type,* and (*ii*) *Integral type. Former* is installed in chamber apart from the boiler setting. The chamber is situated at the passage of the flow of the flue gases from the boiler or boiler to the chimney. *Latter* is a part of the boiler heating surface and is installed within the boiler setting.

Fig. 3.67 shows an independent type vertical tube economiser (called Green's economiser). It is employed for boilers of medium pressure range up to about 25 bar. It consists of a large number of vertical cast iron pipes P which are connected with two horizontal pipes, one at the top and the other at the bottom. A is the bottom pipe through which the feed water is pumped into the economiser. The water comes into the top pipe B from the bottom pipe (*via.* vertical pipes) and finally flows to the boiler. The flue gases move around the pipes in the direction opposite to the flow of water. Consequently, heat transfer through the surfaces of the pipes takes place and water is thereby heated.

A blow-off cock is provided at the back of end vertical pipes to remove sediments deposited in the bottom boxes. The soot of the flue gases which gets deposited on the pipes reduces the efficiency of the economiser. To prevent the soot deposit, the scrapers S move up and down to keep the external surface of the pipe clean (for better heat transfer).



A = Bottom pipe *P* = Vertical C.I. pipes
B = Top pipe *S* = Scrapers

Fig. 3.67. Economiser.

By-pass arrangement (Fig. 3.68) *enables to isolate or include the economiser in the path of flue gases.*

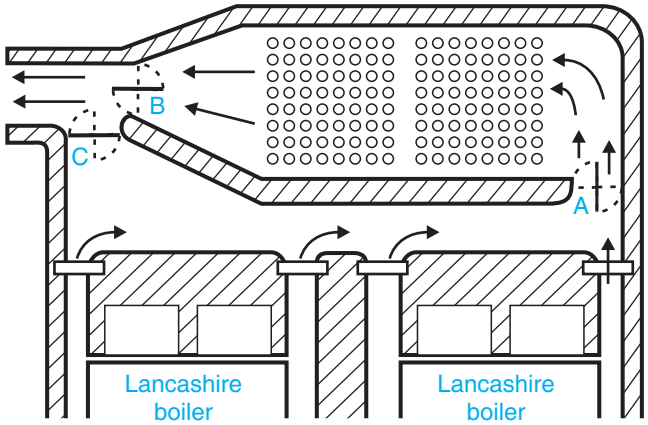


Fig. 3.68. By-pass arrangement of flues.

The use of an economiser entails the following *advantages* :

1. The temperature range between various parts of the boiler is reduced which results in reduction of stresses due to unequal expansion.

2. If the boiler is fed with cold water it may result in chilling the boiler metal. Hot feed water checks it.

3. Evaporative capacity of the boiler is increased.

4. Overall efficiency of the plant is increased.

3.15.4. Air Preheater

The function of the air preheater is to increase the temperature of air before it enters the furnace. It is generally placed after the economiser ; so the flue gases pass through the economiser and then to the air preheater.

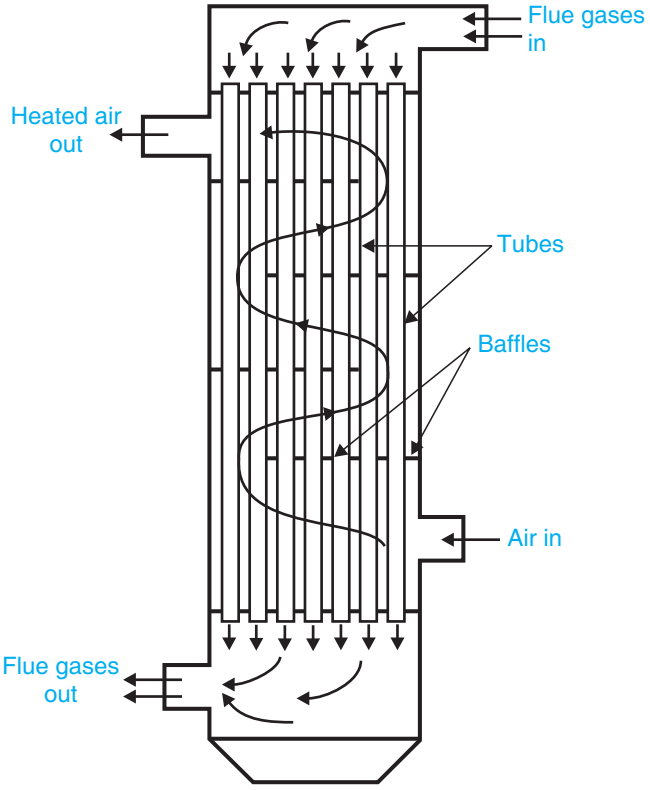


Fig. 3.69. Tubular type air preheater.

An air preheater consists of plates or tubes with hot gases on one side and air on the other. It preheats the air to be supplied to the furnace. Preheated air accelerates the combustion and facilitates the burning of coal.

Degree of preheating depends on :

(*i*) Type of fuel,

(*ii*) Type of fuel burning equipment, and

(*iii*) Rating at which the boiler and furnace are operated.

There are *three* types of air preheaters :

1. Tubular type
2. Plate type
3. Storage type.

Fig. 3.69 shows a *tubular type air preheater*. After leaving the boiler or economiser the gaseous products of combustion travel through the inside of the tubes of air preheater in a direction opposite to that of air travel and transfer some of their heat to the air to be supplied to the furnace. Thus the air gets initially heated before being supplied to the furnace. The gases reverse their direction near the bottom of the air heater, and a soot hopper is fitted to the bottom of air heater casing to collect soot.

In the *plate type air preheater* the air absorbs heat from the hot gases being swept through the heater at high velocity on the opposite side of a plate.

Fig. 3.70 shows a self explanatory sketch of a *storage type air preheater* (heat exchanger).

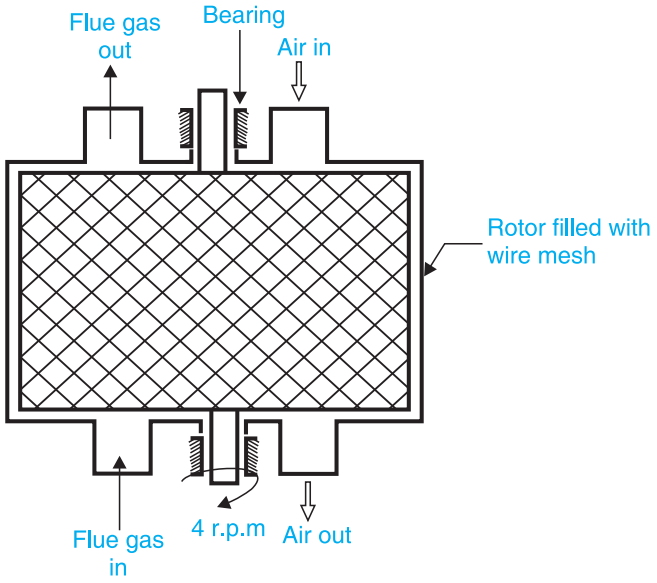


Fig. 3.70. Storage type air preheater.

Finally the gases escape to the atmosphere through the stack (chimney). The temperature of the gases leaving the stack should be kept as low as possible so that there is minimum loss of heat to the stack.

3.15.5. Superheater

The function of a superheater is to increase the temperature of the steam above its saturation point. The superheater is very important accessory of a boiler and can be used both on fire-tube and water-tube boilers. The small boilers are not commonly provided with a superheater.

Superheated steam has the following *advantages* :

(*i*) Steam consumption of the engine or turbine is reduced.

(*ii*) Losses due to condensation in the cylinders and the steam pipes are reduced.

(*iii*) Erosion of turbine blade is eliminated.

(*iv*) Efficiency of the steam plant is increased.

Superheaters are located in the path of the furnace gases so that heat is recovered by the superheater from the hot gases.

There are two types of superheaters :

1. Convective superheater
2. Radiant superheater.

Convective superheater makes use of heat in flue gases whereas a *radiant superheater* is placed in the furnace and wall tubes receives heat from the burning fuel through radiant process. The *radiant type of superheater is generally used where a high amount of superheat temperature is required.*

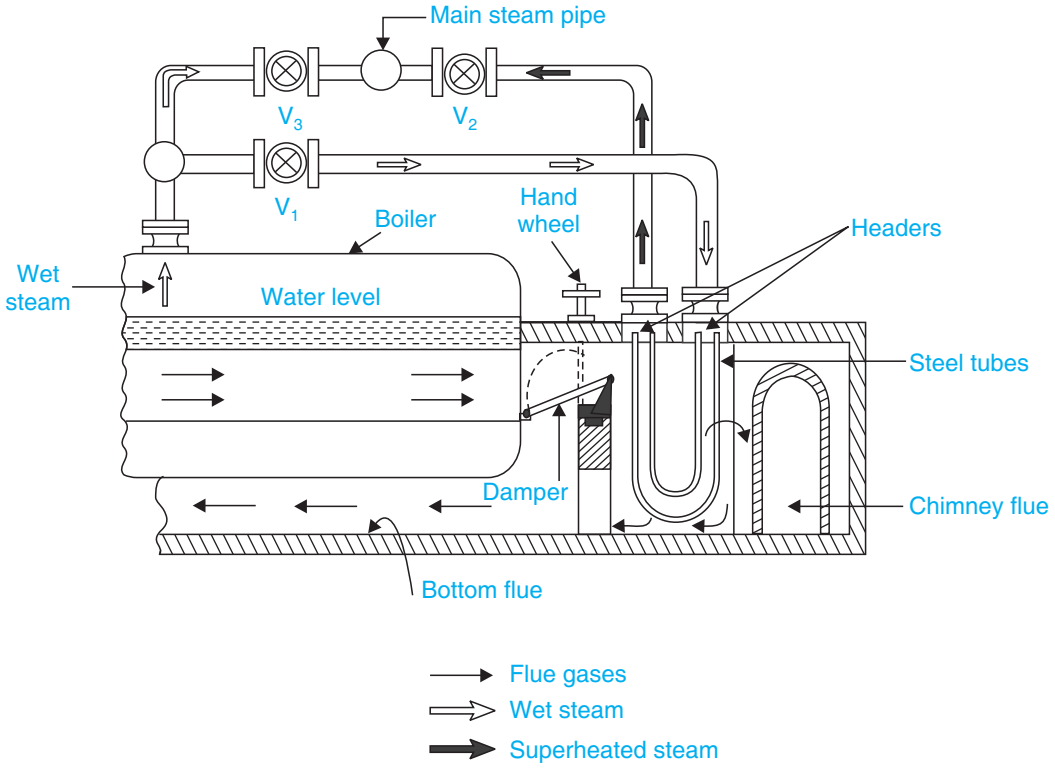


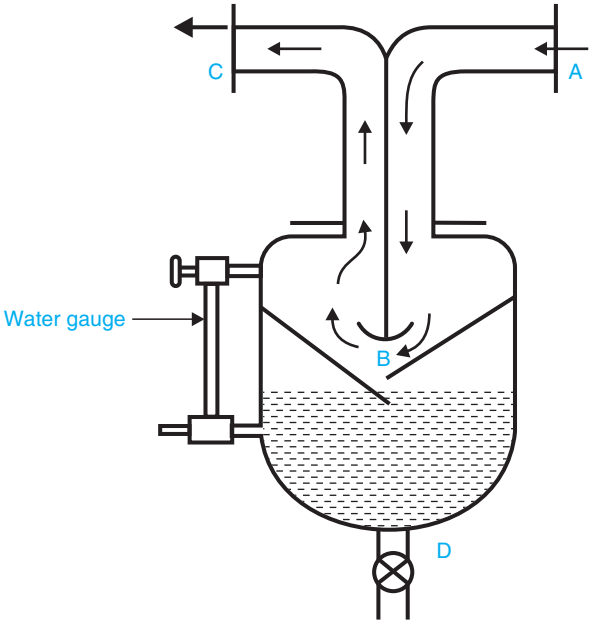
Fig. 3.71. Sugden's superheater.

Fig. 3.71 shows Sugden's superheater installed in a Lancashire boiler. It consists of two steel headers to which are attached solid drawn 'U' tubes of steel. These tubes are arranged in groups of four and one pair of the headers generally carries ten of these groups or total of forty tubes. The steam from the boiler enters and leaves the headers as shown by the arrows. Fig. 3.71 also shows how the steam pipes may be arranged so as to pass the steam through the superheater or direct to the main steam pipe. When the steam is taken from the boiler direct to the main steam pipe, the valves V_1 and V_2 are closed and V_3 is opened ; when the steam is passed through the superheater *i.e.,* when the superheater is in action the valve V_3 is closed the valve V_1 and V_2 are opened.

The path of the gases is controlled by the damper which is operated by the hand wheel.

3.15.6. Steam Separator

The steam available from a boiler may be either wet, dry ; or superheated ; but in many cases there will be loss of heat from it during its passage through the steam pipe from the boiler to the engine tending to produce wetness. The use of wet steam in an engine or turbine is uneconomical besides involving some risk ; hence it is usual to endeavour to separate any water that may be present from the steam before the latter enters the engine. This is accomplished by the use of a steam separator. Thus *the function of a steam separator is to remove the entrained water particles from the steam conveyed to the steam engine or turbine.* It is installed as close to the steam engine as possible on the main steam pipe from the boiler.



A, *C* = Flanges *D* = Drain pipe
B = Baffles

Fig. 3.72. Baffle plate steam separator.

According to the *principle of operation* the steam separators are *classified* as follows :

1. Impact or baffle type
2. Reverse current type
3. Centrifugal type.

Fig. 3.72 shows *baffle plate steam separator.* The steam enters the flange *A* and flows down. In its passage it strikes the baffles *B* ; as a result it gets deflected, but water particles having greater density and greater inertia fall to the bottom of the separator. The drier steam discharges through the flange *C*. To see the level of water collected a water gauge is provided. The water collected in the vessel is removed at intervals through the drain pipe *D*.

3.16. FEED WATER HEATERS AND EVAPORATORS

The main condensate in most of the power plants returns to the steam generator as feed water. Some make-up water may be added to replace losses in the cycle. In a few plants the boiler feed water may be 100 per cent make-up, in this case the plant turbines exhaust at back pressures above atmospheric to supply steam for other purposes. Feed water is heated by bleeding steam to heaters as in a regenerative cycle from the main turbine, or by using exhaust steam from auxiliary-drive turbines, or by by-product steam from processes. *Feed water heating with steam at a lower pressure than boiler pressure usually raises overall plant efficiency.*

3.16.1. Feed Water Heaters

The feed water heaters may be classified as follows :

1. Open or contact heaters

(*i*) Tray type (*ii*) Jet type.

2. Closed or surface heaters

Heated feed water enables steam generators to produce more kg of steam and avoids severe thermal stressing by cold water entering a hot drum. Preheating feed water also causes scale-forming dissolved salts to precipitate outside the boiler and removes dissolved O_2 and CO_2, which corrode boiler material.

3.16.1.1. Open heaters

(i) Tray type open heater. The construction of an open heater employs a shell of rolled steel plates riveted or welded along a longitudinal seam. Dished steel ends are joined to the shell at two ends through riveting or welding. In the *tray type heater* (Fig. 3.73), the upper half of the shell contains two tray sections and the spray distributor, while the lower half is mostly empty and serves as a storage for heated water. Above the shell is placed a vent condenser. Feed water after passing through the vent condenser flows into the spray distributor from where it cascades over the

staggard trays. Exhaust steam from auxiliaries or low pressure steam from a suitable point in the turbine is passed into the heater, entering opposite the tray sections and flowing upward counter to the direction of water, through the heating section. The flow of two liquids through the heater, thus, results in thorough mixing up so that heat of steam is transferred to water, the steam itself also being condensed. O_2, CO_2 and NH_3 are also removed by this type of heater.

In addition to the heating of feed water, the *contact type heater* is often constructed for *deaerating action*. The only difference between the simple heater and a deaerating open heater is *in the addition of a section of air removing trays* below the heating trays. After the water has been heated in the heating section, it is made to pass over the air separating trays which provide a complete separation of air and water. Water then flows down while air and non-condensable gases together with water vapour pass to the top of the shell and from there to the vent condenser. The vent condenser is a small surface condenser of U-type. The vapour content is condensed here and drained to the air separating section while air and gases are vented to the atmosphere. *The interior of the shell of deaerating heat, as also the trays, is made of corrosion resistant material such as stainless steel.*

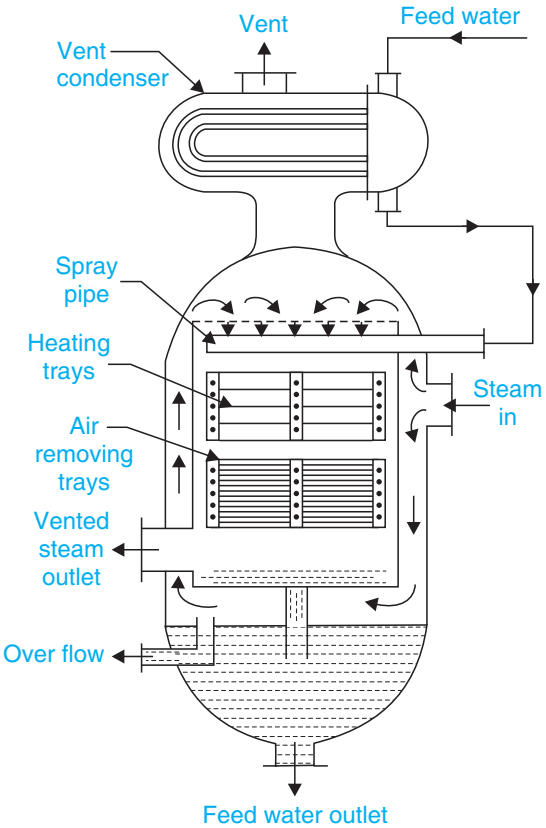


Fig. 3.73. Tray type open heater.

(ii) Jet type open heaters. In this type of deaerating contact heater spring loaded spray valves atomise the feed water coming from the vent condenser and spray it upwards against a baffle. The low pressure steam enters a conical steam jacket fitted in the upper part of the shell, and is alowed to expand in the same direction as the water spray, mixes with water, and the mixture falls down to the lower part of the shell which serves as a storage. The non-condensing gases travel upwards as in the tray type heater and are passed on to the vent condenser. *It is mainly used in marine where tray type of heaters do not work well due to the pitching and rolling of the vessel. They can handle water containing scaling impurities and are lighter in weight. These heaters do not work well at low pressures, specially at sub-atmospheric pressure.*

3.16.1.2. Closed or Surface feed heaters

These heaters usually have shell and tube construction and may be made *horizontal* and *vertical*. The construction of a closed heater and a surface condenser are identical *except that the heater is designed for higher temperatures and pressures and has greater strength than the condenser*.

Fig. 3.74 shows a *closed feed water heater*. It consists of a shell (made of a steel plate of suitable thickness) which has a welded longitudinal seam. To each end of the shell is welded a steel flange for fitting the covers, and on the top and bottom connections are provided for inlet of steam and exit of condensate. A baffle plate is provided below the steam inlet to spread the steam evenly over the tubes. The water tubes (16 to 25 mm diameter) of admiralty brass or other suitable material, are stretched between two end sheets of Muntz metal or soft steel, one of these being fixed and the other '*floating*' to take up expansion strain in tubes. The floating tube sheet is covered with a head cover bolted on to it and prevents the leakage of water into space.

The heater may have single pass or the water box may be divided to give two-pass design. A pair of air pockets provided at the bottom of the shell permits the withdrawal of air.

The flow of steam and water through the heater is usually counter to each other. Low pressure heaters may use steam under vacuum and high-pressure heaters at pressures above 40 bar. Steam and water need not be at the same pressure, and one pump may push water through several heaters in series. Water pressure may be as high as 250 bar.

For good performance heaters must be *drained* and *vented*.

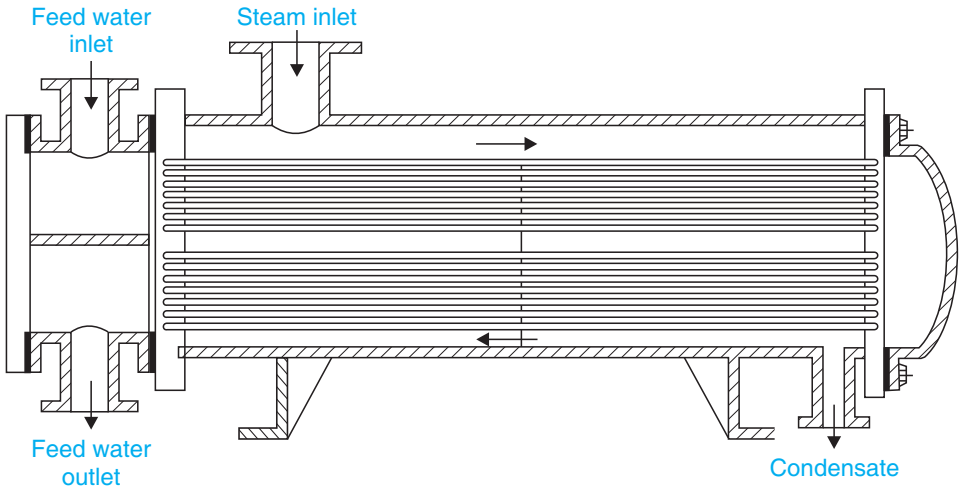


Fig. 3.74. Closed feed water heater.

3.16.2. Miscellaneous Heaters

Water may also be heated by "*waste heat*" in a variety of heater arrangements, some of which are as listed below :

1. The blow off heat exchanger.
2. The turbine tube oil cooler.
3. Generator air and hydrogen coolers.
4. The steam-jet air-ejector condenser.
5. The deaerating vent condenser.
6. The evaporator condenser.
7. The drain cooler.

3.16.3. Evaporators

These are used to give a supply of pure water as make-up feed for the boilers. Raw water is evaporated by using extracted steam and then condensed to give distilled and pure feed water.

Two main classes of evaporators are :

1. The film type evaporators. In this type water is sprayed on the surface of tubes through which steam is passed. As the water falls on the surface of heated tubes it evaporates.

2. The submerged type evaporators. In this case the bundle of tubes is submerged in water. Vapours formed in the shell pass out of the shell through a moisture separator and enter a feed water condenser or water heater where these condense and mix with feed water.

In practice, two or more evaporators may be connected in parallel or in series.

The raw water used causes sludge and scale formation in the evaporator drum and on the surface of the tubes. Regular blow-downs keep the sludge concentration low. Scales from the outer surface of tubes are removed by cracking them with sprays of cold water, steam flow inside the tubes being continued.

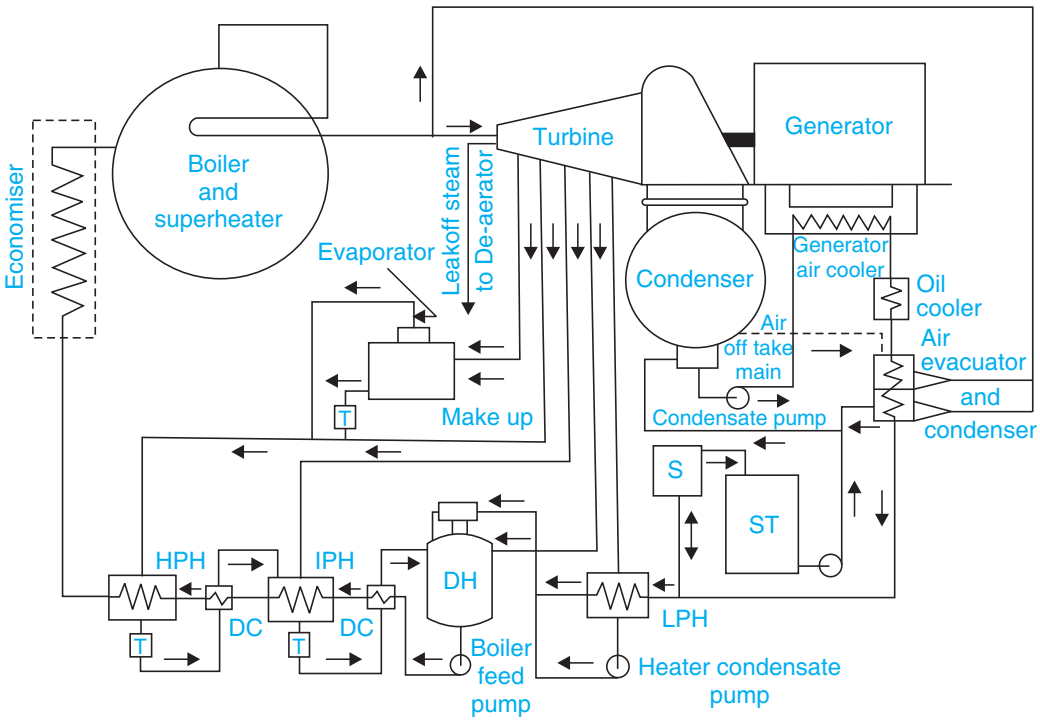
3.16.4. Typical Utility Cycle Layout

Fig. 3.75 shows a typical utility cycle layout with four feed water heater, an evaporator, and miscellaneous heat exchangers.

Industrial plant layouts vary widely depending on the following :

(*i*) The product of the manufacturing plant.

(*ii*) Need for electric power and steam at various pressures.



HPH = High pressure heater
IPH = Intermediate pressure heater
LPH = Low pressure heater
DH = De-aerating heater
DC = Drain cooler
T = Trap
S = Surge tank
ST = Storage tank

Fig. 3.75. Schematic layout of a central station to illustrate general relationship of equipment used in feed heating cycle.

3.17. PERFORMANCE OF BOILERS

3.17.1. Evaporative Capacity

The evaporative capacity of a boiler may be expressed in terms of :

(*i*) kg of steam/h
(*ii*) kg of steam/h/m^2 of heating surface
(*iii*) kg of steam/kg of fuel fired.

3.17.2. Equivalent Evaporation

Generally the output or evaporative capacity of the boiler is given as kg of water evaporated per hour but as different boilers generate steam at different pressures and temperatures (from feed water at different temperatures) and as such have different amounts of heat ; the number of kg of water evaporated per hour in no way provides the exact means for comparison of the performance of the boilers. Hence to compare the evaporative capacity or performance of different boilers working under different conditions it becomes imperative to provide a common base so that water be supposed to be evaporated under standard conditions. The *standard conditions* adopted are : *Temperature of feed water 100°C and converted into dry and saturated steam at 100°C*. As per these standard conditions 1 kg of water at 100°C necessitates 2257 kJ (539 kcal in MKS units) to get converted to steam at 100°C.

Thus the ***equivalent evaporation*** *may be defined as the amount of water evaporated from water at 100°C to dry and saturated steam at 100°C.*

Consider a boiler generating m_a kg of steam per hour at a pressure p and temperature T.

Let, h = Enthalpy of steam per kg under the generating conditions, and

$h = h_f + h_{fg}$ ..... dry saturated steam at pressure p
$h = h_f + x h_{fg}$ ..... wet steam with dryness fraction x at pressure p
$h = h_f + h_{fg} + c_p\,(T_{sup} - T_s)$ ..... superheated steam at pressure p and temperature T_{sup}

h_{f_1} = Specific enthalpy of water at a given feed temperature.

Then heat gained by the steam from the boiler per unit time

$$= m_a\,(h - h_{f_1})$$

The equivalent evaporation (m_e) from the definition is obtained as :

$$m_e = \frac{m_a\,(h - h_{f_1})}{h_{fg}} = \frac{m_a\,(h - h_{f_1})}{2257} \qquad ...(3.19)$$

The evaporation rate of the boiler is also sometimes given in terms of *kg of steam / kg of fuel*.

The presently accepted standard of expressing the capacity of a boiler is in terms of the total heat added per hour.

3.17.3. Factor of Evaporation

It is defined as *the ratio of heat received by 1 kg of water under working conditions to that received by 1 kg of water evaporated from and at 100°C*. It is denoted by F_e.

∴ Factor of evaporation,

$$F_e = \frac{h - h_{f_1}}{2257} \qquad ...[3.19(a)]$$

3.17.4. Boiler Efficiency

'Boiler efficiency' *is the ratio of heat actually utilised in generation of steam to the heat supplied by the fuel in the same period.*

i.e., Boiler efficiency $= \dfrac{m_a\,(h - h_{f_1})}{C}$ ...(3.20)

where, m_a = Mass of water actually evaporated into steam per kg of fuel at the working pressure, and

C = Calorific value of the fuel in kJ/kg.

If the boiler, economiser, and superheater are considered as a single unit, then the *boiler efficiency is termed as overall efficiency of the boiler plant.*

The following are the *factors* on which the boiler efficiency depends :

1. Fixed factors 2. Variable factors.

1. Fixed factors. These are :

(i) Boiler design. It includes the arrangement and effectiveness of the heating surfaces, the shape and volume of the furnace, the arrangement of flues, the arrangement of steam and water circulation.

(ii) Heat recovery equipment. It includes the economiser, superheater, air preheater and feed water heater.

(iii) Built in losses. It includes the heat transfer properties of the settings and construction materials, flue gas and ash heat losses.

(iv) Rated rate of firing, the furnace volume and heating surface.

(v) Properties and characteristics of fuel burnt.

2. Variable factors. These are :

(*i*) Actual firing rate.

(*ii*) Fuel condition as it is fired.

(*iii*) The condition of heat absorbing surfaces.

(*iv*) Excess air fluctuations.

(*v*) Incomplete combustion and combustibles in the refuse.

(*vi*) Change in draught from the rated, due to atmospheric conditions.

(*vii*) Humidity and temperature of the combustion air.

3.17.5. Heat Losses in a Boiler Plant

The following heat losses occur in a boiler plant :

1. Heat lost to flue gases.
2. Heat lost due to incomplete combustion.
3. Heat lost due to unburnt fuel.
4. Convection and radiation losses.

1. Heat lost to flue gases. The flue gases contain dry products of combustion as well as the steam generated due to combustion of hydrogen in the fuel.

Heat lost through *dry flue gases*, Q_g :

$$Q_g = m_g\,c_{pg}\,(T_g - T_a) \qquad ...(3.21)$$

where, m_g = Mass of gases formed per kg of coal,

c_{pg} = Specific heat of gases,

T_g = Temperature of the gases, and

T_a = Temperature of air entering the combustion chamber of boiler.

Heat carried away by the steam in flue gases, Q_s :

$$Q_s = m_{s_1}\,(h_{s_1} - h_{f_1}) \qquad ...(3.22)$$

where, m_{s_1} = Mass of steam formed per kg of fuel due to the combustion of H_2 in the flue,

h_{f_1} = Enthalpy of water at boiler house temperature, and

h_{s_1} = Enthalpy of steam at the gas temperature and at a partial pressure of steam vapour in the gas.

This heat lost to flue gases can be reduced by passing the flue gases through the economiser and air preheater.

2. Heat lost due to incomplete combustion. The combustion is said to be incomplete if the carbon burns to CO instead of CO_2. One kg of carbon releases 10120 kJ of heat if it burns to CO, whereas, it can release 33800 kJ/kg if it burns to CO_2.

∴ Heat loss due to incomplete combustion of 1 kg of carbon = 33800 – 10120 = 23680 kJ.

If CO is present in the flue gases it indicates that combustion of fuel is incomplete. If the percentages of CO and CO_2 in flue gases by volume are known, then carbon burnt to CO instead of CO_2 per kg of fuel is given by

$$\text{Mass of carbon burnt to CO} = \frac{\text{CO} \times \text{C}}{\text{CO}_2 + \text{CO}} \quad ...(3.23)$$

where, CO and CO_2 are expressed as % by volume in flue gases and C as the fraction of carbon in one kg of fuel.

$\therefore$ Heat lost due to incomplete combustion of carbon per kg of fuel

$$= \frac{\text{CO} \times \text{C}}{\text{CO}_2 + \text{CO}} \times 23680 \text{ kJ/kg of fuel.}$$

This loss (due to incomplete combustion) can be reduced by supplying excess quantity of air and giving a turbulent motion to the air before it enters the furnace in order to help the mixing process.

3. Heat lost due to unburnt fuel. If m_{f_1} is the mass of unburnt fuel per kg of fuel used and C is the calorific value of the fuel, then heat lost due to unburnt fuel,

$$Q = m_{f_1} \times \text{C} \quad ...(3.24)$$

In case of solid fuels this loss cannot be completely avoided.

4. Convection and radiation losses. As the hot surfaces of the boiler are exposed to the atmosphere, therefore, heat is lost to atmosphere by convection and radiation.

The loss of heat due to convection and radiation losses

= Heat released per kg of fuel – total of the heat losses given by eqns. (3.21), (3.22), (3.23) and (3.24).

These losses can be reduced by providing heat insulation on the boiler surface.

Table 3.1 is a resume of the more common causes of thermal losses associated with steam generators.

Table 3.1 Causes of Heat Loss in Steam Generators

1. Loss due to moisture in coal :

(*i*) Excessive wetting down of coal before firing.

(*ii*) High moisture absorption by coal in yard storage.

2. Loss due to moisture formed by combustion of hydrogen :

Irreducible for any specific fuel. This loss is larger for oil and gas fuels than for coal.

3. Loss due to heat carried away in dry chimney gas :

(*i*) High excess air as revealed in low CO_2 content of flue gas.

(*ii*) High flue gas temperature.

1. Dirty heating surfaces.
2. Poor water circulation. Scale on water side.
3. Dead gas pockets. Leaky or ineffective baffles.
4. Gas velocity too high.

4. Loss due to incomplete combustion :

(*i*) Insufficient air supply.

(*ii*) Fuel bed in poor condition.

(*iii*) Undercooling of furnace at low ratings.

(*iv*) Improper setting of boilers.

5. Loss due to combustible in ashpit :

(*i*) Grate or stoker not proportioned to the kind of fuel used.

(*ii*) Too high rate of combustion attempted.

(*iii*) Grates dumped or fuel bed sliced too frequently.

(*iv*) Furnace temperature is above fusion temperature of ash.

6. Loss from radiation and convection from boiler and setting :

(*i*) Boiler drums uninsulated.

(*ii*) Wall of setting too thin or of poor quality.

(*iii*) Furnace refractories in need of repair or renewal.

7. Loss due to moisture in the air :

(*i*) Moisture-laden air as from steam jet.

(*ii*) High excess air on days of high humidity. This loss is small and frequently included with several other small losses, usually unaccounted for, such as soot or cinder in the chimney gas, heat in ashes, etc.

Example 3.5. *The steam used by the turbine is 5.4 kg/kWh at a pressure of 50 bar and a temperature of 350°C. The efficiency of boiler is 82 per cent with feed water at 150°C.*

(*i*) *How many kg of 28100 kJ coal are required/kWh?*

(*ii*) *If the cost of coal/tonne is ₹ 500, what is fuel cost/kWh?*

Solution. Mass of steam used, m_s = 5.4 kg/kWh

Pressure of steam, p = 50 bar

Temperature of steam, t_{sup} = 350°C

Boiler efficiency = 82%

Feed water temperature = 150°C

Calorific value of coal, C = 28100 kJ

Cost of coal/tonne = ₹ 500.

(*i*) Boiler efficiency is given by,

$$\eta_{\text{boiler}} = \frac{m_s (h - h_{f_1})}{m_f \times C} \quad ...(i)$$

where, m_f is the mass of fuel used, kg/kWh.

At 45 bar and 350°C. From steam tables,

$$h_{sup} = 3068.4 \text{ kJ/kg}$$

$$h_{f_1} \text{ (at 150°C)} = 1 \times 4.18 \times (150 - 0)$$

$$= 627 \text{ kJ/kg}$$

Putting these values in eqn. (*i*), we get :

$$0.82 = \frac{5.4\,(3068.4 - 627)}{m_f \times 28100}$$

$$\therefore \quad m_f = \frac{5.4\,(3068.4 - 627)}{0.82 \times 28100}$$

$$= \mathbf{0.572 \text{ kg/kWh.}} \quad \textbf{(Ans.)}$$

(*ii*) The cost of fuel (coal)/kWh = m_f in tonnes/kWh × cost/tonne

$$= \frac{0.572}{1000} \times 500 \times 100$$

$$= \mathbf{28.6 \text{ paise/kWh.}} \quad \textbf{(Ans.)}$$

Example 3.6. *The following data refer to a boiler plant consisting of an economiser, a boiler and a superheater :*

Mass of water evaporated per hour = 5940 kg, mass of coal burnt per hour = 675 kg, L.C.V. of coal = 31600 kJ/kg, pressure of steam at boiler stop valve = 14 bar, temperature of feed water entering the economiser = 32°C, temperature of feed water leaving the economiser = 115°C, dryness fraction of steam leaving the boiler and entering superheater is 0.96, temperature of steam leaving the superheater = 260°C, specific heat of superheater steam = 2.3. Determine :

(*i*) *Percentage of heat in coal utilized in economiser, boiler and superheater.*

(*ii*) *Overall efficiency of boiler plant.*

Solution. Mass of water evaporated

= 5940 kg/h

Mass of coal burnt = 675 kg/h

Lower calorific value of coal

= 31600 kJ/kg

Pressure of steam at boiler stop valve,

$$p_1 = 14 \text{ bar}$$

Temperature of feed water entering the economiser,

$$t_{e_1} = 32°C$$

Temperature of feed water leaving the economiser,

$$t_{e_2} = 115°C$$

Dryness fraction of steam entering superheater

= 0.96

Temperature of steam leaving the superheater,

$$t_{sup} = 260°C$$

Specific heat of superheated steam,

$$c_{ps} = 2.3 \text{ kJ/kg K}$$

Heat utilized by 1 kg of feed water in *economiser* :

$$h_{f_1} = 1 \times 4.18 \times (t_{e_2} - t_{e_1})$$

$$= 1 \times 4.18 \times (115 - 32) = 346.9 \text{ kJ/kg}$$

Heat utilized in *boiler* per kg of feed water :

$$h_{\text{boiler}} = (h_f + x h_{fg}) - h_{f_1}$$

At 14 bar pressure : From steam tables,

$$t_s = 195°C,\ h_f = 830.1 \text{ kJ/kg},$$

$$h_{fg} = 1957.7 \text{ kJ/kg}$$

$$\therefore \quad h_{\text{boiler}} = (830.1 + 0.96 \times 1957.7) - 346.9$$

$$= 2362.6 \text{ kJ/kg}$$

Heat utilized in *superheater* by 1 kg of feed water :

$$h_{\text{superheater}} = (1 - x)\, h_{fg} + c_{ps}\,(T_{sup} - T_s)$$

$$= (1 - 0.96) \times 1957.7 + 2.3\,(260 - 195)$$

$$= 78.3 + 149.5 = 227.8 \text{ kJ/kg.}$$

Also, mass of water evaporated/hour/kg of coal burnt

$$= \frac{5940}{675} = 8.8 \text{ kg.}$$

(*i*) Percentage of heat utilized in economiser

$$= \frac{346.9}{31600} \times 8.8 \times 100 = \mathbf{9.66\%.} \quad \textbf{(Ans.)}$$

Percentage of heat utilized in boiler

$$= \frac{2362.6}{31600} \times 8.8 \times 100 = \mathbf{65.7\%.} \quad \textbf{(Ans.)}$$

Percentage of heat utilized in superheater

$$= \frac{227.8}{31600} \times 8.8 \times 100 = \mathbf{6.34\%.} \quad \textbf{(Ans.)}$$

(*ii*) Overall efficiency of boiler plant, η_{overall} :

Total heat absorbed in kg of water

$$= h_{f_1} + h_{\text{boiler}} + h_{\text{superheater}}$$

$$= 346.9 + 2362.6 + 227.8 = 2937.3 \text{ kJ/kg}$$

Overall efficiency

$$\eta_{\text{overall}} = \frac{8.8 \times 2937.3}{31600}$$

$$= \mathbf{0.8179 \text{ or } 81.79\%.} \quad \textbf{(Ans.)}$$

Example 3.7. *A boiler produces 200 kg of dry and saturated steam per hour at 10 bar and feed water is heated by an economiser to a temperature of 110°C. 225 kg of coal of a calorific value of 30100 kJ/kg are fired per hour. If 10% of coal remains unburnt, find the thermal efficiency of the boiler and boiler and grate combined.*

Solution. Rate of production of steam

= 2000 kg/h

Quality of steam, $x = 1$
Steam pressure, $p = 10$ bar
Feed water temperature rise
$= 110°C$
Rate of coal firing $= 225$ kg/h
Calorific value of coal $= 30100$ kJ/kg
Percentage of coal unburnt
$= 10\%$

From steam tables, corresponding to 10 bar,

$$h = h_g = 2776.2 \text{ kJ/kg}$$

Heat contained in 1 kg of feed water before entering the boiler,

$$h_{f_1} = 1 \times 4.18 \times (110 - 0) = 459.8 \text{ kJ}$$

Total heat given to produce 1 kg of steam in boiler

$$= h - h_{f_1} = 2776.2 - 459.8 = 2316.4 \text{ kJ/kg}$$

Mass of coal actually burnt $= 225 \times \dfrac{90}{100} = 202.5$ kg

Mass of steam produced per kg of coal (actually burnt),

$$m_a = \frac{2000}{202.5} = 9.87 \text{ kg}$$

Thermal efficiency of the boiler

$$= \frac{m_a (h - h_{f_1})}{C} = \frac{9.87 (2776.2 - 459.8)}{30100}$$

$$= \mathbf{0.759 \text{ or } 75.9\%.} \quad \textbf{(Ans.)}$$

Thermal efficiency of boiler and grate combined

$$= \frac{\frac{2000}{225} (2776.2 - 459.8)}{30100}$$

$$= \mathbf{0.684 \text{ or } 68.4\%.} \quad \textbf{(Ans.)}$$

Example 3.8. *A boiler generates 7.5 kg of steam per kg of coal burnt at a pressure of 11 bar, from feed water having a temperature of 70°C. The efficiency of boiler is 75% and factor of evaporation 1.15, specific heat of steam at constant pressure is 2.3 kJ/kg K. Calculate :*

(i) Degree of superheat and temperature of steam generated.

(ii) Calorific value of coal in kJ/kg.

(iii) Equivalent evaporation in kg of steam per kg of coal.

Solution. Steam generated per kg of coal,

$m_a = 7.5$ kg
Steam pressure, $p = 11$ bar
Temperature of feed water $= 70°C$
Efficiency of boiler $= 75\%$
Factor of evaporation, $F_e = 1.15$
Specific heat of steam, $c_{ps} = 2.3$ kJ/kg K

At 11 bar : From steam tables,

$h_f = 781.1$ kJ/kg, $h_{fg} = 1998.5$ kJ/kg,
$t_s = 184.1°C$ ($T_s = 273 + 184.1 = 457.1$ K)

Factor of evaporation,

$$F_e = \frac{[\{h_f + h_{fg} + c_{ps} (T_{sup} - T_s)\} - h_{f_1}]}{2257}$$

$$1.15 = \frac{[781.1 + 1998.5 + 2.3 (T_{sup} - 457.1) - 1 \times 4.18 \times (70 - 0)]}{2257}$$

$$= \frac{2779.6 + 2.3 (T_{sup} - 457.1) - 292.6}{2257}$$

$$= \frac{2487 + 2.3 (T_{sup} - 457.1)}{2257}$$

$$\therefore \quad (T_{sup} - 457.1) = \frac{(1.15 \times 2257 - 2487)}{2.3} = 47.2$$

i.e., $T_{sup} = 504.3$ K.

(i) Degree of superheat

$= (T_{sup} - T_s) = 504.3 - 457.1$
$= \mathbf{47.2°C.}$ **(Ans.)**

(ii) Calorific value of coal, C :

$$\text{Boiler efficiency} = \frac{m_a (h - h_{f_1})}{C}$$

$$0.75 = \frac{m_a [\{h_f + h_{fg} + c_{ps} (T_{sup} - T_s)\} - h_{f_1}]}{C}$$

$$0.75 = \frac{7.5 [\{781.1 + 1998.5 + 2.3 (504.3 - 457.1)\} - 1 \times 4.18 \times (70 - 0)]}{C}$$

$$= \frac{7.5 (2888.16 - 292.6)}{C} = \frac{19466.7}{C}$$

$$\therefore \quad C = \frac{19466.7}{0.75} = 25955 \text{ kJ/kg}$$

i.e., *Calorific value of coal* = **25955 kJ/kg.** **(Ans.)**

(iii) Equivalent evaporation,

$$m_e = \frac{m_a (h - h_{f_1})}{2257} = \frac{7.5 (2888.16 - 292.6)}{2257}$$

$$= \mathbf{8.625 \text{ kg.}} \quad \textbf{(Ans.)}$$

Example 3.9. *During the trial of water-tube boiler the following data were obtained :*

Steam pressure, $p = 13$ *bar*
Degree of superheat $= 77°C$

Temperature of feed water = *85°C*
Water evaporated = *3000 kg per hour*
Coal fired = *410 kg per hour*
Ash = *40 kg per hour*
Percentage of combustible in ash = *9.6%*
Moisture in coal = *4.5%*
Calorific value of dry coal / kg = *30500 kJ / kg.*

Determine : (i) The efficiency of the boiler plant including superheater.

(ii) The efficiency of the boiler and furnace combined.

Take specific heat of superheated steam = 2.1 kJ / kg K.

Solution. ***At 13 bar :*** From steam tables,

$t_s = 191.6°C$, $h_f = 814.7$ kJ/kg,

$h_{fg} = 1970.7$ kJ/kg

$h = h_{sup} = h_f + h_{fg} + c_{ps}\,(T_{sup} - T_s)$

$= 814.7 + 1970.7 + 2.1 \times 77 = 2947.1$ kJ/kg

Also, $h_{f_1} = 1 \times 4.18 \times (85 - 0) = 355.3$ kJ/kg

$\therefore$ Total heat supplied to produce 1 kg of steam

$= h_{sup} - h_{f_1} = 2947.1 - 355.3$

$= 2591.8$ kJ/kg.

(i) Efficiency of boiler plant including superheater

$$= \frac{m_a\,(h_{sup} - h_{f_1})}{C}$$

$$\left[\text{Dry coal} = 410 - 410 \times \frac{4.5}{100} = 391.55 \text{ kg}\right]$$

$$= \frac{\frac{3000}{391.55}(2947.1 - 355.3)}{30500}$$

$$= \mathbf{0.651 \text{ or } 65.1\%.} \quad \textbf{(Ans.)}$$

Combustible in ash per hour $= 40 \times \frac{9.6}{100} = 3.84$ kg.

The combustible present in ash is practically carbon and its value may be taken as 33860 kJ/kg.

Heat actually supplied per hour

= Heat of dry coal – heat of combustible in the ash

$= 391.55 \times 30500 - 3.84 \times 33860$

$= 11812253$ kJ

Heat usefully utilised in the boiler per hour

$= 3000(h_{sup} - h_{f_1}) = 3000\ (2947.1 - 355.3)$

$= 777400$ kJ.

(ii) Efficiency of the boiler and furnace combined

$$= \frac{\text{Heat usefully utilised in boiler per hour}}{\text{Heat actually supplied per hour}}$$

$$= \frac{7775400}{11812253} = \mathbf{0.658 \text{ or } 65.8\%.} \quad \textbf{(Ans.)}$$

3.18. STEAM NOZZLES

3.18.1. Introduction

*A **steam nozzle** may be defined as a passage of varying cross section, through which heat energy of steam is converted to kinetic energy.* Its major function is to produce steam jet with high velocity to drive steam turbines. A turbine nozzle performs *two functions* :

(*i*) It transforms a portion of energy of steam (obtained from steam generating unit) into kinetic energy.

(*ii*) In the impulse turbine it directs the steam jet of high velocity against blades, which are free to move in order to convert kinetic energy into shaft work. In reaction turbines the nozzles which are free to move, discharge high velocity steam. The reactive force of the steam against the nozzle produces motion and work is obtained.

The cross-section of a nozzle at first tapers to a smaller section (*to allow for changes which occur due to changes in velocity, specific volume and dryness fraction as the steam expands*) ; the smallest section being known as ***throat,*** and then it diverges to a large diameter. The nozzle which converges to throat and diverges afterwards is known as ***convergent-divergent*** nozzle (Fig. 3.76). In convergent nozzle there is no divergence after the throat as shown in Fig. 3.77.

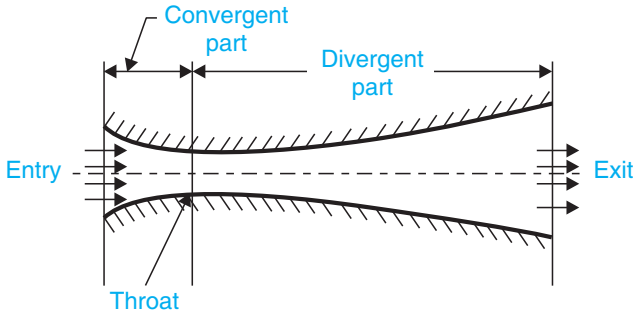


Fig. 3.76. Convergent-divergent nozzle.

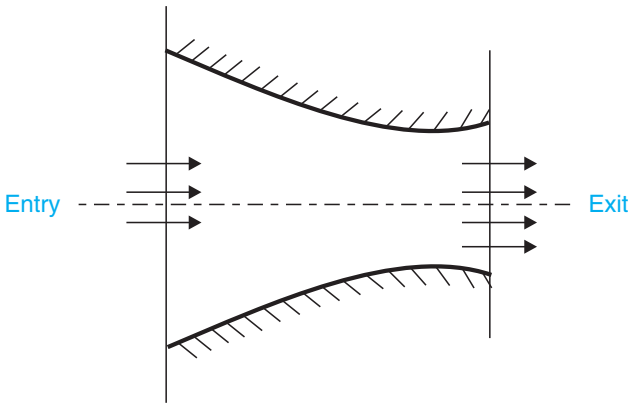


Fig. 3.77. Convergent nozzle.

In a convergent-divergent nozzle, because of the higher expansion ratio, addition of divergent portion produces steam at higher velocities as compared to a convergent nozzle.

3.18.2. Steam Flow Through Nozzles

The steam flow through the nozzle may be assumed as *adiabatic flow* since during the expansion of steam in nozzle neither any heat is supplied nor rejected, work, however, is per-formed by increasing the kinetic energy of the steam. As the steam passes through the nozzle it loses its pressure as well as the heat. *The work done is equal to the adiabatic heat drop which in turn is equal to Rankine area.*

3.18.2.1. Velocity of steam

Steam enters the nozzle with high pressure and low initial velocity (it is so small as compared to the final velocity that it is generally *neglected*) and leaves it with high velocity and low pressure. This is due to the reason that heat energy of steam is *converted* into kinetic energy as it (steam) passes through the nozzle. The final or outlet velocity of steam can be found as follows :

Let C = Velocity of steam at the section considered (m/sec),

h_1 = Enthalpy of steam entering the nozzle,

h_2 = Enthalpy of steam at section considered, and

h_d = Heat drop during expansion of steam is the nozzle = $(h_1 - h_2)$.

Consider 1 kg of steam and flow to be frictionless adiabatic.

Gain in kinetic energy = Adiabatic heat drop

$$\frac{C^2}{2} = h_d$$

$$\therefore \quad C = \sqrt{2 \times 1000\, h_d}\ , \text{ where } h_d \text{ is in kJ}$$

$$= 44.72\ \sqrt{h_d} \qquad ...(3.25)$$

In practice, there is loss due to friction in the nozzle and its value varies from 10 to 15 per cent of total heat drop. Due to this, total heat drop is minimized. Let heat drop after deducting friction loss be kh_d.

The velocity, $C = 44.72\ \sqrt{kh_d}$ ...(3.26)

3.18.3. Discharge through the Nozzle and Conditions for its Maximum Value

Let p_1 = Initial pressure of steam,

v_1 = Initial volume of 1 kg of steam at pressure p_1 (m^3),

p_2 = Steam pressure at the throat,

v_2 = Volume of 1 kg of steam at pressure p_2 (m^3),

A = Cross-sectional area of nozzle at throat (m^2), and

C = Velocity of steam (m/s).

The steam flowing through the nozzle follows approximately the equation given below :

pv^n = Constant

where, n = 1.135 for ***saturated steam***

and = 1.3 for ***superheated steam.***

[For **wet steam,** the value of n can be calculated by *Dr. Zenner's equation*,

$n = 1.035 + 0.1x$,

where x is the initial dryness fraction of steam]

Work done per kg of steam during the cycle (Rankine area)

$$= \frac{n}{n-1}\ (p_1v_1 - p_2v_2)$$

and, Gain in kinetic energy = Adiabatic heat drop

= Work done during Rakine cycle

or, $$\frac{C^2}{2} = \frac{n}{n-1}\ (p_1v_1 - p_2v_2)$$

$$= \frac{n}{n-1}\ p_1v_1\left(1 - \frac{p_2v_2}{p_1v_1}\right) \qquad ...(3.27)$$

Also, $p_1v_1^{\,n} = p_2v_2^{\,n}$ or $\frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{1/n}$ ...(3.28)

or, $$v_2 = v_1\left(\frac{p_1}{p_2}\right)^{1/n} \qquad ...(3.29)$$

Putting the value of v_2/v_1 from eqn. (3.28) in eqn. (3.27), we get :

$$\frac{C^2}{2} = \frac{n}{n-1}\ p_1v_1\left[1 - \frac{p_2}{p_1}\left(\frac{p_1}{p_2}\right)^{1/n}\right]$$

$$= \frac{n}{n-1}\ p_1v_1\left[1 - \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{n}}\right]$$

$$= \frac{n}{n-1} p_1 v_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$$

$$C^2 = 2\left(\frac{n}{n-1}\right) p_1 v_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$$

$$C = \sqrt{2\left(\frac{n}{n-1}\right) p_1 v_1 \left\{1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right\}} \quad ...(3.30)$$

If m is the mass of steam discharged in kg/s.

Then $$m = \frac{AC}{v_2} \quad ...(3.31)$$

Substituting the value of v_2 from eqn. (3.29) in eqn. (3.31),we get :

$$m = \frac{AC}{v_1\left(\frac{p_1}{p_2}\right)^{1/n}}$$

$$\text{or } m = \frac{A}{v_1\left(\frac{p_1}{p_2}\right)^{1/n}} \sqrt{2\left(\frac{n}{n-1}\right) p_1 v_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

$$= \frac{A}{v_1} \sqrt{\left[2\left(\frac{n}{n-1}\right) p_1 v_1 \left\{\left(\frac{p_2}{p_1}\right)^{2/n} - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \left(\frac{p_2}{p_1}\right)^{2/n}\right\}\right]}$$

$$= \frac{A}{v_1} \sqrt{\left[2\left(\frac{n}{n-1}\right) p_1 v_1 \left\{\left(\frac{p_2}{p_1}\right)^{2/n} - \left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}}\right\}\right]} \quad ...(3.32)$$

It is obvious from above equation that there is only one value of the ratio (called *critical ratio pressure*) p_2/p_1 which will produce the *maximum discharge*. This can be obtained by differentiating 'm' with respect to (p_2/p_1) and equating it to zero.

As other quantities except the ratio p_2/p_1 are constant

$$\therefore \quad \frac{d}{d\left(\frac{p_2}{p_1}\right)} \left[\left(\frac{p_2}{p_1}\right)^{2/n} - \left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}}\right] = 0$$

$$\text{or,} \quad \frac{2}{n}\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}-1} - \left(\frac{n+1}{n}\right)\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}-1} = 0$$

$$\text{or,} \quad \left(\frac{p_2}{p_1}\right)^{\frac{2}{n}-1} = \frac{n+1}{2}\left(\frac{p_2}{p_1}\right)^{1/n}$$

$$\text{or,} \quad \left(\frac{p_2}{p_1}\right)^{2-n} = \left(\frac{n+1}{2}\right)^n \left(\frac{p_2}{p_1}\right)$$

$$\text{or,} \quad \left(\frac{p_2}{p_1}\right)^{2-n-1} = \left(\frac{n+1}{2}\right)^n \quad \text{or} \quad \mathbf{\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}} \quad ...(3.33)$$

Hence the discharge through the nozzle will be the maximum when critical pressure ratio, *i.e.*,

$$\frac{\text{Throat pressure}}{\text{Inlet pressure}} = \frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

For saturated steam : $n = 1.135$

$$\frac{p_2}{p_1} = \left(\frac{2}{1.135+1}\right)^{\frac{1.135}{1.135-1}}$$

$$= \left(\frac{2}{2.135}\right)^{\frac{1.135}{0.135}} = 0.58$$

For superheated steam : $n = 1.3$

$$\frac{p_2}{p_1} = \left(\frac{2}{1.3+1}\right)^{\frac{1.3}{1.3-1}} = \left(\frac{2}{2.3}\right)^{\frac{1.3}{0.3}} = 0.546$$

Substituting the value of $\frac{p_2}{p_1}$ from eqn. (3.33) into eqn. (3.32), we get the *maximum discharge*, m_{max}

$$= \frac{A}{v_1} \sqrt{2\left(\frac{n}{n-1}\right) p_1 v_1 \left[\left\{\left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}\right\}^{\frac{2}{n}} \left\{\left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}\right\}^{\frac{n+1}{n}}\right]}$$

$$= \frac{A}{v_1} \sqrt{2\left(\frac{n}{n-1}\right) p_1 v_1 \left[\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}} - \left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\right]}$$

$$= A \sqrt{2\left(\frac{n}{n-1}\right) \frac{p_1}{v_1} \left[\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}} - \left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\right]}$$

$$= A\sqrt{2\left(\frac{n}{n-1}\right)\frac{p_1}{v_1}\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\left[\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}-\frac{n+1}{n-1}}-1\right]}$$

$$= A\sqrt{2\left(\frac{n}{n-1}\right)\left(\frac{p_1}{v_1}\right)\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\left[\left(\frac{2}{n+1}\right)^{\frac{1-n}{n-1}}-1\right]}$$

$$= A\sqrt{2\left(\frac{n}{n-1}\right)\left(\frac{p_1}{v_1}\right)\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\left[\left(\frac{2}{n+1}\right)^{-1}-1\right]}$$

$$= A\sqrt{2\left(\frac{n}{n-1}\right)\left(\frac{p_1}{v_1}\right)\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\left(\frac{n-1}{2}\right)}$$

i.e.,
$$m_{max} = A\sqrt{n\left(\frac{p_1}{v_1}\right)\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}} \qquad ...[3.33\,(a)]$$

From the above equation it is evident that *the maximum mass flow depends only on the initial condition of the steam (p_1, v_1) and the throat area* and is *independent of the final pressure of steam i.e.* at the exit of the nozzle. *The addition of the divergent part of the nozzle after the throat does not affect the discharge of steam passing through the nozzle but it only accelerates the steam leaving the nozzle.*

It may be noted that the discharge through nozzle increases as the pressure at the throat of the nozzle (p_2) decreases, when the supply pressure p_1 is constant. But once the nozzle pressure p_2 reaches the critical value [given by equation (3.33)], the discharge reaches a maximum and after that the throat pressure and mass flow remains constant irrespective of the pressure at the exit.

The velocity of steam at the throat of the nozzle when the discharge is maximum is obtained by substituting the value of $\frac{p_2}{p_1}$ from eqn. (3.33) into eqn. (3.30).

$$C_{max} = \sqrt{2\left(\frac{n}{n-1}\right)p_1v_1\left[1-\left\{\left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}\right\}^{\frac{n-1}{n}}\right]}$$

$$= \sqrt{2\left(\frac{n}{n-1}\right)p_1v_1\left(1-\frac{2}{n+1}\right)}$$

$$= \sqrt{2\left(\frac{n}{n-1}\right)p_1v_1\left(\frac{n-1}{n+1}\right)}$$

i.e.,
$$C_{max} = \sqrt{2\left(\frac{n}{n+1}\right)p_1v_1} \qquad ...(3.34)$$

The above equation indicates that the *velocity is also dependent on the initial conditions of the steam.*

3.18.4. Nozzle Efficiency

When the steam flows through a nozzle the final velocity of steam for a given pressure drop is *reduced* due to the following reasons :

(*i*) *The friction between the nozzle surface and steam ;*

(*ii*) *The internal friction of steam itself ; and*

(*iii*) *The shock losses.*

Most of these frictional losses occur between the throat and exit in convergent-divergent nozzle. These frictional losses entail the following *effects* :

(*i*) *The expansion is no more isentropic and enthalpy drop is reduced ;*

(*ii*) *The final dryness friction of steam is increased as the kinetic energy gets converted into heat due do friction and is absorbed by steam ;*

(*iii*) *The specific volume of steam is increased as the steam becomes more dry due to this frictional reheating.*

Fig. 3.78 represents on Mollier diagram the **effect of friction** on steam flow through a nozzle.

The point 1 represents the initial condition of steam which enters the nozzle in a dry saturated state. If the friction is neglected, the expansion of steam from entry to throat is represented by the vertical line 1-2 and that from the throat to the exit by 2-3. Now if the friction were taken into account the heat drop would have been somewhat less than 1-3. Let this heat drop be 1-3′. From 3′ draw a horizontal line which cuts the same pressure line on which point 3 lies, at the point 2′ which represents the final condition of steam. It may be noted that dryness fraction of steam is **more** at point 2′ than at point 3. Hence *the effect of friction is to improve the quality of steam.* The value of co-efficient '*k*' in the equation for the velocity of expanding steam is given by :

$$k = \frac{\text{Actual heat drop}}{\text{Isentropic heat drop}} = \frac{1-3'}{1-3} = \frac{h_1-h_3'}{h_1-h_3}.$$

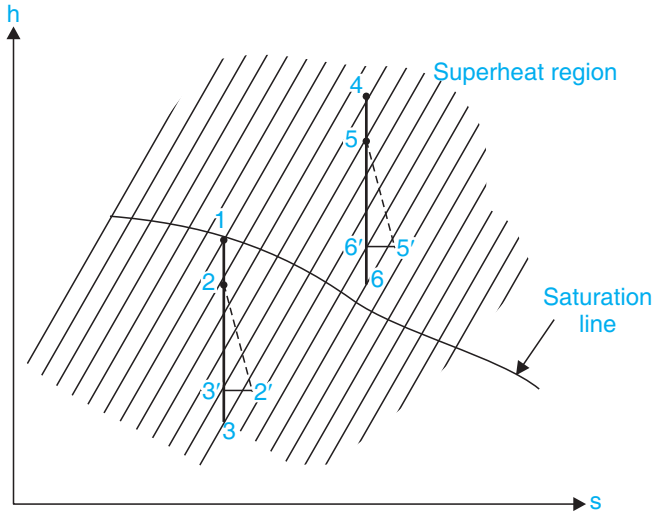


Fig. 3.78. Effect of friction on steam flow through a nozzle.

The actual expansion is represented by the curve 1-2-2′ since the *friction occurs mainly between the throat and exit*.

On the other hand, if the steam at entry to nozzle were superheated corresponding to the point 4, the expansion can be represented by the vertical line 4-6 if friction were neglected and by 4-5-5′ if the friction were taken into account. In this case, k = 4-6′/4-6 = $(h_4 - h_6')/(h_4 - h_6)$. The point 5′ represents the final condition of steam. It may be noted that *the friction tends to superheat steam*. Therefore, it can be concluded that *friction tends to decrease the velocity of steam and increase the final dryness fraction or superheat the steam*.

The *nozzle efficiency* is, therefore, defined *as the ratio of the actual enthalpy drop to the isentropy enthalpy drop between the same pressures*,

i.e., Nozzle efficiency = $\dfrac{h_1 - h_3'}{h_1 - h_3}$

or $\dfrac{h_4 - h_6'}{h_4 - h_6}$ as the case may be ...(3.35)

If the actual velocity at exit from the nozzle is C_2' and the velocity at exit when the flow is isentropic is C_3, then using the steady flow energy equation, in each case we have :

$$h_1 + \frac{C_1^2}{2} = h_3 + \frac{C_3^2}{2}$$

or, $$h_1 - h_3 = \frac{C_3^2 - C_1^2}{2}$$

and, $$h_1 + \frac{C_1^2}{2} = h_2' + \frac{C_2'^2}{2}$$

or $$h_1 - h_2' = \frac{C_2'^2 - C_1^2}{2}$$

$$\therefore \quad \text{Nozzle efficiency} = \frac{C_2'^2 - C_1^2}{C_3^2 - C_1^2} \qquad ...(3.36)$$

When the inlet velocity, C_1, is negligibly small than

$$\text{Nozzle efficiency} = \frac{C_2'^2}{C_3^2} \qquad ...(3.37)$$

Sometimes a *velocity co-efficient is defined as the ratio of the actual exit velocity to the exit velocity when the flow is isentropic between the same pressures,*

i.e., $$\text{Velocity co-efficient} = \frac{C_2'}{C_3} \qquad ...(3.38)$$

It can be seen from eqns. (3.37) and (3.38) that the velocity co-efficient is the square root of the nozzle efficiency, when the inlet velocity is assumed to be negligible.

3.18.5. Supersaturated or Metastable Expansion of Steam in a Nozzle

When steam flows through a nozzle, it would normally be expected that the discharge of steam through the nozzle would be slightly less than the theoretical value. But it has been observed during experiments on flow of wet steam that the *discharge is slightly greater than that calculated by the formula.* This phenomenon is explained as follows : The converging part of the nozzle is so short and the steam velocity so high that the molecules of steam have insufficient time to collect and form droplets so that normal condensation does not take place. Such rapid expansion is said to be *metastable* and produces a *supersaturated state*. In this state of supersaturation the steam is undercooled to a temperature less than that corresponding to its pressure ; consequently the density of steam increases and hence the weight of discharge. Prof. Wilson through experiments showed that dry saturated steam, when suddenly expanded *in the absence of dust, does not condense until it density is about 8 times that of the saturated vapour of the same pressure*. This effect is discussed below :

Refer to Fig. 3.79. The point 1 represents initial state of the steam. The steam expands isentropically without any condensation to point 2, 2 being on the superheat constant pressure curve *AB* produced. At point 2 the limit of supersaturation is reached and steam reverts to its normal condition at 3 at the same enthalpy value as 2, and at the same pressure. The steam continues expanding isentropically to a lower pressure to point 4 instead of 4′ which would have been reached if thermal equilibrium had

been maintained. Consequently, enthalpy drop is reduced and the condition of the final steam is improved. *The limiting condition of under-cooling at which condensation commences and is assumed to restore conditions of normal thermal equilibrium is called the "Wilson Line".*

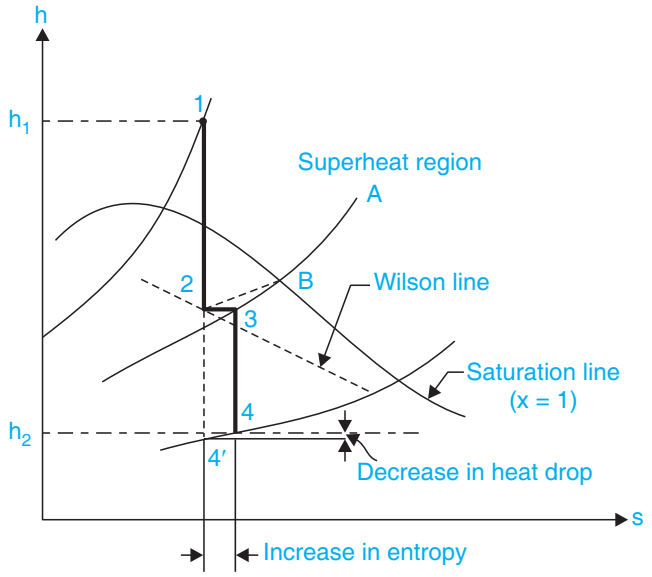


Fig. 3.79. Supersaturated flow of steam.

It may be noted that when metastable conditions prevail the h-s chart / diagram should not be used and the expansion must be considered to follow the law $pv^{1.3} = C$, *i.e., with the index of expansion for superheated steam.* Thus,

$$\text{Enthalpy drop} = \frac{n}{(n-1)} = p_1 v_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$$

The relationship, $T_2/T_1 = (p_2/p_1)^{\frac{n-1}{n}}$ may be used to calculate *supercooled temperature.* The *'degree of undercooling' is then the difference between the saturation temperature and the supercooled temperature.*

Effects of supersaturation. In a nozzle in which supersaturation occurs the effects may be summarised as follows :

(*i*) There is an increase in the entropy and specific volume of steam.

(*ii*) The heat drop is reduced below that for thermal equilibrium as a consequence the exit velocity of steam is reduced.

(*iii*) Since the condensation does not take place during supersaturated expansion, so the temperature at which the supersaturation occurs will be *less* than the saturation temperature corresponding to the pressure. Therefore, the density of supersaturated steam will be more than that for the equilibrium conditions which gives the increase in the mass of steam discharged.

(*iv*) The dryness fraction of steam is improved.

The problems on supersaturated flow cannot be solved by Mollier chart unless Wilson line is drawn on it.

The velocity of steam at the end of expansion is found by using the relation,

$$C_2 = \sqrt{2 \times \left(\frac{n}{n-1}\right) p_1 v_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

Specific volume, $v_2 = v_1 \left(\frac{p_2}{p_1}\right)^{1/n}$

Apparent temperature, $T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$

and $A_2 = \frac{m \times v_2}{C_2}$.

Example 3.10. *Dry saturated steam at a pressure of 11 bar enters a convergent-divergent nozzle and leaves at a pressure of 2 bar. If the flow is adiabatic and frictionless, determine :*

(*i*) *The exit velocity of steam.*

(*ii*) *Ratio of cross-section at exit and that at throat.*

Assume the index of adiabatic expansion to be 1.135.

Solution. Refer to Fig. 3.80.

$p_1 = 11$ bar ; $p_3 = 2$ bar ; p_2 = Throat pressure ; $n = 1.135$

Now, $\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$

$$= \left(\frac{2}{1.135+1}\right)^{\frac{1.135}{1.135-1}} = \left(\frac{2}{2.135}\right)^{\frac{1.135}{0.135}}$$

$= 0.58$

or $p_2 = 0.58 \times p_1 = 0.58 \times 11 = 6.38$ bar.

- From Mollier chart (Fig. 3.80) point 1 is located on the dry saturation line corresponding to 11 bar pressure.
- From '1' vertical line 1-3 is drawn cutting the pressure line 2 bar.
- Point '2' corresponding to throat pressure 6.38 bar is located on the vertical line.

Adiabatic heat drop between inlet and throat,

$h_d = h_1 - h_2$

$= 2780 - 2679 = 101$ kJ/kg

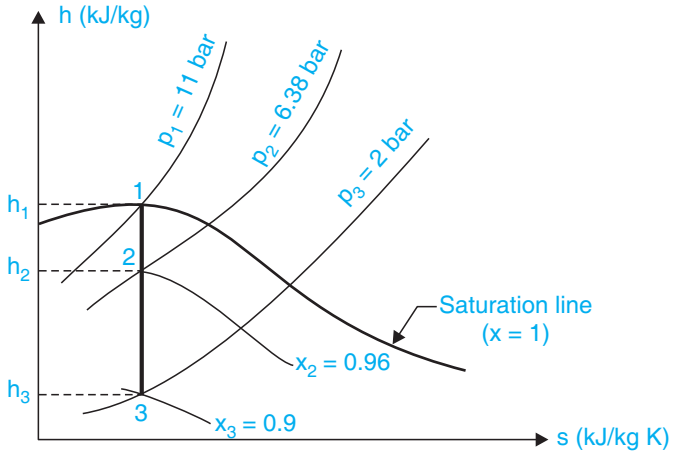


Fig. 3.80

$x_2 = 0.96$

$v_{g_2} = 0.297$ m³/kg

Throat velocity,

$$C_2 = 44.72 \sqrt{h_d} = 44.72 \sqrt{101} = 449.4 \text{ m/s}$$

Also, $$\dot{m} = \frac{A_2 C_2}{v_2} = \frac{A_2 C_2}{x_2 v_{g_2}}$$

(where $\dot{m}$ = Mass flow rate in kg/s)

or Throat area,

$$A_2 = \frac{\dot{m}\, x_2\, v_{g_2}}{C_2}$$

$$= \frac{\dot{m} \times 0.96 \times 0.297}{449.4} = 0.000634\ \dot{m}$$

From Mollier chart, $x_3 = 0.9$

From steam tables, $v_{g_3} = 0.885$ m³/kg (at 2 bar)

h_d' = Adiabatic heat drop between inlet and exit

$= h_1 - h_3 = 2780 - 2480 = 300$ kJ/kg

Exit velocity, $C_3 = 44.72 \sqrt{h_d'}$

$= 44.72 \sqrt{300}$

$=$ **774.6 m/s.** **(Ans.)**

Exit area, $$A_3 = \frac{\dot{m}\, x_3\, v_{g_3}}{C_3} = \frac{\dot{m} \times 0.9 \times 0.885}{774.6}$$

$$= 0.001028\ \dot{m}$$

$$\therefore \quad \textbf{Ratio of } \frac{\text{exit area}}{\text{throat area}} = \frac{0.001028\,\dot{m}}{0.000638\,\dot{m}}$$

$=$ **1.62.** **(Ans.)**

Example 3.11. *The nozzles of a De laval steam turbine are supplied with dry saturated steam at a pressure of 9 bar. The pressure at the outlet is 1 bar. The turbine has two nozzles with a throat diameter of 2.5 mm. Assuming nozzle efficiency as 90% and that of turbine rotor 35%, find the quality of steam used per hour and the power developed.*

Solution. $p_1 = 9$ bar, $p_3 = 1$ bar, p_2 = throat pressure, Number of nozzles = 2

We know that, $$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

Since the steam is dry and saturated, $n = 1.135$

$$\therefore \quad \frac{p_2}{p_1} = \left(\frac{2}{1.135+1}\right)^{\frac{1.135}{1.135-1}} = 0.58$$

or $p_2 = 0.58\, p_1 = 0.58 \times 9 = 5.22$ bar.

From Mollier chart :

$h_1 = 2770$ kJ/kg, $h_2 = 2670$ kJ/kg

$h_3 = 2400$ kJ/kg

$x_{2'} = 0.96$, $x_{3'} = 0.88$

Now, $h_d = h_1 - h_2 = 2770 - 2670 = 100$ kJ/kg

$h_d' = h_1 - h_3 = 2770 - 2400 = 370$ kJ/kg

From steam tables :

$v_{g_2} = 0.361$ m³/kg (at 5.22 bar)

$v_{g_3} = 1.694$ m³/kg (at 1.0 bar)

Velocity of steam at throat,

$$C_2' = 44.72 \sqrt{k h_d} = 44.72 \sqrt{0.9 \times 100}$$

$= 424.2$ m/s

Exit velocity,

$$C_3' = 44.72 \sqrt{k h_{d'}}$$

$$= 44.72 \sqrt{0.9 \times 370} = 816 \text{ m/s}$$

$D_2 = 2.5$ mm,

$$A_2 = \frac{\pi}{4} D_2^2 \times 2 = \frac{\pi}{4} \times \left(\frac{2.5}{1000}\right)^2 \times 2$$

$= 9.82 \times 10^{-6}$ m²

Mass of steam used per sec.,

$$\dot{m} = \frac{A_2\, C_2'}{x_2'\, v_{g_2}} = \frac{9.82 \times 10^{-6} \times 424.2}{0.96 \times 0.361}$$

$= 0.012$ kg/s

Energy supplied by the steam to the wheel per sec

$$= \frac{\dot{m}\, C_3'^2}{2} = \frac{0.012 \times 816^2}{2}$$

$= 3995$ W $\simeq 4$ kW.

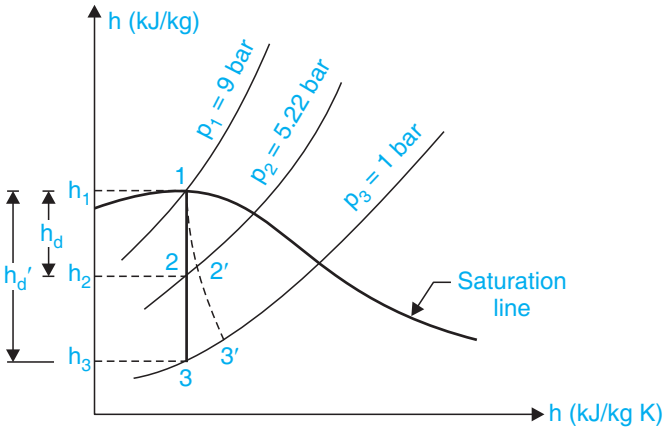


Fig. 3.81

$\therefore$ Useful work = $\eta_{turbine} \times 4 = 0.35 \times 4 = 1.44$ kW.

i.e., *Power developed* = **1.44 kW.** **(Ans.)**

Example 3.12. *An impulse turbine having a set of 16 nozzles receives steam at 20 bar, 400°C. The pressure of steam at exit is 12 bar. If the total discharge is 260 kg/min and nozzle efficiency is 90%, find the cross-sectional area of the exit of each nozzle. If the steam has a velocity of 80 m/s at entry to the nozzles, find the percentage increase in discharge.*

Solution. Set of nozzles = 16, p_1 = 20 bar, 400°C

Total discharge = 260 kg/min,

η_{nozzle} = 90%.

Since the steam supplied to the nozzle is superheated, the throat pressure is given by :

$$\frac{p_2}{p_1} = 0.546$$

$\therefore$ $p_2 = 20 \times p_1 = 20 \times 0.546 = 10.9$ bar

[For superheated steam : $n = 1.3$

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} = \left(\frac{2}{1.3+1}\right)^{\frac{1.3}{1.3-1}}$$

$= 0.546$]

Since the pressure is *less* than the exit pressure of steam from nozzle, as such the nozzle is *convergent type.*

From Mollier chart :

h_1 = 3250 kJ/kg

h_2 = 3065 kJ/kg

$h_d = h_1 - h_2 = 3250 - 3065 = 185$ kJ/kg.

Velocity at exit neglecting initial velocity of steam,

$$C_2' = 44.72 \sqrt{kh_d} = 44.72 \sqrt{0.9 \times 185}$$

$= 577$ m/s

Specific volume at exit,

v_2' = 0.235 m³/kg (From Mollier chart)

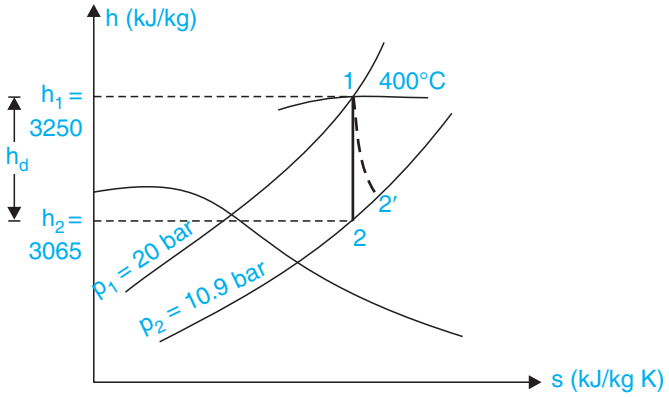


Fig. 3.82

Area at exit for one nozzle,

$$A_2 = \frac{m \times v_2}{C_2' \times \text{no. of nozzles}} = \frac{260 \times 0.235}{60 \times 577 \times 16}$$

$= \mathbf{1.1 \times 10^{-4}\ m^2.}$ **(Ans.)**

Taking into account the initial velocity of steam as 80 m/s, the velocity of steam at exit, C_2' is calculated as follows :

$$\frac{C_2'^2 - C_1^2}{2} = kh_d$$

i.e., $C_2'^2 = 2\,kh_d + C_1^2$

$= 2 \times 0.9 \times 185 \times 1000 + 80^2$

$= 339400$

$\therefore$ $C_2' = 582.6$ m/s

Percentage increase in velocity

$$= \frac{582.6 - 577}{577} \times 100 = \mathbf{0.97\%.}$$

This will result in 0.97% increase in discharge as specific volume will not be affected by velocity of approach.

Hence *percentage increase in discharge* = **0.97%.** **(Ans.)**

3.19. STEAM TURBINES

3.19.1. Introduction

*The **steam turbine** is a prime mover in which the potential energy of the steam is transformed into kinetic energy, and latter in its turn is transformed into the mechanical energy of rotation of the turbine shaft.* The turbine shaft, directly or with the help of a reduction gearing, is connected with the driven mechanism. Depending on the type of the driven mechanism a steam turbine may be *utilised in most diverse*

fields of industry, for power generation and *for transport*. Transformation of the potential energy of steam into the mechanical energy of rotation of the shaft is brought about by different means.

3.19.2. Classification of Steam Turbines

There are several ways in which the steam turbines may be classified. The most important and common division being with respect to the *action of the steam*, as :

(*a*) Impulse.

(*b*) Reaction.

(*c*) Combination of impulse and reaction.

Other classification are :

1. According to the number of pressure stages :

(*i*) *Single-stage turbines* with one or more velocity stages usually of small-power capacities ; these turbines are mostly used for driving centrifugal compressors, blowers and other similar machinery.

(*ii*) *Multi-stage impulse and reaction turbines* ; they are made in a wide range of power capacities varying from small to large.

2. According to the direction of steam flow :

(*i*) *Axial turbines* in which steam flows in a direction parallel to the axis of the turbine.

(*ii*) *Radial turbines* in which steam flows in a direction perpendicular to the axis of the turbine ; one or more low-pressure stages in such turbines are made axial.

3. According to the number of cylinders :

(*i*) Single-cylinder turbines.

(*ii*) Double-cylinder turbines.

(*iii*) Three-cylinder turbines.

(*iv*) Four-cylinder turbines.

Multi-cylinder turbines which have their rotors mounted on one and the same shaft and coupled to a single generator are known as *single shaft turbines* ; turbines with separate rotor shafts for each cylinder placed parallel to each other are known as ***multiaxial turbines.***

4. According to the method of governing :

(*i*) *Turbines with throttle governing* in which fresh steam enters through one or more (depending on the power developed) simultaneously operated throttle valves.

(*ii*) *Turbines with nozzle governing* in which fresh steam enters through two or more consecutively opening regulators.

(*iii*) *Turbines with by pass governing* in which steam turbines besides being fed to the first stage is also directly fed to one, two or even three intermediate stages of the turbine.

5. According to heat drop process :

(*i*) *Condensing turbines with generators* ; in these turbines steam at a pressure less than atmospheric is directed to a condenser ; besides, steam is also extracted from intermediate stages for feed water heating, the number of such extractions usually being from 2-3 to as much 8-9. The latent heat of exhaust steam during the process of condensation is completely lost in these turbines.

(*ii*) *Condensing turbines with one or two intermediate stage extractions* at specific pressures for industrial and heating purposes.

(*iii*) *Back pressure turbines*, the exhaust steam from which is utilised for industrial or heating purposes ; to this type of turbines can also be added (in a relative sense) turbines with deteriorated vacuum, the exhaust steam of which may be used for heating and process purposes.

(*iv*) *Topping turbines* ; these turbines are also of the back pressure type with the difference that the exhaust steam from these turbines is further utilised in medium and low-pressure condensing turbines. These turbines, in general, operate at high initial conditions of steam pressure and temperature, and are mostly used during extension of power station capacities, with a view to obtain better efficiencies.

(*v*) *Back pressure turbines with steam extraction from intermediate stages at specific pressure* ; turbines of this type are meant for supplying the consumer with steam of various pressures and temperature conditions.

(*vi*) *Low pressure turbines* in which the exhaust steam from reciprocating steam engines, power hammers, etc., is utilised for power generation purposes.

(*vii*) *Mixed pressure turbines* with two or three pressure stages, with supply of exhaust steam to its intermediate stages.

6. According to steam conditions at inlet to turbine :

(*i*) *Low pressure turbines*, using steam at a pressure of 1.2 to 2 ata.

(*ii*) *Medium pressure turbines*, using steam at pressure of up to 40 ata.

(*iii*) *High pressure turbines*, utilising steam at pressures above 40 ata.

(*iv*) *Turbines of very high pressures*, utilising steam at pressures of 170 ata and higher and temperatures of 550°C and higher.

(*v*) *Turbines of supercritical pressures*, using steam at pressures of 225 ata and above.

7. According to their usage in industry :

(*i*) *Stationary turbines with constant speed of rotation* primarily used for driving alternators.

(*ii*) *Stationary steam turbines* with variable speed meant for driving turbo-blowers, air circulators, pumps, etc.

(*iii*) *Non-stationary* turbines with variable speed ; turbines of this type are usually employed in steamers, ships and railway locomotives.

3.19.3. Advantages of Steam Turbine over the Steam Engines

The following are the principal *advantages* of steam turbine over steam engines :

1. The thermal efficiency of a steam turbine is much higher than that of a steam engine.
2. The power generation in a steam turbine is at a uniform rate, therefore necessity to use a flywheel (as in the case of steam engine) is not felt.
3. Much higher speeds and greater range of speed is possible than in case of a steam engine.
4. In large thermal stations where we need higher outputs, the steam turbines prove very suitable as these can be made in big sizes.
5. With the absence of reciprocating parts (as in steam engine) the balancing problem is minimised.
6. No internal lubrication is required as there are no rubbing parts in the steam turbine.
7. In a steam turbine there is no loss due to initial condensation of steam.
8. It can utilise high vacuum very advantageously.
9. Considerable overloads can be carried at the expense of slight reduction in overall efficiency.

3.19.4. Description of Common Types of Turbines

The common types of steam turbines are :

1. Simple Impulse turbine.
2. Reaction turbine.

The main difference between these turbines lies *in the way in which the steam is expanded while it moves through them. In the former type steam expands in the nozzles and its pressure does not alter as it moves over the blades while in the latter type the steam expands continuously as it passes over the blades and thus there is gradual fall in the pressure during expansion.*

1. Simple impulse turbine :

Fig. 3.83 shows a simple impulse turbine diagrammatically. The top portion of the figure exhibits a longitudinal section through the upper half of the turbine,

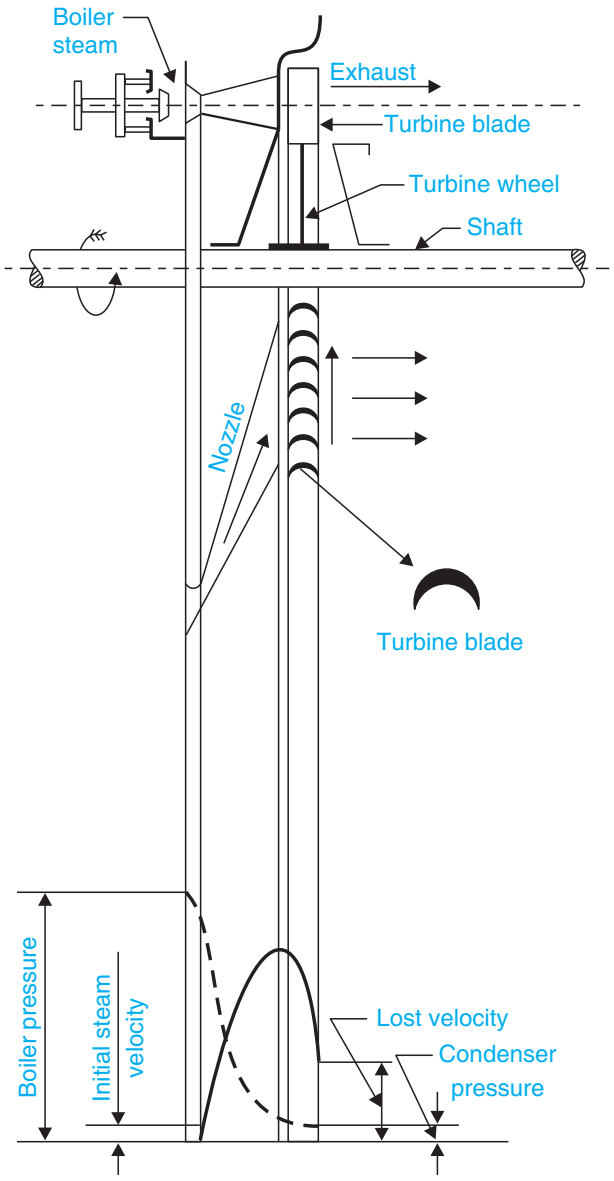


Fig. 3.83. Simple impulse turbine.

the middle portion shows one set of nozzles which is followed by a ring of moving blades, while lower part of the diagram indicates approximately changes in pressure and velocity during the flow of steam through the turbine. This turbine is called *'simple'* impulse turbine since the expansion of the steam takes place in one set of the nozzles.

As the steam flows through the nozzle its pressure falls from steam chest pressure to condenser pressure (or atmospheric pressure if the turbine is non-condensing). Due to this relatively higher ratio of expansion of steam in the nozzles the steam leaves the nozzle with a very high velocity. Refer to Fig. 3.83, it is evident that the velocity of the steam leaving the moving blades is a large portion of the maximum velocity of the steam when leaving the nozzle. The loss of energy due to this higher exit velocity is commonly the ***"carry over loss"*** or ***"leaving loss"***.

The principal example of this turbine is the well known ***"De laval turbine"*** and in this turbine the 'exit velocity' or 'leaving velocity' or 'lost velocity' may amount to 3.3 per cent of the nozzle outlet velocity. Also since all the kinetic energy is to be absorbed by one ring of the moving blades only, the velocity of wheel is too high (varying from 25,000 to 30,000 r.p.m.). This wheel or rotor speed however, can be reduced by different methods (discussed in the Art. 3.19.5).

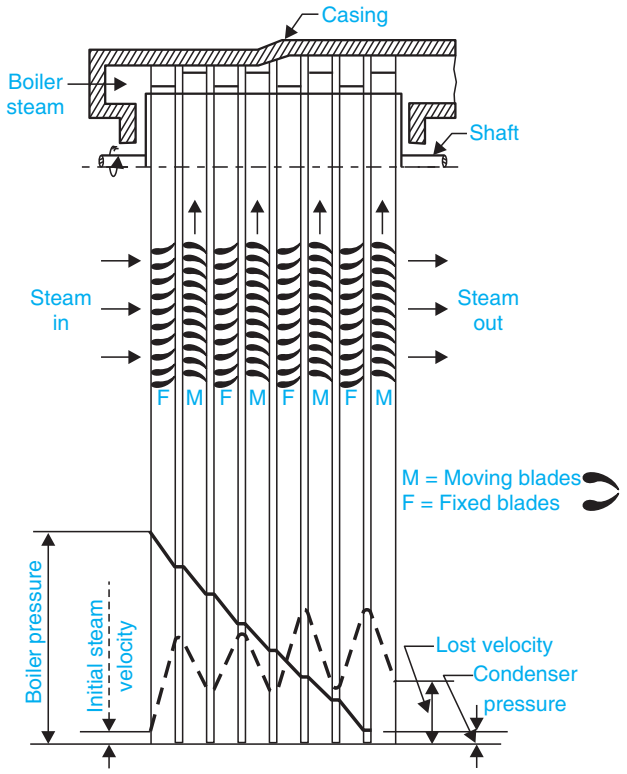


Fig. 3.84. Reaction turbine (three stage).

2. Reaction turbine :

In this type of turbine, *there is a gradual pressure drop which takes place continuously over the fixed and moving blades*. The function of the fixed blades is (the same as the nozzle) that they alter the direction of the steam as well as allow it to expand to a larger velocity. As the steam passes over the moving blades its kinetic energy (obtained due to fall in pressure) is absorbed by them. Fig. 3.84 shows a *multi-stage* reaction turbine. The changes in pressure and velocity are also shown therein.

As the volume of steam increases at lower pressures therefore, the diameter of the turbine must increase after each group of blade rings. It may be noted that in this turbine since the pressure drop per stage is small, therefore, the number of stages required is much higher than an impulse turbine of the same capacity.

3.19.5. Methods of Reducing Wheel or Rotor Speed

As already discussed under the heading 'simple impulse turbine' that if the steam is expanded from the boiler pressure to condenser pressure in one stage the speed of the rotor becomes *tremendously high which crops up practical complicacies*. There are several methods of reducing this speed to lower value ; all these methods utilise a multiple system of rotor in series, keyed on a common shaft and the steam pressure of jet velocity is absorbed in stages as the steam flows over the blades. This is known as '**compounding**'. The different methods of compounding are :

1. Velocity compounding.
2. Pressure compounding.
3. Pressure velocity compounding.
4. Reaction turbine.

1. Velocity compounding :

Steam is expanded through a stationary nozzle from the boiler or inlet pressure to condenser pressure. So the pressure in the nozzle drops, the kinetic energy of the steam increases due to increase in velocity. A portion of this available energy is absorbed by a row of moving blades. The steam (whose velocity has decreased while moving over the moving blades) then flows through the second row of blades which are fixed. The function of these fixed blades is to redirect the steam flow without altering its velocity to the following next row moving blades where again work is done on them and steam leaves the turbine with a low velocity. Fig. 3.85 shows a cut away section of such a stage and changes in pressure and velocity as the steam passes through the nozzle, fixed and moving blades.

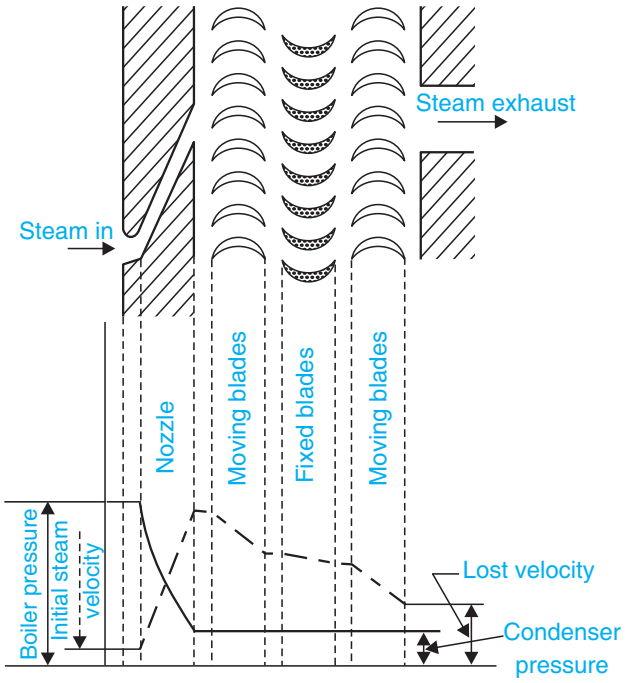


Fig. 3.85. Velocity compounding.

Though this method has the advantage that the initial cost is low due to lesser number of stages yet its efficiency is low.

2. Pressure compounding :

Fig. 3.86 shows rings of fixed nozzles incorporated between the rings of moving blades. The steam at boiler pressure enters the first set of nozzles and expands partially. The kinetic energy of the steam thus obtained is absorbed by the moving blades (stage 1). The steam then expands partially in the second set of nozzles where its pressure again falls and the velocity increases ; the kinetic energy so obtained is absorbed by the second ring of moving blades (stage 2). This is repeated in stage 3 and steam finally leaves the turbine at low velocity and pressure. The number of stages (or pressure reductions) depends on the number of rows of nozzles through which the steam must pass.

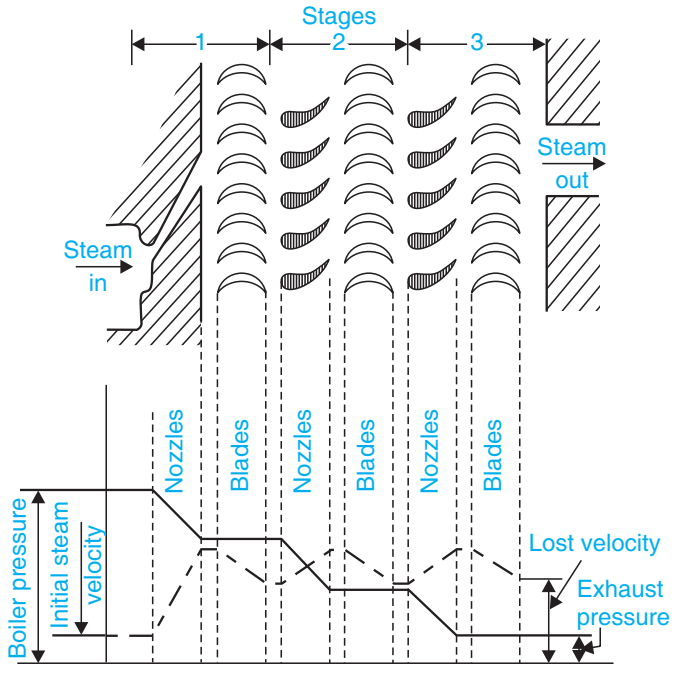


Fig. 3.86. Pressure compounding.

This method of compounding is used in *Rateau and Zoelly turbine. This is most efficient turbine since the speed ratio remains constant but it is expensive owing to a large number of stages*.

3. Pressure velocity compounding :

This method of compounding is the combination of two previously discussed method. The total drop in steam pressure is divided into stages and the velocity obtained in each stage is also compounded. The rings of nozzles are fixed at the beginning of each stage and pressure remains constant during each stage. The changes in pressure and velocity are shown in Fig. 3.87.

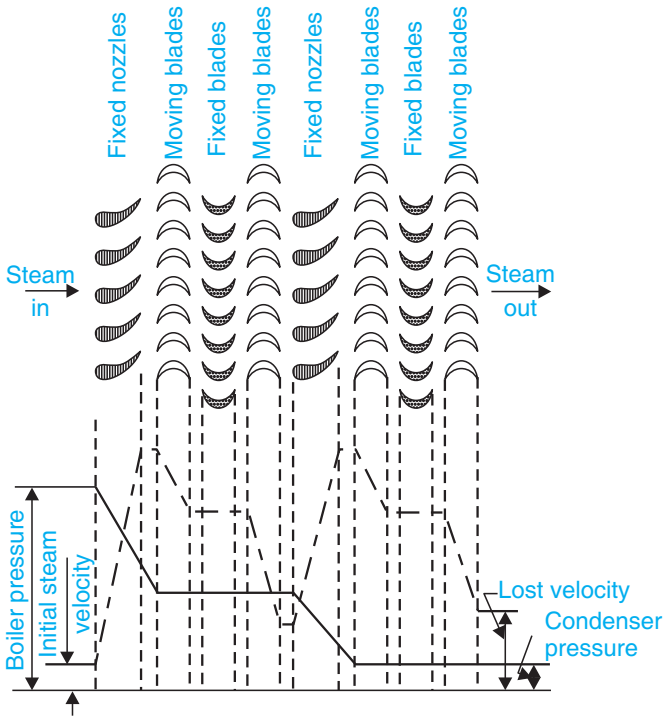


Fig. 3.87. Pressure velocity compounding.

This method of compounding is used in *Curits and Moore turbine.*

4. Reaction turbine:

It has been discussed in Article 3.19.4.

3.19.6. Difference between Impulse and Reaction Turbines

S. No.	Particulars	Impulse turbine	Reaction turbine
1.	*Pressure drop*	Only in nozzles and not in moving blades.	In fixed blades (nozzles) as well as in moving blades.
2.	*Area of blade channels*	Constant.	Varying (converging type).
3.	*Blades*	Profile type.	Aerofoil type.
4.	*Admission of steam*	Not all round or complete.	All round or complete.
5.	*Nozzles/fixed blades*	Diaphram contains the nozzle.	Fixed blades similar to moving blades attached to the casing serve as nozzles and guide the steam.
6.	*Power*	Not much power can be developed.	Much power can be developed.
7.	*Space*	Requires less space for same power.	Requires more space for same power.
8.	*Efficiency*	Low.	High.
9.	*Suitability*	Suitable for small power requirements.	Suitable for medium and higher power requirements.
10.	*Blade manufacture*	Not difficult.	Difficult.

3.19.7. Impulse Turbines

3.19.7.1. Velocity diagram for moving blade

Fig. 3.88 shows the velocity diagram of a *single stage impulse turbine*.

C_{bl} = Linear velocity of moving blade (m/s)

C_1 = Absolute velocity of steam entering moving blade (m/s)

C_0 = Absolute velocity of steam leaving moving blade (m/s)

C_{w_1} = Velocity of whirl at the entrance of moving blade = tangential component of C_1

C_{w_0} = Velocity of whirl at exit of the moving blade = tangential component of C_0

C_{f_1} = Velocity of flow at entrance of moving blade = axial component of C_1

C_{f_0} = Velocity of flow at exit of the moving blade = axial component of C_0

C_{r_1} = Relative velocity of steam to moving blade at entrance

C_{r_0} = Relative velocity of steam to moving blade at exit

α = Angle with the tangent of the wheel at which the steam with velocity C_1 enters. This is also called **nozzle angle**

β = Angle which the discharging steam makes with the tangent of the wheel at the exit of moving blade

θ = Entrance angle of moving blade

ϕ = Exit angle of moving blade.

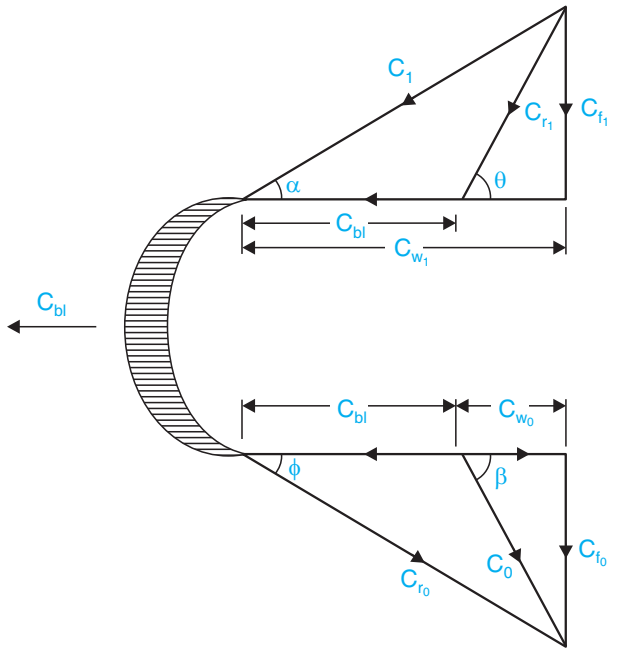


Fig. 3.88. Velocity diagram for moving blade.

The steam jet issuing from the nozzle at a velocity of C_1 impinges on the blade at an angle α. The tangential component of this jet (C_{w_1}) performs work on the blade, the axial component (C_{f_1}) however does no work but causes the steam to flow through the turbine. As the blades move with a tangential velocity of C_{bl}, the entering steam jet has a relative velocity C_{r_1} (with respect to blade) which makes an angle θ with the wheel tangent. The steam then

glides over the blade without any shock and discharges at a relative velocity of C_{r_0} at an angle ϕ with the tangent of the blades. The relative velocity at the inlet (C_{r_1}) is the same as the relative velocity at the outlet (C_{r_0}) if *there is no frictional loss at the blade*. The absolute velocity (C_0) of leaving steam make an angle β to the tangent at the wheel.

To have convenience in solving the problems on turbines it is a common practice to combine the two vector velocity diagrams on a common base which represents the blade velocity (C_{bl}) as shown in Fig. 3.89. This diagram has been obtained by superimposing the inlet velocity diagram on the outlet diagram in order that the blade velocity lines C_{bl} coincide.

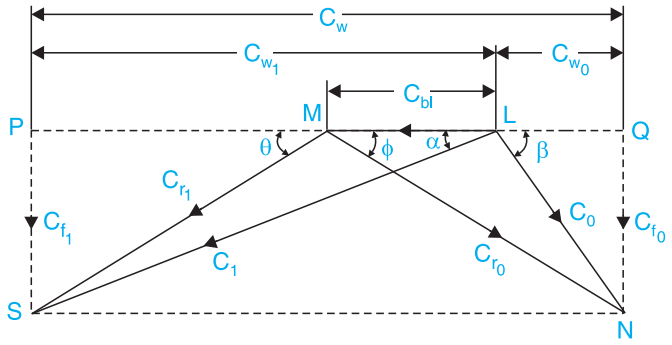


Fig. 3.89

3.19.7.2. Work done on the blade

The work done on the blade may be found out from the change of momentum of the steam jet during its flow over the blade. As earlier discussed, it is only the velocity of whirl which performs work on the blade since it acts in its (blade) direction of motion.

From Newton's second law of motion,

Force (tangential) on the wheel

= Mass of steam × acceleration

= Mass of steam/sec. × change of velocity

$$= \dot{m}_s(C_{w_1} - C_{w_0}) \qquad ...(3.39)$$

The value of C_{w_0} is actually negative as the steam is discharged in the *opposite direction* to the blade motion, therefore, due consideration should be given to the fact that the *values of* C_{w_1} *and* C_{w_0} *are to be added while doing the solution of the problem.*

Work done on blades/sec.

= Force × distance travelled/sec.

$$= \dot{m}_s(C_{w_1} + C_{w_0}) \times C_{bl}$$

Power per wheel $= \dot{m}_s(C_{w_1} + C_{w_0}) \times C_{bl}$

$$= \frac{\dot{m}_s C_w C_{bl}}{1000}\text{kW} \qquad ...(3.40)$$

$(\because \quad C_w = C_{w_1} + C_{w_0})$

Blade or diagram efficiency

$$= \frac{\text{Work done on the blade}}{\text{Energy supplied to the blade}}$$

$$= \frac{\dot{m}_s(C_{w_1} + C_{w_0}) \cdot C_{bl}}{\dot{m}\, C_1^{\,2}}$$

$$= \frac{2\, C_{bl}(C_{w_1} + C_{w_0})}{C_1^{\,2}} \qquad ...(3.41)$$

If h_1 and h_2 be the total heats before and after expansion through the nozzles, then $(h_1 - h_2)$ is the heat drop through a stage of fixed blades ring and moving blades ring.

$\therefore$ **Stage efficiency,**

$$\eta_{stage} = \frac{\text{Work done on blade per kg of steam}}{\text{Total energy supplied per kg of steam}}$$

$$= \frac{C_{bl}(C_{w_1} + C_{w_0})}{(h_1 - h_2)} \qquad ...(3.42)$$

Now, nozzle efficiency

$$= \frac{C_1^{\,2}}{2(h_1 - h_2)}$$

Also, η_{stage} = Blade efficiency × nozzle efficiency

$$= \frac{2\, C_{bl}(C_{w_1} + C_{w_0})}{C_1^{\,2}} \times \frac{C_1^{\,2}}{2(h_1 - h_2)}$$

$$= \frac{C_{bl}(C_{w_1} + C_{w_0})}{(h_1 - h_2)}$$

The ***axial thrust*** on the wheel is due to *difference* between the velocities of flow at entrance and outlet.

Axial force on the wheel

= Mass of steam × axial acceleration

$$= \dot{m}_s(C_{f_1} - C_{f_0}) \qquad ...(3.43)$$

The *axial force on the wheel must be balanced or must be taken by a thrust bearing.*

Energy converted to heat by blade friction

= Loss of kinetic energy during flow over blades

$$= \dot{m}_s(C_{r_1}^{\,2} - C_{r_0}^{\,2}) \qquad ...(3.44)$$

3.19.7.3. Blade velocity coefficient

In an impulse turbine, if friction is neglected the relative velocity will remain unaltered as it passes over blades. In

practice the flow of steam over the blades is resisted by friction. The effect of the friction is to reduce the relative velocity of steam as it passes over the blades. In general, there is a loss of 10 to 15 per cent in the relative velocity. Owing to friction in the blades, C_{r_0} is less than C_{r_1} and we may write

$$C_{r_0} = K \cdot C_{r_1} \qquad ...(3.45)$$

where K is termed a ***blade velocity coefficient.***

3.19.7.4. Expression for optimum value of the ratio of blade speed to steam speed (for maximum efficiency) for a single stage impulse turbine

Refer to Fig. 3.89.

$$C_w = PQ = MP + MQ = C_{r_1} \cos\theta + C_{r_0} \cos\phi$$

$$= C_{r_1} \cos\theta \left[1 + \frac{C_{r_0} \cos\phi}{C_{r_1} \cos\theta}\right]$$

$$= C_{r_1} \cos\theta\,(1 + K \cdot Z), \text{ where } Z = \frac{\cos\phi}{\cos\theta}$$

...(*i*)

Generally, *the angles* θ *and* ϕ *are nearly equal for impulse turbine* and hence it can safely be assumed that Z is a constant.

But, $C_{r_1} \cos\theta = MP = LP - LM = C_1 \cos\alpha - C_{bl}$

From equation (*i*),

$$C_w = (C_1 \cos\alpha - C_{bl})(1 + K \cdot Z)$$

We know that, Blade efficiency, $\eta_{bl} = \dfrac{2C_{bl} \cdot C_w}{C_1^2}$ ...(*ii*)

$$\eta_{bl} = \frac{2C_{bl}(C_1 \cos\alpha - C_{bl})(1 + KZ)}{C_1^2}$$

$$= 2(\rho \cos\alpha - \rho^2)(1 + KZ)$$

$$= 2\rho(\cos\alpha - \rho)(1 + KZ) \qquad ...(iii)$$

where $\rho = \dfrac{C_{bl}}{C_1}$ is the ratio of *blade speed to steam speed* and is commonly called as ***"Blade speed ratio".***

For particular impulse turbine α, K and Z may assumed to be constant and from equation (*iii*) it can be seen clearly that η_{bl} depends on the value of ρ only. Hence differentiating (*iii*),

$$\frac{d\eta_{bl}}{d\rho} = 2(\cos\alpha - 2\rho)(1 + KZ)$$

For a maximum or minimum value of η_{bl} this should be zero.

$$\cos\alpha - 2\rho = 0, \quad \therefore \quad \rho = \frac{\cos\alpha}{2}$$

$$\text{Now, } \frac{d^2\eta_{bl}}{d\rho^2} = 2(-2)(1 + KZ) = -4(1 + KZ)$$

which is a negative quantity and thus the value so obtained is the maximum.

Optimum value of ratio of blade speed to steam speed is

$$\rho_{opt} = \frac{\cos\alpha}{2} \qquad ...(3.46)$$

Substituting this value of ρ in eqn. (*iii*), we get

$$(\eta_{bl})_{max} = 2 \times \frac{\cos\alpha}{2}\left(\cos\alpha - \frac{\cos\alpha}{2}\right)(1 + K \cdot Z)$$

$$= \frac{\cos^2\alpha}{2}(1 + KZ) \qquad ...(3.47)$$

It is sufficiently accurate to assume symmetrical blades ($\theta = \phi$) and no friction in fluid passage for the purpose of analysis.

$\therefore \quad Z = 1$ and $K = 1$

$\therefore \quad (\eta_{bl})_{max} = \cos^2\alpha$ ...(3.48)

The work done per kg of steam is given by

$$W = (C_{w_1} + C_{w_0})\ C_{bl}$$

Substituting the value of $C_{w_1} + C_{w_0}$ $(= C_w)$

$$W = (C_1 \cos\alpha - C_{bl})(1 + KZ)C_{bl}$$

$$= 2C_{bl}(C_1 \cos\alpha - C_{bl})$$

When $K = 1$ and $Z = 1$

The maximum value of W can be obtained by substituting the value of $\cos\alpha$ from equation (3.46),

$$\cos\alpha = 2\rho = 2\,\frac{C_{bl}}{C_1}$$

$\therefore \quad W_{max} = 2C_{bl}\,(2C_{bl} - C_{bl}) = 2C_{bl}^2$ ...(3.49)

It is obvious from the equation (3.46) that the blade velocity should be *approximately* half of absolute velocity of steam jet coming out from the nozzle (fixed blade) for *the maximum work developed per kg of steam or for maximum efficiency. For the other values of blade speed the absolute velocity at outlet from the blade will increase, consequently, more energy will be carried away by the steam and efficiency will decrease.*

For equiangular blades with no friction losses, optimum value of $\dfrac{C_{bl}}{C_1}$ corresponds to the case, when the outlet absolute velocity is axial as shown in Fig. 3.90.

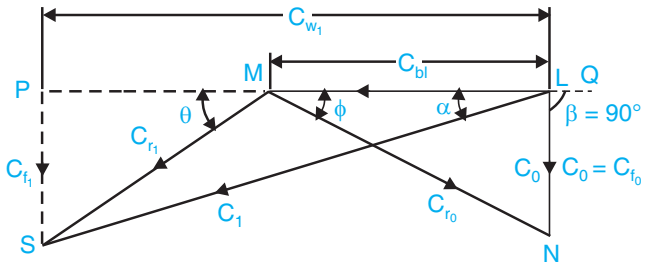


Fig. 3.90

Since the discharge is axial,

$$\beta = 90°,$$

$$\therefore \quad C_0 = C_{f_0} \quad \text{and} \quad C_{w_0} = 0.$$

The variations of η_{bl} or work developed per kg of steam with $\frac{C_{bl}}{C_1}$ is shown in Fig. 3.91. This figure shows that :

(*i*) When $\frac{C_{bl}}{C_1} = 0$, the work done becomes zero as the distance travelled by the blade (C_{bl}) is zero, even through the torque on the blade is maximum.

(*ii*) The maximum efficiency is $\cos^2 \alpha$ and maximum work done per kg of steam is $2C^2_{bl}$ when $\frac{C_{bl}}{C_1} = \cos \alpha/2$.

(*iii*) When $\frac{C_{bl}}{C_1} = 1$, the work done is zero as the torque acting on the blade becomes zero even though the distance travelled by the blade is maximum.

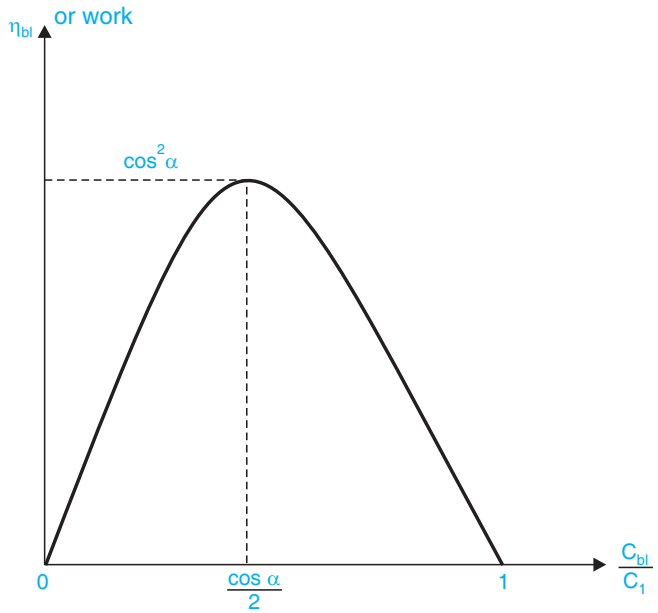


Fig. 3.91

When the high pressure steam is expanded from the boiler pressure to condenser pressure in a single stage of nozzle, the absolute velocity of steam becomes maximum and blade velocity also becomes tremendously high. In such a case, *a velocity compounded stage is used to give lower blade speed ratio* and *better utilization of the kinetic energy of the steam*. The arrangement of velocity compounding has already been dealt with.

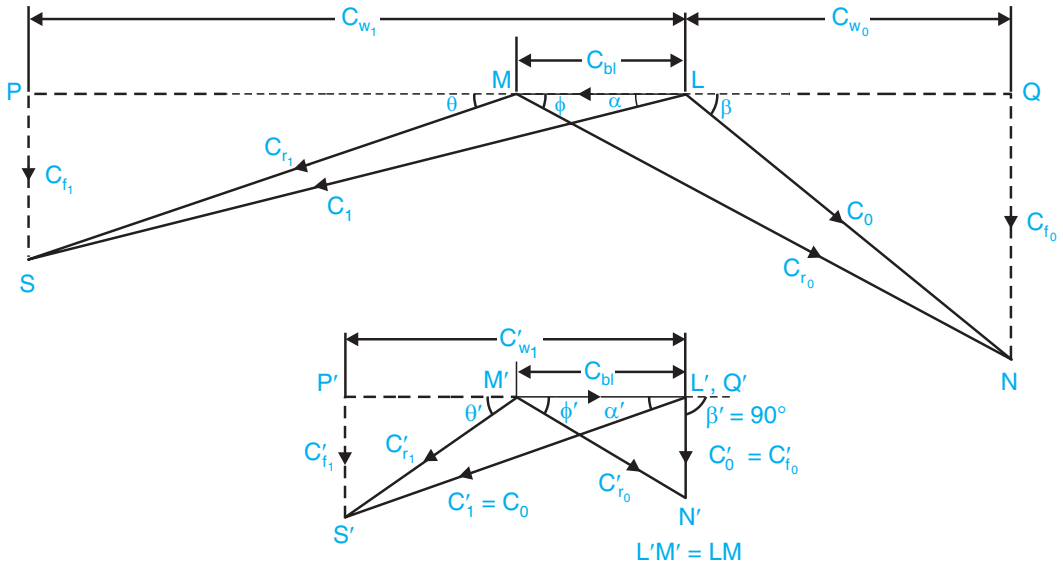


Fig. 3.92

Fig. 3.92 shows the velocity diagrams for the first and second row of moving blades of *velocity compounded unit*. The speed and angles are such that the final absolute velocity of the steam leaving the second row is *axial*. With this arrangement, *the K.E. carried by the steam is minimum*, therefore, *efficiency becomes maximum*.

The velocity of blades (C_{bl}) is same for both the rows since they are mounted on the same shaft.

Consider **first row of moving blades**

Work done per kg of steam,

$$W_1 = C_{bl}\,(C_{w_1} + C_{w_0})$$

$$= C_{bl}\,[C_{r_1}\cos\theta + C_{r_0}\cos\phi]$$

If there is *no friction loss and symmetrical blading* is used, then:

$$C_{r_1} = C_{r_0} \quad \text{and} \quad \theta = \phi$$

$$\therefore \quad W_1 = C_{bl} \times 2C_{r_1}\cos\theta = 2C_{bl}(C_1\cos\alpha - C_{bl}) \qquad ...(3.50)$$

The magnitude of absolute velocity of steam leaving the first row and entering into the second row of moving blades is same and *its direction only is changed*.

$$\therefore \quad C_1' = C_0$$

Consider **second row of moving blades :**

Work done per kg,

$$W_2 = C_{bl} \cdot C'_{w_1} \text{ as } C'_{w_0}$$

= 0 because discharge is *axial* and $\beta' = 90°$

Alternately, $W_2' = C_{bl}\left[C'_{r_1}\cos\theta' + C'_{r_0}\cos\phi'\right]$

For symmetrical blades $\theta' = \phi'$

and, if there is *no friction loss*, then

$$C'_{r_1} = C'_{r_0}$$

$$\therefore \quad W_2 = 2C_{bl}\,C'_{r_1}\cos\theta'$$

$$= 2C_{bl}\,(C_1'\cos\alpha' - C_{bl}) \qquad ...(3.51)$$

Now α' may be equal to β.

$$\therefore \quad C_1'\cos\alpha' = C_0\cos\beta = C_{r_0}\cos\phi - C_{bl}$$

$$= C_{r_1}\cos\theta - C_{bl} = (C_1\cos\alpha - C_{bl}) - C_{bl}$$

$$= C_1\cos\alpha - 2C_{bl}$$

Substituting the value of $C_1'\cos\alpha'$ in eqn. (3.51), we get:

$$W_2 = 2C_{bl}\,[(C_1\cos\alpha - 2C_{bl}) - C_{bl}]$$

$$= 2C_{bl}\,(C_1\cos\alpha - 3C_{bl}) \qquad ...(3.52)$$

Total work done per kg of steam passing through both stages is given by:

$$W_t = W_1 + W_2$$

$$= 2C_{bl}\,[C_1\cos\alpha - C_{bl}] + 2C_{bl}\,[C_1\cos\alpha - 3C_{bl}]$$

$$= 2C_{bl}\,[2C_1\cos\alpha - 4C_{bl}]$$

$$= 4C_{bl}\,(C_1\cos\alpha - 2C_{bl}) \qquad ...(3.53)$$

The blade efficiency for two stage impulse turbine is given by

$$\eta_{bl} = \frac{W_t}{\frac{C_1^2}{2}} = 4C_{bl}\,[C_1\cos\alpha_1 - 2C_{bl}] \times \frac{2}{C_1^2}$$

$$= \frac{8C_{bl}}{C_1^2}\,(C_1\cos\alpha - 2C_{bl})$$

$$= 8\,\frac{C_{bl}}{C_1}\left(\cos\alpha - 2\,.\frac{C_{bl}}{C_1}\right)$$

$$= 8\rho\,(\cos\alpha - 2\rho) \qquad ...(3.54)$$

where, ρ (velocity ratio) $= \dfrac{C_{bl}}{C_1}$.

The blade efficiency for two stage turbine will be maximum when $\dfrac{d\eta_{bl}}{d\rho} = 0$

$$\therefore \quad \frac{d}{d\rho}\,[8\rho\cos\alpha - 16\rho^2] = 0$$

$$\therefore \quad 8\cos\alpha - 32\rho = 0$$

From which, $\rho = \dfrac{\cos\alpha}{4}$ ...(3.55)

Substituting this value in eqn. (3.54), we get

$$(\eta_{bl})_{max} = 8\cdot\frac{\cos\alpha}{4}\left[\cos\alpha - 2\,\frac{\cos\alpha}{4}\right] = \cos^2\alpha \qquad ...(3.56)$$

The maximum work done per kg of steam is obtained by substituting the value of

$$\rho = \frac{C_{bl}}{C_1} = \frac{\cos\alpha}{4}$$

or, $C_1 = \dfrac{4C_{bl}}{\cos\alpha}$ in the eqn. (3.53).

$$\therefore (W_b)_{max} = 4C_{bl}\left(\frac{4C_{bl}}{\cos\alpha}\,.\cos\alpha - 2C_{bl}\right)$$

$$= 8C_{bl}^2 \qquad ...(3.57)$$

The present analysis is done for *two stages* only. The similar procedure is adopted for analysing the problem with three or four stages.

In general, optimum blade speed ratio for maximum blade efficiency or maximum work done is given by

$$\rho = \frac{\cos\alpha}{2\cdot n} \qquad ...(3.58)$$

and work done in the last row = $\dfrac{1}{2^n}$ of total work ...(3.59)

where, n is the number of moving/rotating blade rows in series.

As the number of rows increases, the utility of last row decreases. In practice, *more than* two rows are hardly preferred.

3.19.7.5. Advantages of velocity-compounded impulse turbine

1. Owing to relatively large heat drop, a velocity-compounded impulse turbine requires a comparatively small number of stages.

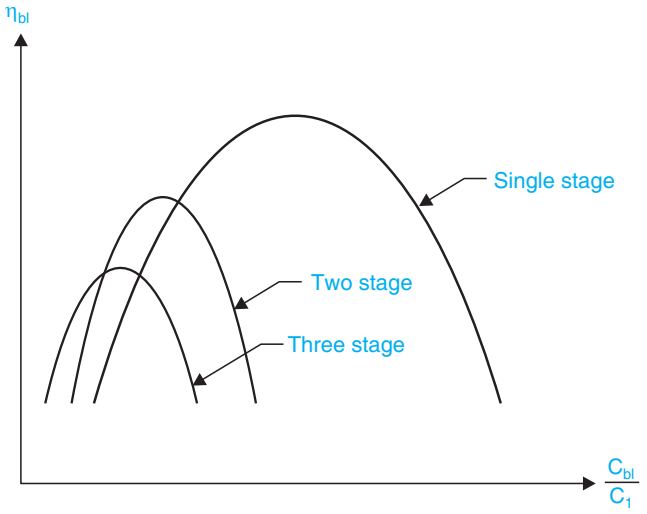


Fig. 3.93

2. Due to number of stages being small, its cost is less.
3. As the number of moving blades rows in a wheel increases, the maximum stage efficiency and optimum value of ρ decreases.
4. Since the steam temperature is sufficiently low in a two or three row wheel, therefore, cast iron cylinder may used. This will cause saving in material cost.

Disadvantages of velocity-compounded impulse turbine :

1. It has high steam consumption and low efficiency (Fig. 3.93).
2. In a single row wheel, the steam temperature is high so cast iron cylinder cannot be used due to phenomenon of growth ; cast steel cylinder is used which is costlier than cost iron.

3.19.8. Reaction Turbines

The reaction turbines which are used these days are really **impulse-reaction** turbines. Pure reaction turbines are not in general use. The expansion of steam and heat drop occur both in fixed and moving blades.

3.19.8.1. Velocity diagram for reaction turbine blade

Fig. 3.94 shows the velocity diagram for reaction turbine blade. In case of an impulse turbine blade the relative velocity of steam either remains constant as the steam glides over the blades or is reduced slightly due to friction. In reaction turbine blades, the steam continuously expands at it flows over the blades. *The effect of the continuous expansion of steam during the flow over the blade is to increase the relative velocity of steam.*

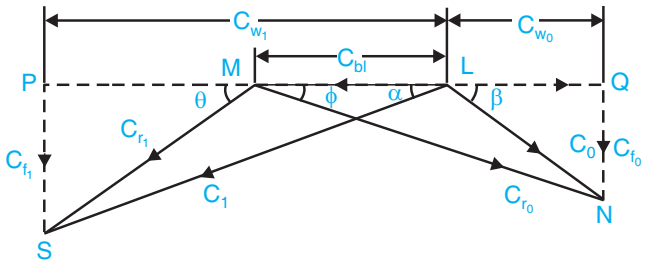


Fig. 3.94. Velocity diagram for reaction turbine blade.

$$\therefore \quad C_{r_0} > C_{r_1} \text{ for } \textit{reaction turbine blade.}$$

$$(C_{r_0} \le C_{r_1} \text{ for } \textit{impulse turbine blade}).$$

3.19.8.2. Degree of reaction (R_d)

The *"degree of reaction"* of *reaction turbine stage is defined* as the *ratio of heat drop over moving blades to the total heat drop in the stage.*

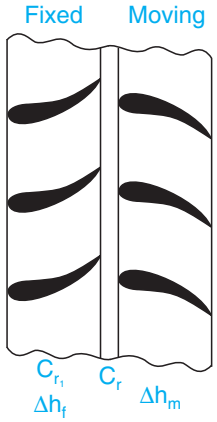
Thus the *degree of reaction of reaction turbine* is given by,

$$R_d = \frac{\text{Heat drop in moving blades}}{\text{Heat drop in the stage}}$$

$$= \frac{\Delta h_m}{\Delta h_f + \Delta h_m} \text{ as shown in Fig. 3.95.}$$

The heat drop in moving blades is equal to increase in relative velocity of steam passing through the blade.

$$\therefore \quad \Delta h_m = \frac{C_{r_0}^{\,2} - C_{r_1}^{\,2}}{2}$$



(a)

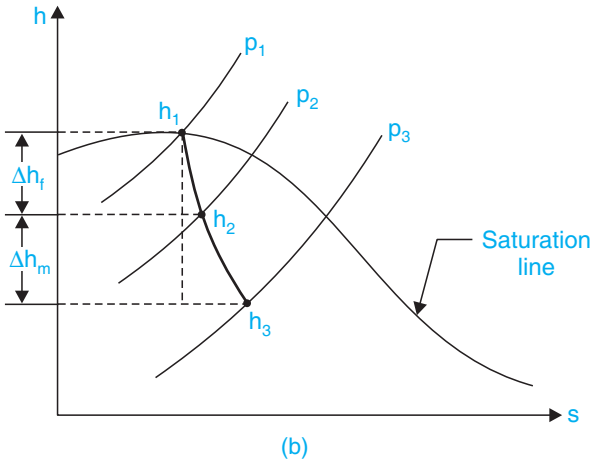


Fig. 3.95

The total heat drop in the stage $(\Delta h_f + \Delta h_m)$ is equal to the work done by the steam in the stage and it is given by

$$\Delta h_f + \Delta h_m = C_{bl}\,(C_{w_1} + C_{w_0})$$

$$\therefore \qquad R_d = \frac{C_{r_0}^{\,2} - C_{r_1}^{\,2}}{2C_{bl}(C_{w_1} + C_{w_0})} \qquad \ldots(3.60)$$

Referring to Fig. 3.94,

$$C_{r_0} = C_{f_0} \text{ cosec } \phi \text{ and } C_{r_1} = C_{f_1} \text{ cosec } \theta$$

and, $(C_{w_1} + C_{w_0}) = C_{f_1} \cot \theta + C_{f_0} \cot \phi$

The velocity of flow generally remains constant through the blades.

$$\therefore \qquad C_{f_1} = C_{f_0} = C_f\,.$$

Substituting the values of C_{r_1}, C_{r_0} and $(C_{w_1} + C_{w_0})$ in eqn. (3.60), we get:

$$R_d = \frac{C_f^{\,2}\,(\text{cosec}^2\,\phi - \text{cosec}^2\,\theta)}{2\,C_{bl}\,C_f\,(\cot\theta + \cot\phi)}$$

$$= \frac{C_f}{2C_{bl}}\left[\frac{(\cot^2\phi + 1) - (\cot^2\theta + 1)}{\cot\theta + \cot\phi}\right]$$

$$= \frac{C_f}{2C_{bl}}\left[\frac{\cot^2\phi - \cot^2\theta}{\cot\phi + \cot\theta}\right]$$

$$= \frac{C_f}{2C_{bl}}\,(\cot\phi - \cot\theta) \qquad \ldots(3.61)$$

If the turbine is designed for 50% reaction $(\Delta h_f = \Delta h_m)$, then the equation (3.61) can be written as

$$\frac{1}{2} = \frac{C_f}{2C_{bl}}\,(\cot\phi - \cot\theta)$$

$$\therefore \qquad C_{bl} = C_f(\cot\phi - \cot\theta) \qquad \ldots(3.62)$$

Also, C_{bl} can be written as:

$$C_{bl} = C_f(\cot\phi - \cot\beta) \qquad \ldots(3.63)$$

and, $$C_{bl} = C_f(\cot\alpha - \cot\theta) \qquad \ldots(3.64)$$

$$C_{f_1} = C_{f_0} = C_f$$

is assumed in writing the above equations.

Comparing the equations (3.62), (3.63), (3.64)

$$\theta = \beta \text{ and } \phi = \alpha$$

which *means that moving blade and fixed blade* must have the same shape if the degree of reaction is 50%. This condition gives symmetrical velocity diagrams. This type of turbine is known as "**Parson's reaction turbine**". Velocity diagram for the blades of this turbine is given in Fig. 3.96.

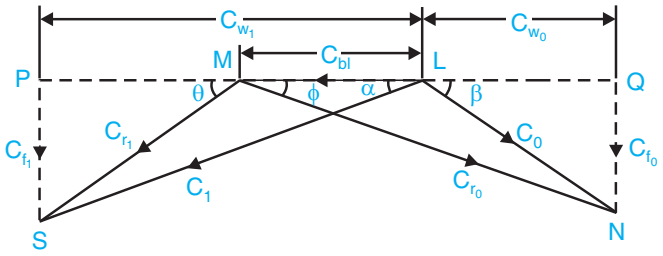


Fig. 3.96

3.19.8.3. Condition for maximum efficiency

The condition for *maximum efficiency* is derived by making the following *assumptions* :

(*i*) The degree of reaction is 50%.

(*ii*) The moving and fixed blades are symmetrical.

(*iii*) The velocity of steam at exit from the preceeding stage is same as velocity of steam at the entrance to the succeeding stage.

Refer to Fig. 3.96 (velocity diagram for reaction blade).

Work done per kg of steam,

$$W = C_{bl}\,(C_{w_1} + C_{w_0})$$

$$= C_{bl}[C_1 \cos\alpha + (C_{r_0} \cos\phi - C_{bl})]$$

as, $\phi = \alpha$ and $C_{r_0} = C_{r_1}$ as per the assumptions.

$$\therefore \qquad W = C_{bl}\,[2C_1 \cos\alpha - C_{bl}]$$

or, $$W = C_1^{\,2}\left[\frac{2C_{bl}\,C_1\cos\alpha}{C_1^{\,2}} - \frac{C_{bl}^{\,2}}{C_1^{\,2}}\right]$$

$$= C_1^{\,2}\,[2\rho \cdot \cos\alpha - \rho^2] \qquad \ldots(3.65)$$

where, $$\rho = \frac{C_{bl}}{C_1}\,.$$

The K.E. supplied to the fixed blade $= \dfrac{C_1^{\,2}}{2g}\,.$

The K.E. supplied to the moving blade $= \dfrac{C_{r_0}^{\,2} - C_{r_1}^{\,2}}{2}\,.$

∴ Total energy supplied to the stage,

$$\Delta h = \frac{C_1^2}{2} + \frac{C_{r_0}^2 - C_{r_1}^2}{2}$$

as $C_{r_0} = C_1$ for symmetrical triangles.

$$\therefore \quad \Delta h = \frac{C_1^2}{2} + \frac{C_1^2 - C_{r_1}^2}{2}$$

$$= C_1^2 - \frac{C_{r_1}^2}{2} \qquad ...(3.66)$$

Considering the ΔLMS (Fig. 3.94)

$$C_{r_1}^2 = C_1^2 + C_{bl}^2 - 2C_1 \cdot C_{bl} \cdot \cos \alpha$$

Substituting this value of $C_{r_1}^2$ is equation (3.66).

Total energy supplied to the stage

$$\Delta h = C_1^2 - (C_1^2 + C_{bl}^2 - 2C_1 \cdot C_{bl} \cdot \cos \alpha)/2$$

$$= (C_1^2 + 2C_1 C_{bl} \cos \alpha - C_{bl}^2)/2$$

$$= \frac{C_1^2}{2}\left[1 + \frac{2C_{bl}}{C_1} . \cos \alpha - \left(\frac{C_{bl}}{C_1}\right)^2\right]$$

$$= \frac{C_1^2}{2}[1 + 2\rho \cos \alpha - \rho^2] \qquad ...(3.67)$$

The blade efficiency of the reaction turbine is given by,

$$\eta_{bl} = \frac{W}{\Delta h}$$

Substituting the value of W and Δh from equations (3.65) and (3.67),

$$\eta_{bl} = \frac{C_1^2 [2\rho \cos \alpha - \rho^2]}{\frac{C_1^2}{2}(1 + 2\rho \cos \alpha - \rho^2)}$$

$$= \frac{2(2\rho \cos \alpha - \rho^2)}{(1 + 2\rho \cos \alpha - \rho^2)}$$

$$= \frac{2\rho(2 \cos \alpha - \rho)}{(1 + 2\rho \cos \alpha - \rho^2)}$$

$$= \frac{2(1 + 2\rho \cos \alpha - \rho^2) - 2}{(1 + 2\rho \cos \alpha - \rho^2)}$$

$$= 2 - \frac{2}{1 + 2\rho \cos \alpha - \rho^2} \qquad ...(3.68)$$

The η_{bl} becomes maximum when the value of $(1 + 2\rho \cos \alpha - \rho^2)$ becomes maximum.

∴ The required equation is

$$\frac{d}{d\rho}(1 + 2\rho \cos \alpha - \rho^2) = 0$$

$$2 \cos \alpha - 2\rho = 0$$

$$\therefore \quad \rho = \cos \alpha \qquad ...(3.69)$$

Substituting the value of ρ from eqn. (3.69) into the eqn. (3.68), the value of maximum efficiency is given by,

$$(\eta_{bl})_{max.} = 2 - \frac{2}{1 + 2\cos^2 \alpha - \cos^2 \alpha}$$

$$= 2\left(1 - \frac{1}{1 + \cos^2 \alpha}\right) = \frac{2\cos^2 \alpha}{1 + \cos^2 \alpha}$$

Hence, $$(\eta_{bl})_{max.} = \frac{2\cos^2 \alpha}{1 + \cos^2 \alpha} \qquad ...(3.70)$$

The variation of η_{bl} with blade speed ratio $\left(\frac{C_{bl}}{C_1}\right)$ for the reaction stage is shown in Fig. 3.97.

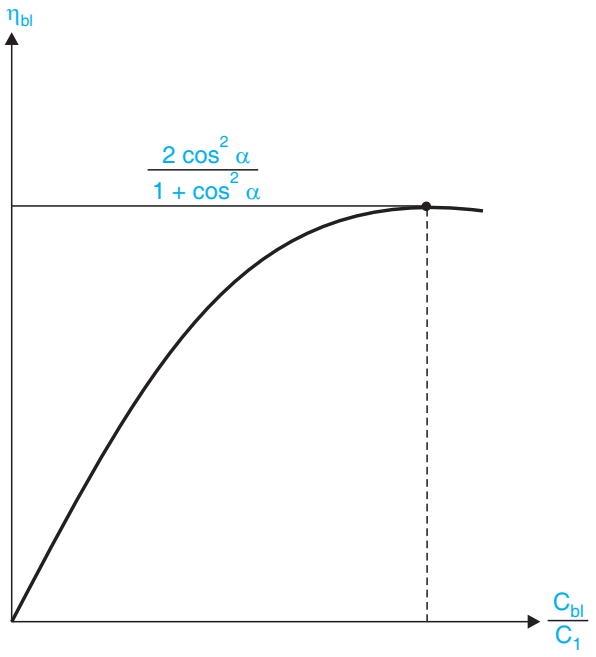


Fig. 3.97

3.19.9. Turbine Efficiencies

1. Blade or diagram efficiency (η_{bl}). *It is the ratio of work done on the blade per second to the energy entering the blade per second.*

2. Stage efficiency (η_{stage}). The stage efficiency covers all the losses in the nozzles, blades, diaphragms and discs that are associated with that stage.

$$\eta_{stage} = \frac{\text{Network done on shaft per stage per kg of steam flowing}}{\text{Adiabatic heat drop per stage}}$$

$$= \frac{\text{Network done on blades} - \text{Disc friction and windage}}{\text{Adiabatic heat drop per stage}}.$$

3. Internal efficiency ($\eta_{internal}$). This is equivalent to the stage efficiency when applied to the whole turbine, and is defined as :

$$= \frac{\text{Heat coverted into useful work}}{\text{Total adiabatic heat drop}}.$$

4. Overall or turbine efficiency ($\eta_{overall}$). This efficiency covers internal and external losses ; for example, bearings and steam friction, leakage, radiation etc.

$$\eta_{overall} = \frac{\text{Work delivered at the turbine coupling in heat units per kg of steam}}{\text{Total adiabatic heat drop}}.$$

.

5. Net efficiency or efficiency ratio (η_{net}). It is the ratio

$$\frac{\text{Brake thermal efficiency}}{\text{Thermal efficiency on the Rankine cycle}}$$

Also the actual thermal efficiency

$$= \frac{\text{Heat converted into useful work per kg of steam}}{\text{Total heat in steam at stop valve} - \text{Water heat in exhaust}}.$$

Again, Rankine efficiency

$$= \frac{\text{Adiabatic heat drop}}{\text{Total heat in steam at stop valve} - \text{Water heat in exhaust}}.$$

$$\eta_{net} = \frac{\text{Heat converted into useful work}}{\text{Total adiabatic heat drop}}.$$

Hence $\eta_{net} = \eta_{overall.}$

It is the overall or net efficiency that is meant when the efficiency of a turbine is spoken of without qualification.

3.19.10. Types of Power in Steam Turbine Practice

In steam turbine performance the following types of power are generally used :

1. Adiabatic power (A.P.). It is the power based on the total internal steam flow and adiabatic heat drop.

2. Shaft power (S.P.). It is the actual power transmitted by the turbine.

3. Rim power (R.P.). It is the power developed at the rim. It is also called *blade power*.

Power losses are usually expressed as follows :

(*i*) $(P)_D$ = Power lost in overcoming disc friction.

(*ii*) $(P)_{bw}$ = Power lost in blade windage losses.

Let us consider the case, of an impulse turbine. Let $\dot{m}_s$ be the total internal steam flow in kg/s.

Refer to Fig. 3.98. The line (1-2) represents the adiabatic or isentropic expansion of steam in the nozzle from pressure p_1 to p_2. But the actual path of the stage point during expansion in nozzles is shown by (1-3) which takes into account the effect of 'nozzles losses'.

Then, A.P. = $\dot{m}_s\ (h_1 - h_2)$ kW ...(3.71)

After expansion in the nozzle the steam enters the blades where the R.P. is developed. Due to blade friction the steam is somewhat reheated and this reheating is shown by (3-4) along the constant pressure p_2 line just for convenience. But in actual practice though the pressure at outlet of the blade is equal to that at the inlet, the pressure in the blade channels is not constant. However, with this simplification ;

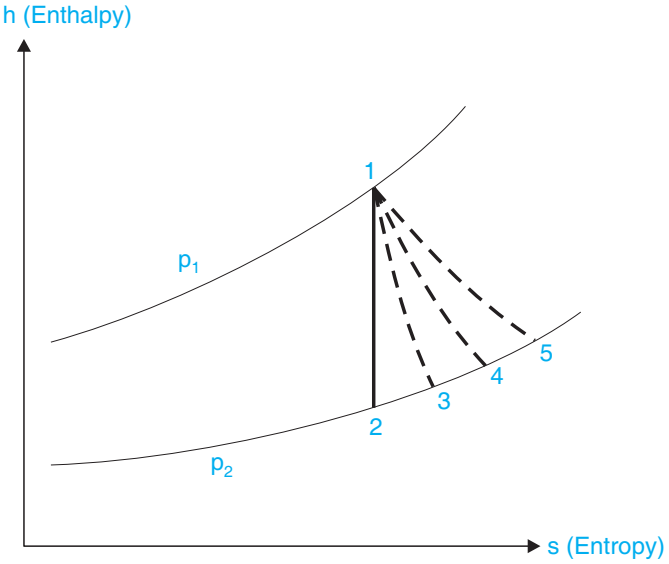


Fig. 3.98

R.P. = $\dot{m}_s\ (h_1 - h_4)$ kW ...[3.71 (*a*)]

4-5 shows the further reheating due to friction and blade windage and these losses are given as

$(P)_{w.f.} = \dot{m}_s\ (h_5 - h_4)$ kW ...[3.71 (*b*)]

Now points 1 and 5 are the initial and final stage points respectively for a single stage impulse turbine. It, therefore, follows that

S.P. = $\dot{m}_s\ (h_1 - h_5)$ kW. ...[3.71 (*c*)]

3.19.11. Energy Losses in Steam Turbines

The increase in heat energy required for doing mechanical work in actual practice as compared to the theoretical value, in which the process of expansion takes place strictly according to the adiabatic process, is termed as energy loss in a steam turbine.

The losses which appear in an actual turbine may be divided into two following groups :

1. Internal losses. Losses directly connected with the steam conditions while in its flow through the turbine

are called *internal losses*. They may be further classified as :

(*i*) Losses in regulating valves.

(*ii*) Losses in nozzles (guide blades).

(*iii*) Losses in moving blades :

(*a*) losses due to trailing edge wake ;

(*b*) impingement losses ;

(*c*) losses due to leakage of steam through the angular space ;

(*d*) frictional losses ;

(*e*) losses due to turning of the steam jet in the blades ;

(*f*) losses due to shrouding.

(*iv*) Leaving velocity losses (exit velocity).

(*v*) Losses due to friction of disc carrying the blades and windage losses.

(*vi*) Losses due to clearance between the rotor and guide blade discs.

(*vii*) Losses due to wetness of steam.

(*viii*) Losses in exhaust piping etc.

2. External losses. Losses which do not influence the steam conditions. They may be further classified as :

(*i*) Mechanical losses.

(*ii*) Losses due to leakage of steam from the labyrinth gland seals.

3.19.12. Steam Turbine Governing and Control

The objective of governing is to keep the turbine speed fairly constant irrespective of load.

The principal methods of steam turbine governing are as follows :

1. Throttle governing
2. Nozzle governing
3. By-pass governing
4. Combination of 1 and 2 and 1 and 3.

1. Throttle governing

Throttle governing is the most widely used particularly on *small turbines,* because *its initial cost is less* and *the mechanism is simple*. The object of throttle governing is to *throttle the steam,* whenever, *there is a reduction of load* compared to economic or design load for maintaining speed and *vice versa*.

Fig. 3.99 (*a*) shows a simple throttle arrangement. To start the turbine for full load running valve *A* is opened. The operation of double beat valve *B* is carried out by an oil servomotor which is controlled by a centrifugal governor. As the steam turbine gains speed the valve *B* closes to throttle the steam and reduces the supply to the nozzle.

For a turbine governed by throttling the relationship between steam consumption and load is given by the well known *Willan's line* as shown in Fig. 3.99 (*b*). Several tests have shown that when a turbine is governed by throttling, the Willan's line is straight. It is expressed as :

$$m_s = KM + m_{s_0} \qquad ...(3.72)$$

where, $\dot{m}_s$ = Steam consumption in kg/h at any load *M*,

m_{s_0} = Steam consumption in kg/h at no load,

m_{s_1} = Steam consumption in kg/h at full load,

M = Any other load in kW,

M_1 = Full load in kW, and

K = Constant.

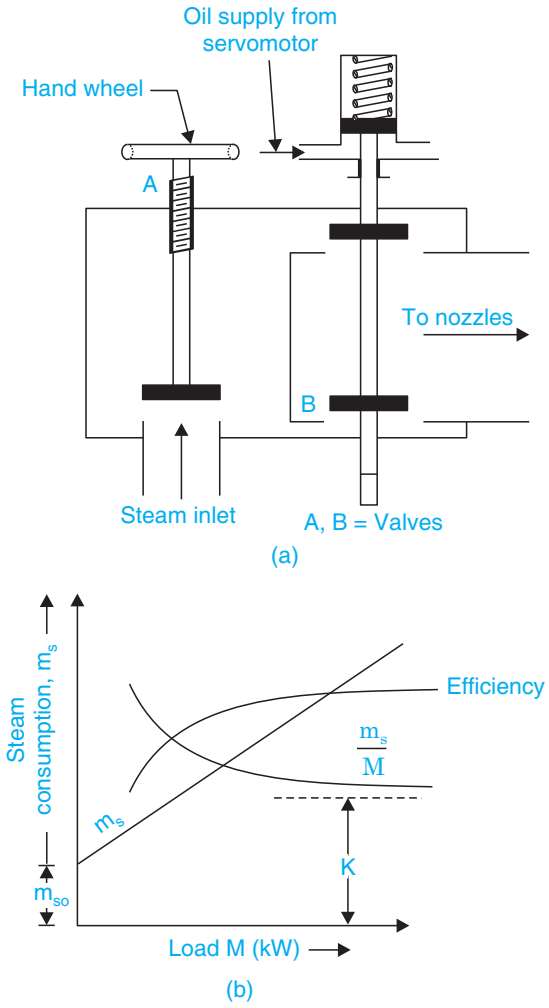


Fig. 3.99. Throttle governing.

m_{s_0} varies from about 0.1 to 0.14 times the full load consumption. The eqns. (3.72) can also be written as :

$$\frac{m_s}{M} = K + \frac{m_{s_0}}{M}$$

where, $\frac{m_s}{M}$ is called the steam consumption per kWh.

2. Nozzle governing

The efficiency of a steam turbine is considerably reduced if throttle governing is carried out at low loads. An alternative, and more efficient form of governing is by means of nozzle control. Fig. 3.100 shows a diagrammatic arrangement of typical nozzle control governing. In this method of governing, the nozzles are grouped together 3 to 5 or more groups and supply of steam to each group is controlled by regulating valves. Under full load conditions the valves remain fully open.

When the load on the turbine becomes more or less than the design value, the supply of steam to a group of nozzles may be varied accordingly so as to restore the original speed.

Nozzle control can only be applied to the first stage of a turbine. It is suitable for *simple impulse turbine* and *larger units which have an impulse stage followed* by an *impulse-reaction turbine*. In pressure compounded impulse turbines, there will be some drop in pressure at entry to second stage when some of the first stage nozzles are cut out.

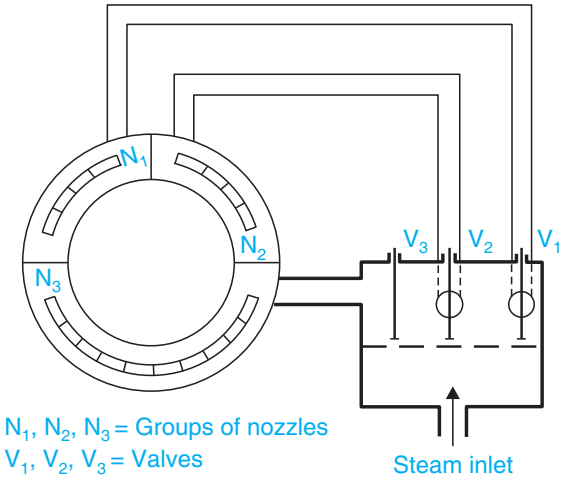


Fig. 3.100. Nozzle governing.

Comparison of Throttle and Nozzle Control Governing

S.No.	Particulars	Throttle control	Nozzle control
1.	*Throttling losses*	Severe	No throttling losses (Actually there are a little throttling losses in nozzles valves which are partially open).
2.	*Partial admission losses*	Low	High
3.	*Heat drop available*	Lesser	Larger
4.	*Use*	Used in impulse and reaction turbines both.	Used in impulse turbine and also in reaction turbine (if initial stage is impulse)
5.	*Suitability*	Small turbines	Medium and larger turbines.

3. By-pass governing

The steam turbines which are designed to work at economic load it is desirable to have full admission of steam in the high pressure stages. At the maximum load, which is greater than the economic load, the additional steam required could not pass through the first stage since additional nozzles are not available. By-pass regulation allows for this in a turbine which is throttle governed, by means of a second by-pass valve in the first stage nozzle (Fig. 3.101). This valve opens when throttle valve has opened a definite amount. Steam is by-passed through the second valve to a lower stage in the turbine. When by-pass valve operates it is under the control of the turbine governor. The secondary and tertiary supplies of steam in the lower stages increase the work output in these stages, but there is a *loss in efficiency* and a curving of the Willian's line.

In reaction turbines, because of the pressure drop required in the moving blades, nozzles control governing is not possible, and *throttle governing plus by-pass governing, is used*.

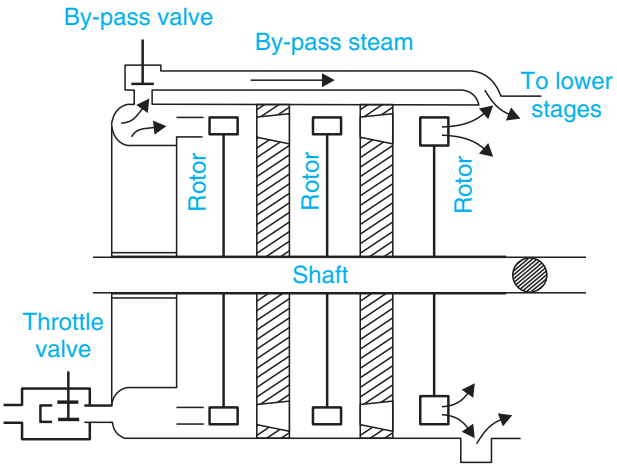


Fig. 3.101. By-pass governing.

3.19.13. Special Forms of Turbines

In many industries such as chemical, sugar refining, paper making, textile etc. where combined use of power and heating and process work is required it is wasteful to generate steam for power and process purposes separately, because about 70 per cent of heat supplied for power purposes will normally be carried away by the cooling water. On the other hand, if the engine or turbine is operated with a normal exhaust pressure then the temperature of the exhaust steam is too low to be of any use for heating process. It would be possible to generate the required power and still have available for process work a large quantity of heat in the exhaust steam, if suitable modification of the initial steam pressure and exhaust pressure is made. Thus in combined power and process plants following types of steam turbines are used : (1) Back pressure turbines, and (2) Steam extraction or pass-out turbines.

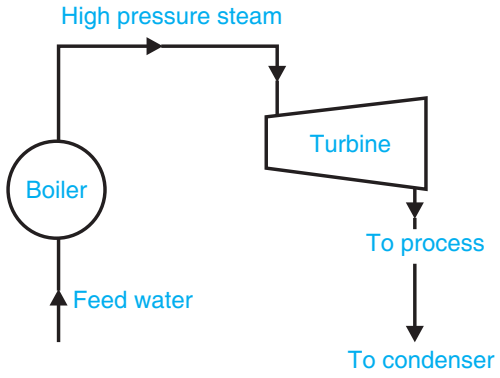


Fig. 3.102. Back pressure turbine.

1. *Back pressure turbine :*

Refer to Fig. 3.102. In this type of turbine steam at boiler pressure enters the turbine and is exhausted into a pipe. This pipe leads to process plant or other turbine. The back pressure turbine may be used in cases where the power generated (by expanding steam) from economical initial pressure down to the heating pressure is equal to, or greater than, the power requirements. The steam exhausted from the turbine is usually superheated and in most cases it is not suitable for process work due to the following *reasons* :

(*i*) It is impossible to control its temperature, and

(*ii*) Rate of the heat transfer from superheated steam to the heating surface is lower than that of saturated steam. Consequently a desuperheater is invariably used. To enhance the power capacity of the existing installation, a high pressure boiler and a back-pressure turbine are added to it. This added high pressure boiler supplies steam to the back pressure turbine which exhaust into the old low pressure turbine.

2. *Extraction pass out turbine :*

Refer to Fig. 3.103. It is found that in several cases the power available from a back pressure turbine (through which the whole of the steam flows) is appreciably less than that required in the factory and this may be due to the following reasons :

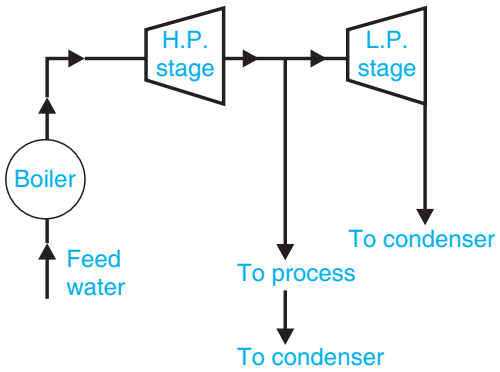


Fig. 3.103. Extraction pass out turbine.

(*i*) Small heating or process requirements ;

(*ii*) A relatively high exhaust pressure ; and

(*iii*) A combination of the both.

In such a case it would be possible to install a back-pressure turbine to provide the heating steam and a condensing tubing to generate extra power, but it is possible, and useful, to combine functions of both machines in a single turbine. Such a machine is called **extraction or pass out turbine** and here at some point intermediate between inlet and exhaust some steam is extracted or passed out for process or heating purposes. In this type of turbine a sensitive governor is used which controls the admission of steam to the high pressure section so that regardless of power or process requirements, constant speed is maintained.

3. *Exhaust or low pressure turbine :*

If an uninterrupted supply of low pressure steam is available (such as from reciprocating steam engines exhaust) it is possible to improve the efficiency of the whole plant by fitting an exhaust or low pressure turbine. The use of exhaust turbine is chiefly made where there are several reciprocating steam engines which work intermittently ; and are non-condensing (*e.g.* rolling mill and colliery engines). The exhaust steam from these engines is expanded in an exhaust turbine and then condensed. In this turbine some form of heat accumulator is needed to collect the more or less irregular supply of low pressure steam from the non-condensing steam engines and deliver it to the turbine at the rate required. In some cases when the supply of low pressure steam falls below the demand, live steam from the boiler, with its pressure and temperature reduced ; is used to make up the deficiency.

The necessary drop in pressure may be obtained by the use of a reducing valve, or for large flows, more economically by expansion through another turbine. The high pressure and low pressure turbines are sometimes combined on a common spindle and because of two supply pressures this combined unit is known as '**mixed pressure turbine**' (Fig. 3.104).

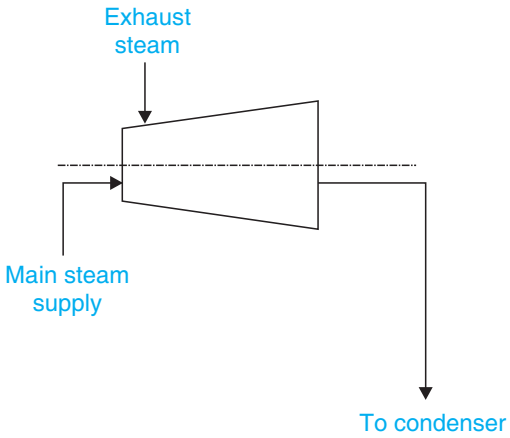


Fig. 3.104. Mixed pressure turbine.

☞**Example 3.13.** *Steam with absolute velocity of 300 m/s is supplied through a nozzle to a single stage impulse turbine. The nozzle angle is 25°. The mean diameter of the blade rotor is 1 metre and it has a speed of 2000 r.p.m. Find suitable blade angles for zero axial thrust. If the blade velocity co-efficient is 0.9 and the steam flow rate is 10 kg/s, calculate the power developed.*

Solution. Absolute velocity of steam entering the blade, C_1 = 300 m/s

Nozzle angle, $\alpha = 25°$

Mean diameter of the rotor blade, D = 1 m

Speed of the rotor, N = 2000 r.p.m.

Blade velocity co-efficient, K = 0.9

Steam flow rate, $\dot{m}_s$ = 10 kg/s

Power developed :

Blade speed, $C_{bl} = \frac{\pi DN}{60} = \frac{\pi \times 1 \times 2000}{60}$

= 105 m/s.

— With the above data (*i.e.*, C_1 = 300 m/s, C_{bl} = 105 m/s and $\alpha = 25°$) draw triangle *LMS* (Fig. 3.105). From *S* draw perpendicular *SP* on *LM* produced. Measure C_{r_1}.

— From *S* draw a line parallel to *LP* ($\because C_{f_1} = C_{f_0}$) and from point *M* draw an arc equal to $C_{r_0} (= 0.9\, C_{r_1})$ to get the point of intersection *N*. Complete the triangle *LMN*. From *N* draw perpendicular *NQ* on *PL* produced to get C_{f_0}.

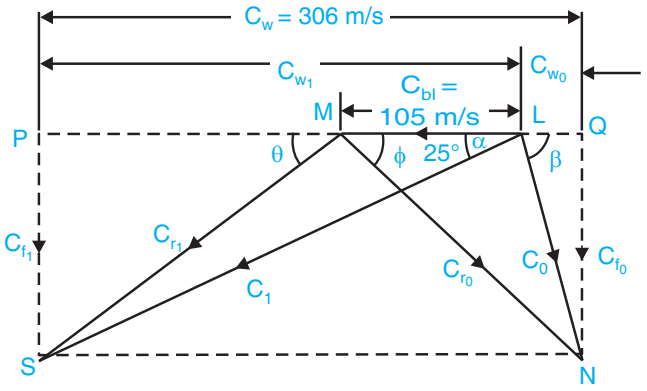


Fig. 3.105

Measure θ and ϕ (the blade angles) from the velocity diagram.

(*i*) θ = **37°** and ϕ = **42°.** **(Ans.)**

(*ii*) *Power developed,*

$$P = \frac{\dot{m}_s (C_{w_1} + C_{w_0}) \times C_{bl}}{1000} = \frac{10 \times 306 \times 105}{1000}$$

= **321.3 kW.** **(Ans.)**

☞**Example 3.14.** *In an impulse turbine (with a single row wheel) the mean diameter of the blades is 1.05 m and the speed is 3000 r.p.m. The nozzle angle is 18°, the ratio of blade speed to steam speed is 0.42 and the ratio of the relative velocity at outlet from the blades to that at inlet is 0.84. The outlet angle of the blade is to be made 3° less than the inlet angle. The steam flow is 10 kg/s. Draw the velocity diagram for the blades and derive the following :*

(*i*) *Tangential thrust on the blades.*

(*ii*) *Axial thrust on the blades.*

(*iii*) *Resultant thrust on the blades.*

(*iv*) *Power developed in the blades.*

(*v*) *Blading efficiency.*

Solution. Mean diameter of the blades, $D = 1.05$ m

Speed of the turbine, $N = 3000$ r.p.m.

Nozzle angle, $\alpha = 18°$

Ratio of blade speed to steam speed,

$\rho = 0.42$

Ratio, $\dfrac{C_{r_1}}{C_{r_0}} = 0.84$

Outlet blade angle, $\phi = \theta - 3°$

Steam flow rate, $\dot{m}_s = 10$ kg/s

Blade speed, $C_{bl} = \dfrac{\pi DN}{60} = \dfrac{\pi \times 1.05 \times 3000}{60}$

$= 164.5$ m/s

But, $\rho = \dfrac{C_{bl}}{C_1} = 0.42$ (given)

$\therefore$ $C_1 = \dfrac{C_{bl}}{0.42} = \dfrac{164.5}{0.42} = 392$ m/s

With the data, $C_1 = 392$ m/s ;

$\alpha = 18°$, complete ΔLMS

$\theta = 30°$ (on measurement)

$\therefore$ $\phi = 30° - 3 = 27°$

Now complete the ΔLMN by taking

$\phi = 27°$ and $C_{r_0} = 0.84\ C_{r_1}$.

Finally complete the whole diagram as shown in Fig. 3.106.

(*i*) Tangential thrust on the blades

$= \dot{m}_s(C_{w_1} + C_{w_0}) = 10 \times 390$

$=$ **3900 N.** **(Ans.)**

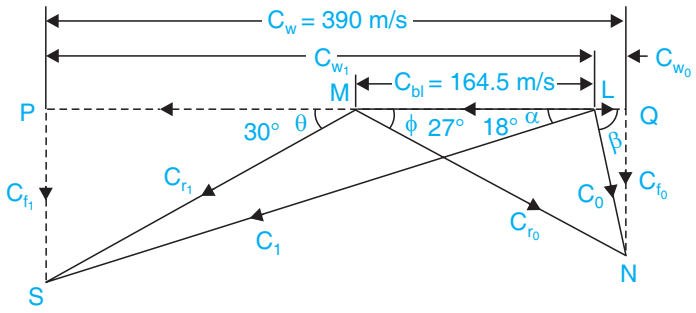


Fig. 3.106

(*ii*) Axial thrust

$= \dot{m}_s(C_{f_1} - C_{f_0}) = 10\ (120 - 95)$

$=$ **250 N.** **(Ans.)**

(*iii*) Resultant thrust

$= \sqrt{(3900)^2 + (250)^2}$ **= 3908 N.** **(Ans.)**

(*iv*) Power developed

$= \dfrac{\dot{m}_s(C_{w_1} + C_{w_0}) \times C_{bl}}{1000}$

$= \dfrac{10 \times 390 \times 164.5}{1000}$

$=$ **641.55 kW.** **(Ans.)**

(*v*) Blading efficiency

$\eta_{bl} = \dfrac{2\,C_{bl}\,(C_{w_1} + C_{w_0})}{C_1^{\,2}} = \dfrac{2 \times 164.5 \times 390}{392^2}$

$=$ **83.5%.** **(Ans.)**

Example 3.15. *In a stage of impulse reaction turbine provided with single row wheel, the mean diameter of the blades in 1 m. It runs at 3000 r.p.m. The steam issues from the nozzle at a velocity of 350 m/s and the nozzle angle is 20°. The rotor blades are equiangular. The blade friction factor is 0.86. Determine the power developed if the axial thrust on the end bearing of a rotor is 118 N.*

Solution. Mean diameter of the blades,

$D = 1$ m

Speed of the turbine, $N = 3000$ r.p.m.

Velocity of steam issuing from the nozzle,

$C_1 = 350$ m/s

Nozzle angle, $\alpha = 20°$

Blade angles, $\theta = \phi$

Blade friction factor, $K = 0.86$

Axial thrust $= 118\ N$

Blade, velocity, $C_{bl} = \dfrac{\pi DN}{60} = \dfrac{\pi \times 1 \times 3000}{60}$

$= 157$ m/s

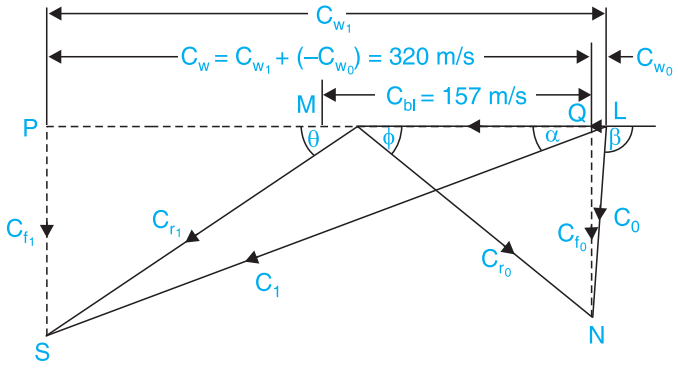


Fig. 3.107

— With the data, $C_{bl} = 157$ m/s, $C_1 = 350$ m/s, $\alpha = 20°$ draw the ΔLMS (Fig. 3.107).

By measurement, $\theta = 35°$

Since the *blades are equiangular,*

$$\theta = \phi = 35°$$

— Now with $\phi = 35°$ and $C_{r_0} = 0.86\ C_{r_1}$, complete the ΔLMN.

On measurement ; $C_{f_1} = 122$ m/s, $C_{f_0} = 102.5$ m/s

Also, axial thrust $\dot{m}_s(C_{f_1} - C_{f_0}) = 118$

$$\therefore \quad \dot{m}_s = \frac{118}{C_{f_1} - C_{f_0}} = \frac{118}{(120 - 102.5)}$$

$$= 6.74 \text{ kg/s}$$

Further in this case,

$$C_w = C_{w_1} + C_{w_0} = C_{w_1} + (-C_{w_0}) = 320 \text{ m/s}$$

Now, *power developed,*

$$P = \frac{\dot{m}_s(C_{w_1} + C_{w_0}) \times C_{bl}}{1000} \text{ kW}$$

$$= \frac{6.74 \times 320 \times 157}{1000}$$

$$= \mathbf{338.6\ kW.} \quad \textbf{(Ans.)}$$

☞ **Example 3.16.** *The first stage of an impulse turbine is compounded for velocity and has two rows of moving blades and one ring of fixed blades. The nozzle angle is 15° and the leaving angles of blades are respectively, first-moving 30°, fixed 20° ; second-moving 30°. The velocity of steam leaving the nozzle is 540 m/s. The friction loss in each blade row is 10% of the relative velocity. Steam leaves the second row of moving blades axially.*

Find : (*i*) *Blade velocity*

(*ii*) *Blade efficiency*

(*iii*) *Specific steam consumption.*

Solution. Refer to Fig. 3.108.

Nozzle angle, $\alpha = 15° ; \alpha' = 20°$

$\beta' = 90°$

[Since the steam leaves the blades *axially*]

$\phi = \phi' = 30°$

Velocity of steam leaving the nozzle, $C_1 = 540$ m/s

$$\frac{C_{r_0}}{C_{r_1}} = 0.9$$

$$\frac{C_1'}{C_0} = 0.9$$

$$\frac{C_{r_0}'}{C_{r_1}'} = 0.9$$

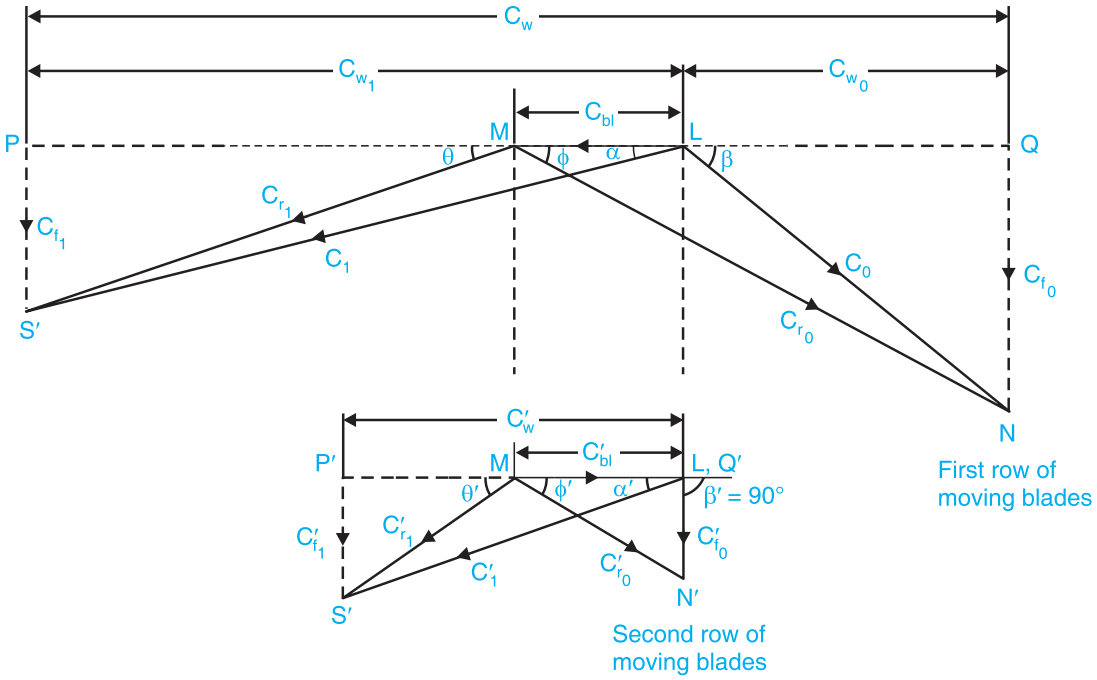


Fig. 3.108

Second row of moving blades :

The velocity triangles should be drawn starting from the second row of moving blades.

The procedure is as follows **:** Refer to Fig. 3.108.

— Draw LM to any convenient scale (say 3 cm) as C_{bl} is not known.

— Draw $\phi' = 30°$ and draw perpendicular through the point L (or Q') to LM as $\beta' = 90°$. This meets the line MN' at N'. This completes the outlet triangle LMN'.

— Measure $C_{r_0}' = MN' = 3.5$ cm

$$C_{r_1}' = \frac{C_{r_0}}{0.9} = \frac{3.5}{0.9} = 3.9 \text{ cm.}$$

— Draw an $\angle\alpha' = 20°$ and draw an arc of radius 3.9 cm with centre at M to cut the line LS' at S'. Join MS'. This completes the inlet velocity $\Delta LMS'$. Measure $LS' = C_1' = 6.5$ cm.

First row of moving blades :

The following steps are involved in drawing velocity triangle for first row of moving blades.

— Draw $LM = C_{bl}$ (= 3 cm)

$$C_0 = \frac{C_1'}{0.9} = \frac{6.5}{0.9} = 7.22 \text{ cm.}$$

— Draw $\angle\phi = 30°$, through the point M to the line LM.

— Draw an arc of radius 7.22 cm with centre L. This arc cuts the line LN at point N. Join MN. This completes the outlet ΔLMN.

— Measure $C_{r_0} = MN = 9.7$ cm

$$MS = C_{r_1} = \frac{C_{r_0}}{0.9} = \frac{9.7}{0.9} = 10.8 \text{ cm}$$

— Draw an $\angle\alpha = 15°$, through a point L. Draw an arc of radius of 10.8 cm with centre at M. This arc cuts the line LS at S. Join MS. This completes the inlet velocity triangle.

Measure LS from the velocity triangle

$LS = 13.8$ cm $= C_1 = 540$ m/s.

The scale is now calculated from the above.

$$\therefore \quad \text{Scale 1 cm} = \frac{540}{13.8} = 39.1 \text{ m/s}$$

Measure the following distances from the velocity diagram and convert into velocities :

(*i*) Blade velocity,

$$C_{bl} = LM = 3 \text{ cm} = 3 \times 39.1$$
$$= \mathbf{117.3 \text{ m/s.}} \quad \textbf{(Ans.)}$$
$$C_w = PQ = 18.8 \text{ cm} = 18.8 \times 39.1 = 735.1 \text{ m/s}$$
$$C_w' = P'Q' = 6.2 \text{ cm} = 6.2 \times 39.1 = 242.4 \text{ m/s}$$

(*ii*) Blade efficiency,

$$\eta_{bl} = \frac{2\,C_{bl}(C_w + C_w')}{C_1^{\,2}}$$
$$= \frac{2 \times 117.3(735.1 + 242.4)}{(540)^2}$$
$$= \mathbf{0.786 \text{ or } 78.6\%.} \quad \textbf{(Ans.)}$$

(*iii*) Specific steam consumption, m_s,

$$1 = \frac{m_s(C_w + C_w')C_{bl}}{3600 \times 1000}$$
$$= \frac{m_s(735.1 + 242.4) \times 117.3}{3600 \times 1000}$$
$$\therefore \quad m_s = \frac{3600 \times 1000}{(735.1 + 242.4) \times 117.3}$$
$$= \mathbf{31.39 \text{ kg/kWh.}} \quad \textbf{(Ans.)}$$

Example 3.17. *The following data relate to a compound impulse turbine having two rows of moving blades and one row of fixed blades in between them.*

The velocity of steam leaving the nozzle = 600 m/s

Blade speed = 125 m/s

Nozzle angle = 20°

First moving blade discharge angle = 20°

First fixed blade discharge angle = 25°

Second moving blade discharge angle = 30°

Friction loss in each ring = 10% of relative velocity.

Find : (*i*) *Diagram efficiency*

(*ii*) *Power developed for a steam flow of 6 kg/s.*

Solution. Refer to Fig. 3.109.

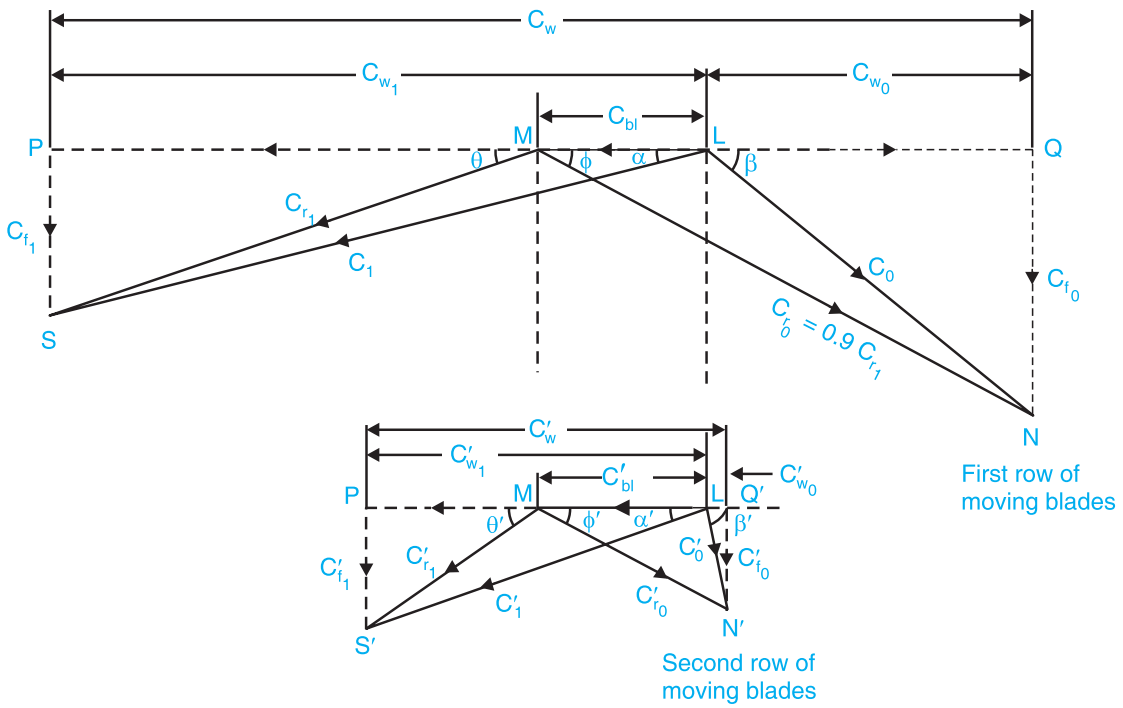


Fig. 3.109

First row of moving blades :

To draw velocity triangles for first row of moving blades the following procedure may be followed :

Select a suitable scale.

— Draw LM = blade velocity (C_{bl}) = 125 m/s.

— Make $\angle MLS$ = nozzle angle, $\alpha = 20°$.

— Draw LS = velocity of steam leaving the nozzle = 600 m/sec.

— Join MS to complete the inlet triangle LMS.

— Make $\angle LMN$ = outlet angle of first moving blades = 20°

and cut $MN = 0.9\ MS$, since $K = 0.9$.

— Join LN to complete the outlet ΔLMN.

Second row of moving blades :

The velocity triangles for second row of moving blades may be drawn as follows :

— Draw LM = blade velocity (C_{bl}) = 125 m/sec.

— Make $\angle MLS'$ = outlet angle of fixed blade = 25°

and cut $LS' = 0.9\ LN$. ($\because$ $K = 0.9$)

— Join MS'. The inlet velocity triangle LMS' is completed.

and cut $MN' = 0.9\ MS'$ ($\because$ $K = 0.9$)

— Join LN'. The outlet velocity triangle is completed.

The following required data may now be scaled off from the diagram :

$$C_w = C_{w_1} + C_{w_0} = PQ = 845 \text{ m/s}$$

$$C_w' = P'Q' = 280 \text{ m/s.}$$

(*i*) Diagram efficiency,

$$\eta_{bl} = \frac{2C_{bl}(C_w + C_w')}{C_1^2}$$

$$= \frac{2 \times 125(845 + 280)}{(600)^2}$$

$$= \mathbf{0.781 \text{ or } 78.1\%.} \quad \textbf{(Ans.)}$$

(*ii*) Power developed,

$$P = \frac{\dot{m}_s(C_w + C_w')}{1000} C_{bl}$$

$$= \frac{6(845 + 280) \times 125}{1000}$$

$$= \mathbf{843.75 \text{ kW.}} \quad \textbf{(Ans.)}$$

Reaction Turbines

Example 3.18. *The following data refer to a particular stage of a Parson's reaction turbine :*

Speed of the turbine	*= 1500 r.p.m.*
Mean diameter of the rotor	*= 1 metre*
Stage efficiency	*= 80 per cent*
Blade outlet angle	*= 20°*
Speed ratio	*= 0.7*

Determine the available isentropic enthalpy drop in the stage.

Solution. Mean diameter of the rotor, $D = 1$ m

Turbine speed, $N = 1500$ r.p.m.

Blade outlet angle, $\phi = 20°$

Speed ratio, $\rho = \dfrac{C_b}{C_1} = 0.7$

Stage efficiency, $\eta_{stage} = 80\%$

Isentropic enthalpy drop :

Blade speed, $C_{bl} = \dfrac{\pi DN}{60} = \dfrac{\pi \times 1 \times 1500}{60}$

$= 78.54$ m/s

But $\rho = \dfrac{C_{bl}}{C_1} = 0.7$ (given)

$\therefore \quad C_1 = \dfrac{C_{bl}}{0.7} = \dfrac{75.54}{0.7} = 112.2$ m/s

In *Parson's Turbine,* $\alpha = \phi$.

With the above data known, the velocity diagram for the turbine can be drawn to a suitable scale as shown in Fig. 3.110.

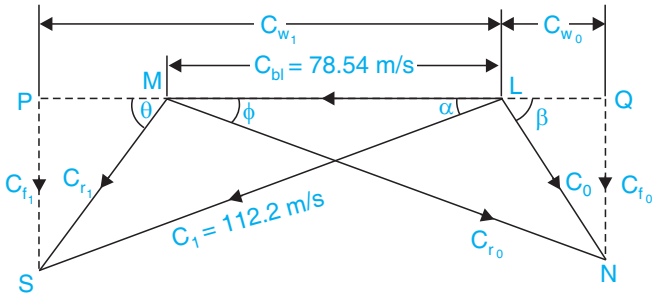


Fig. 3.110

By measurement (from the diagram),

$C_{w_1} = 106.5$ m/s ; $C_{w_0} = 27$ m/s

$$\eta_{stage} = \frac{C_{bl}(C_{w_1} + C_{w_0})}{h_d}$$

where h_d = Isentropic enthalpy drop.

i.e., $0.8 = \dfrac{78.54(106.25 + 27)}{h_d \times 1000}$

$\therefore \quad h_d = \dfrac{78.54(106.25 + 27)}{0.8 \times 1000} = \mathbf{13.08\ kJ}$

Hence, *isentropic enthalpy drop*

$= \mathbf{13.08\ kJ/kg.}$ **(Ans.)**

Example 3.19. *In a reaction turbine, the blade tips are inclined at 35° and 20° in the direction of motion. The guide blades are of the same shape as the moving blades, but reversed in direction. At a certain place in the turbine, the drum diameter is 1 metre and the blades are 10 cm high. At this place, the steam has a pressure of 1.75 bar and dryness 0.935. If the speed of this turbine is 250 r.p.m. and the steam passes through the blades without shock, find the mass of steam flow and power developed in the ring of moving blades.*

Solution. Refer to Fig. 3.111.

Angles, $\alpha = \phi = 20°$, and $\theta = \beta = 35°$

Mean drum diameter,

$D_m = 1 + 0.1 = 1.1$ m

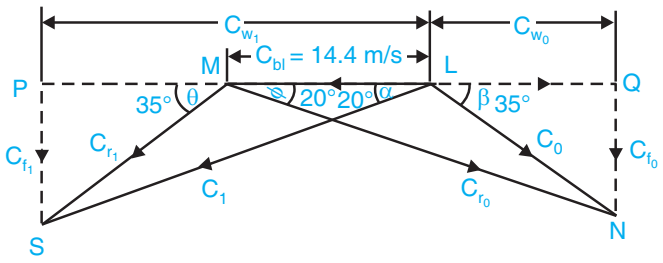


Fig. 3.111

Area of flow $= \pi D_m h$, where h is the height of blade.

$= \pi \times 1.1 \times 0.1 = 0.3456$ m^2

Steam pressure $= 1.75$ bar

Dryness fraction of steam, $x = 0.935$

Speed of the turbine, $N = 250$ r.p.m.

Rate of steam flow, $\dot{m}_s$:

Power developed, P :

Blade speed, $C_{bl} = \dfrac{\pi DN}{60} = \dfrac{\pi \times 1.1 \times 250}{60}$

$= 14.4$ m/s

With the above given data the velocity diagram can be drawn to a suitable scale as shown in Fig. 3.111.

By measurement (from diagram),

$C_{w_1} = 30$ m/s ; $C_{w_0} = 15.45$ m/s ;

$C_{f_1} = C_{f_0} = 10.8$ m/s

From steam tables corresponding to 1.75 bar pressure,

v_g = Specific volume of dry saturated steam

$= 1.004$ m^3/kg

$x = 0.935$

∴ Specific volume of wet steam

$= xv_g = 0.935 \times 1.004 = 0.938 \text{ m}^3/\text{kg}$

Mean flow rate is given by,

$$\dot{m}_s = \frac{\text{Area of flow} \times \text{Velocity of flow}}{\text{Specific volume of steam}}$$

$$= \frac{0.3456 \times 10.8}{0.938} = 3.98 \text{ kg/s.}$$

Power developed,

$$P = \frac{\dot{m}_s (C_{w_1} + C_{w_0}) C_{bl}}{1000}$$

$$= \frac{3.98(30 + 15.45) \times 14.4}{1000}$$

$$= \mathbf{2.6 \text{ kW.}} \quad \textbf{(Ans.)}$$

Example 3.20. *In a reaction turbine, the fixed blades and moving blades are of the same shape but reversed in direction. The angles of the receiving tips are 35° and of the discharging tips 20°. Find the power developed per pair of blades for a steam consumption of 2.5 kg/s, when the blade speed is 50 m/s. If the heat drop per pair is 10.04 kJ/kg, find the efficiency of the pair.*

Solution. Angles of receiving tips, $\theta = \beta = 35°$

Angles of discharging tips, $\alpha = \phi = 20°$

Steam consumption, $\dot{m}_s = 2.5$ kg/s

Blade speed, $C_{bl} = 50$ m/s

Heat drop per pair, $h_d = 10.04$ kJ/kg

Power developed = ?

Efficiency of the pair = ?

Refer to Fig. 3.112.

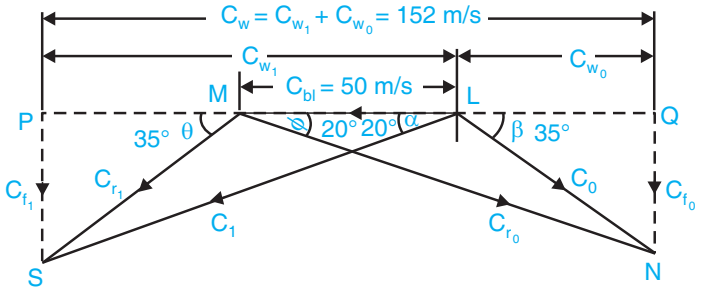


Fig. 3.112

$NS = PQ = 152$ m/s

Work done per pair per kg of steam

$= (C_{w_1} + C_{w_0})\ C_{bl} = 152 \times 50$

$= 7600$ Nm/kg of steam.

$$Power/pair = \frac{\dot{m}_s (C_{w_1} + C_{w_0}) C_{bl}}{1000}$$

$$= \frac{2.5 \times 7600}{1000} = \mathbf{19 \text{ kW.}} \quad \textbf{(Ans.)}$$

$$Efficiency = \frac{\text{Work done per pair per kg of steam}}{h_d}$$

$$= \frac{7600}{10.04 \times 1000} = 0.757 = \mathbf{75.7\%.} \quad \textbf{(Ans.)}$$

Example 3.21. *A twenty-stage Parson turbine receives steam at 15 bar at 300°C. The steam leaves the turbine at 0.1 bar pressure. The turbine has a stage efficiency of 80% and the reheat factor 1.06. The total power developed by the turbine is 10665 kW. Find the steam flow rate through the turbine assuming all stages develop equal power.*

The pressure of steam, at certain stage of the turbine is 1 bar abs., and is dry and saturated. The blade exit angle is 25° and the blade speed ratio is 0.75. Find the mean diameter of the rotor of this stage and also the rotor speed. Take blade height as 1/12th of the mean diameter. The thickness of the blades may be neglected.

Solution. Number of stage = 20

Steam supply pressure = 15 bar, 300°C

Exhaust pressure = 0.1 bar

Stage efficiency of turbine, η_{stage} = 80%

Reheat factor = 1.06

Total power developed = 10665 kW

Steam flow rate, m_s :

Steam pressure at a certain stage = 1 bar abs., $x = 1$

Blade exit angle = 25°

Blade speed ratio, $\rho = \frac{C_{bl}}{C_1} = 0.75$

Height of the blade, $h = \frac{1}{12}$ D (mean dia. of rotor)

***(i)* Steam flow rate, $\dot{m}_s$:**

Refer to Fig. 3.113.

Isentropic drop, $(\Delta h)_{isentropic} = h_1 - h_2$

$= 3040 - 2195 = 845$ kJ/kg

$\eta_{overall} = \eta_{stage} \times$ Reheat factor

$= 0.8 \times 1.06 = 0.848$

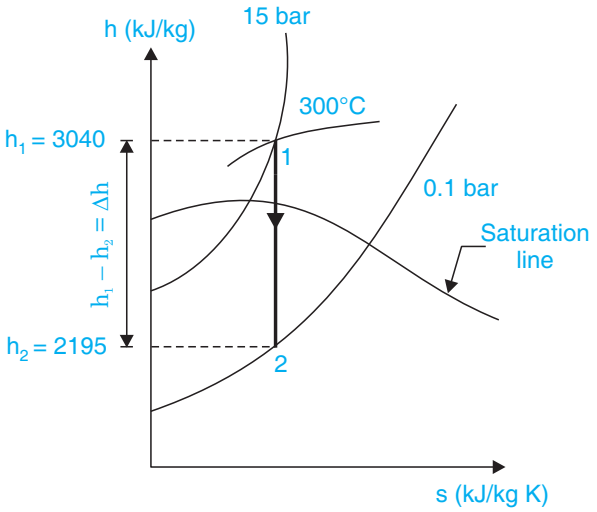


Fig. 3.113

Work done = Actual enthalpy drop
$= (\Delta h)_{\text{isentropic}} \times \eta_{\text{overall}}$
$= 845 \times 0.848 = 716.56$ kJ/kg

Work done per stage per kg

$$= \frac{716.56}{20} = 35.83 \text{ kJ} \qquad ...(i)$$

Also, total power = no. of stages × $\dot{m}_s$ × work done/kg stage

$$\therefore \quad 10665 = 20 \times \dot{m}_s \times 35.83$$

$$\therefore \quad \dot{m}_s = \frac{10665}{20 \times 35.83}$$

$$= \mathbf{14.88 \text{ kg/s.}} \quad \textbf{(Ans.)}$$

(*ii*) Mean diameter of rotor, D :

Rotor speed, N :

Refer to Fig. 3.114.

Work done per kg per stage

$$= C_{bl} \times C_w = C_{bl}\,(2C_1 \cos 25° - C_{bl})$$

Also, $\dfrac{C_{bl}}{C_1} = 0.75$ ...(Given)

$$\therefore \quad C_1 = \frac{C_{bl}}{0.75} = 1.33 C_{bl}$$

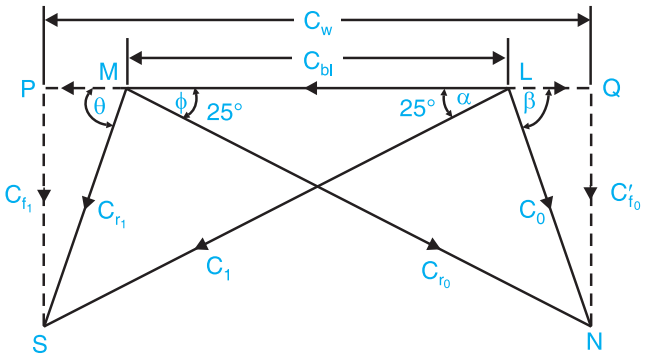


Fig. 3.114

i.e., Work done per kg per stage

$$= C_{bl}\,(2 \times 1.33 C_{bl} \times 0.906 - C_{bl})$$

$$= 1.41\ C_{bl}^2 \qquad ...(ii)$$

Equations (*i*) and (*ii*), we get:

$$1.41\ C_{bl}^2 = 35.83 \times 1000$$

$$\therefore \quad C_{bl}^2 = \frac{35.83 \times 1000}{1.41} \quad i.e., \quad C_{bl} = 159.41 \text{ m/s}$$

$$\therefore \quad C_1 = 159.41 \times 1.33 = 212 \text{ m/s}$$

From Fig. 3.114, we have:

$$C_{f_1} = C_1 \sin \alpha = 212 \sin 25° = 89.59 \text{ m/s}$$

v_g = Specific volume at 1 bar when steam is dry and saturated
$= 1.694$ m^3/kg (from steam tables)

Mass flow rate, $\dot{m}_s = \dfrac{\pi D h C_{f_1}}{v}$

$$\therefore \quad 14.88 = \frac{\pi \times D \times \left(\frac{D}{12}\right) \times 89.59}{1.694}$$

or, $$D^2 = \frac{14.88 \times 1.694 \times 12}{\pi \times 89.59}$$

$$\therefore \quad D = \mathbf{1.036 \text{ m.}} \quad \textbf{(Ans.)}$$

Now, $$h = \frac{D}{12} = \frac{1.036}{12} = 0.086 \text{ m}$$
$$= \mathbf{8.6 \text{ cm.}} \quad \textbf{(Ans.)}$$

Also, $$C_{bl} = \frac{\pi D N}{60}$$

$$\therefore \quad N = \frac{C_{bl} \times 60}{\pi D} = \frac{159.41 \times 60}{\pi \times 1.036}$$
$$= \mathbf{2938.7 \text{ r.p.m.}} \quad \textbf{(Ans.)}$$

Example 3.22. *The following data relate to a stage of reaction turbine :*

Mean rotor diameter = 1.5 m ; speed ratio = 0.72 ; blade outlet angle = 20° ; rotor speed = 3000 r.p.m.

(i) Determine the diagram efficiency.

(ii) Determine the percentage increase in diagram efficiency and rotor speed if the rotor is designed to run at the best theoretical speed, the exit angle being 20°.

Solution. Mean rotor diameter,

$$D = 1.5 \text{ m}$$

Speed ratio, $$\rho = \frac{C_{bl}}{C_1} = 0.72$$

Blade outlet angle = 20°

Rotor speed, $N = 3000$ r.p.m.

(This example solved purely by calculations (Fig. 3.115) is not drawn to scale.)

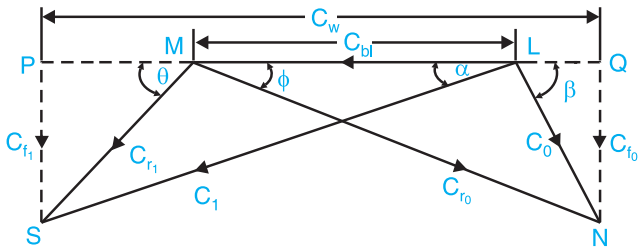


Fig. 3.115

(*i*) Diagram efficiency :

Blade velocity, $C_{bl} = \dfrac{\pi DN}{60} = \dfrac{\pi \times 1.5 \times 3000}{60}$

$= 235.6$ m/s

Speed ratio, $\rho = \dfrac{C_{bl}}{C_1} = 0.72$

$\therefore \quad C_1 = \dfrac{C_{bl}}{0.72} = \dfrac{235.6}{0.72} = 327.2$ m/s

Assuming that velocity triangles are symmetrical,

$\alpha = \phi = 20°$

From the velocity ΔLMS,

$$C_{r_1}^{\,2} = C_1^{\,2} + C_{bl}^{\,2} - 2C_1 C_{bl} \cos \alpha \qquad ...(i)$$

$$C_{r_1} = \sqrt{(327.2)^2 + (235.6)^2 - 2 \times 327.2 \times 235.6 \cos 20°}$$

$= 100\sqrt{10.7 + 5.55 - 14.48} = 133$ m/s

i.e., $C_{r_1} = 133$ m/s

Work done per kg of steam

$= C_{bl} C_w = C_{bl}(2C_1 \cos \alpha - C_{bl})$

$= 235.6\ (2 \times 327.2 \cos 20° - 235.6)$

$= 89371.3$ Nm.

Energy supplied per kg of steam

$$= \frac{C_1^{\,2} + C_{r_0}^{\,2} - C_{r_1}^{\,2}}{2}$$

$$= \frac{2C_1^{\,2} - C_{r_1}^{\,2}}{2} \quad (\text{as} \quad C_1 = C_{r_0})$$

$$= \frac{2 \times (327.2)^2 - (133)^2}{2} = 98215.3 \text{ Nm}$$

$\therefore$ *Diagram efficiency*

$= \dfrac{89371.3}{98215.3} = 0.91 = \mathbf{91\%}$. **(Ans.)**

(*ii*) Percentage increase in diagram efficiency :

For the best diagram efficiency (maximum), the required condition is

$\rho = \dfrac{C_{bl}}{C_1} = \cos \alpha$

$\therefore \quad C_{bl} = C_1 \cos \alpha = 372.2 \cos 20° = 307.46$ m/s

For this blade speed, the value of C_{r_1} is again calculated by using eqn. (*i*),

$$C_{r_1} = \sqrt{(327.2)^2 + (307.46)^2 - 2 \times 327.2 \times 307.46 \times \cos 20°}$$

$= 100\sqrt{10.7 + 9.45 - 18.906} = 111.5$ m/s

Diagram efficiency

$$= \frac{2C_{bl}(2C_1 \cos \alpha - C_{bl})}{(C_1^{\,2} + C_{r_0}^{\,2} - C_{r_1}^{\,2})}$$

$$= \frac{2 \times 307.46(2 \times 327.2 \cos 20° - 307.46)}{(327.2)^2 + (327.2)^2 - (111.5)^2}$$

$= 0.937$ or 93.7%

Percentage increase in diagram efficiency

$= \dfrac{0.937 - 0.91}{0.91}$

$= \mathbf{0.0296}$ **or** $\mathbf{2.96\%}$. **(Ans.)**

The best theoretical speed of the rotor is given by,

$C_{bl} = \dfrac{\pi DN}{60}$

$\therefore \quad N = \dfrac{60\ C_{bl}}{\pi D} = \dfrac{60 \times 307.46}{\pi \times 1.5}$

$= \mathbf{3914.7\ r.p.m.}$ **(Ans.)**

☞ **Example 3.23. (Impulse reaction turbine).** *The following data relate to a stage of an impulse reaction turbine :*

Steam velocity coming out of nozzle = 245 m/s ; nozzle angle = 20° ; blade mean speed = 145 m/s ; speed of the rotor = 300 r.p.m. ; blade height = 10 cm ; specific volume of steam at nozzle outlet and blade outlet respectively = 3.45 m^3/kg and 3.95 m^3/kg ; H.P. developed by the turbine = 390 ; efficiency of nozzle and blades combinedly = 90% ; carry over co-efficient = 0.82.

Find : (i) The heat drop in each stage ;

(ii) Degree of reaction ;

(iii) Stage efficiency.

Solution. Steam velocity coming out of nozzle,

$C_1 = 245$ m/s

Nozzle angle, $\alpha = 20°$

Blade mean speed, $C_{bl} = 145$ m/s

Speed of the rotor, $N = 3000$ r.p.m.

Blade height, $h = 10$ cm $= 0.1$ m

Specific volume of steam at nozzle outlet or blade inlet, $v_1 = 3.45$ m^3/kg

Specific volume of steam at blade outlet,

$v_0 = 3.95$ m^3/kg

H.P. developed by the turbine = 390 H.P.

Efficiency of nozzle and blades combinedly = 90%

Carry over co-efficient, $\psi = 0.82$

Blade speed, $C_{bl} = \dfrac{\pi DN}{60}$

$\therefore \quad D = \dfrac{60\ C_{bl}}{\pi N} = \dfrac{60 \times 145}{\pi \times 3000} = 0.923$ m

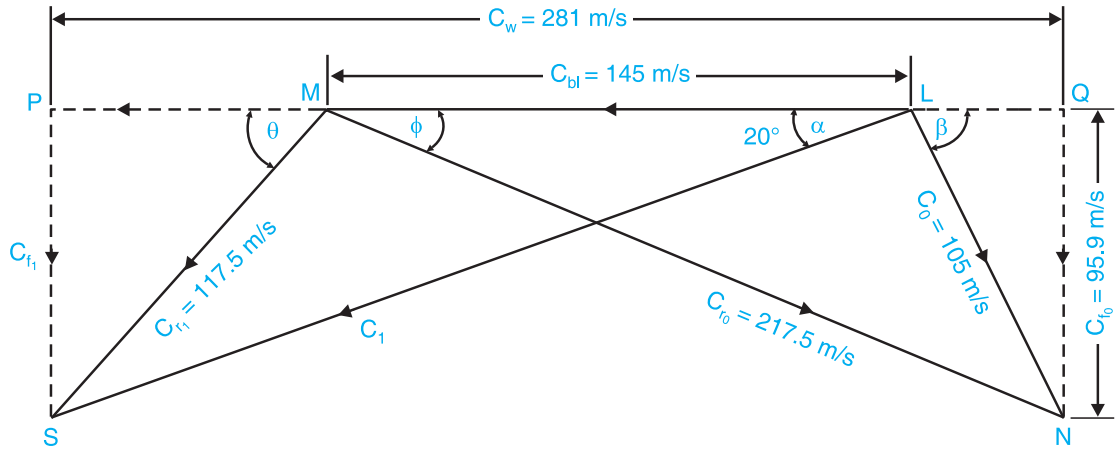


Fig. 3.116

Mass flow rate,

$$\dot{m}_s = \frac{C_{f_1} \times \pi Dh}{v_1} = \frac{C_1 \sin\alpha \times \pi Dh}{v_1}$$

$$= \frac{245 \times \sin 20° \times \pi \times 0.923 \times 0.1}{3.45}$$

$$= 7.04 \text{ kg/s}$$

Also, $$\dot{m}_s = \frac{C_{f_0}\, \pi Dh}{v_0}$$

$$\therefore \quad C_{f_0} = \frac{\dot{m}_s v_0}{\pi Dh} = \frac{7.04 \times 3.95}{\pi \times 0.923 \times 0.1}$$

$$= 95.9 \text{ m/s}$$

The H.P. is given by, $\text{H.P.} = \dfrac{\dot{m}_s \times C_{bl} \times C_w}{g \times 75}$

$$390 = \frac{7.04 \times 145 \times C_w}{9.81 \times 75}$$

$$\therefore \quad C_w = \frac{390 \times 9.81 \times 75}{7.04 \times 145} = 281 \text{ m/s}$$

Now draw velocity triangles as follows :

Select a suitable scale (say 1 cm = 25 m/s)

— Draw LM = blade velocity = 145 m/s ; $\angle MLS$ = nozzle angle = 20°

Join MS to complete the inlet ΔLMS.

— Draw a perpendicular from S which cuts the line through LM at point P.

Mark the point Q such that $PQ = C_w$ = 281 m/s.

— Draw a perpendicular through point Q and the point N as QN = 95.9 m/s.

Join LN and MN to complete the *outlet* velocity triangle.

From the velocity triangles ;

$$C_{r_1} = 117.5 \text{ m/s}$$

$$C_{r_0} = 217.5 \text{ m/s}$$

$$C_0 = 105 \text{ m/s}.$$

(*i*) Heat drop in each stage, $(\Delta h)_{\text{stage}}$:

Heat drop in *fixed blades* $(\Delta h_f) = \dfrac{C_1^2 - \psi\, C_0^2}{2gJ\ \eta_{\text{nozzle}}}$, where ψ is a carry over coefficient

$$= \frac{(245)^2 - 0.82 \times (105)^2}{2 \times 9.81 \times 427 \times 0.9} = 6.76 \text{ kcal/kg}$$

Heat drop in *moving blades* (Δh_m)

$$= \frac{C_{r_0}^2 - C_{r_1}^2}{2gJ\ \eta_{\text{nozzle}}} = \frac{(217.5)^2 - (117.5)^2}{2 \times 9.81 \times 427 \times 0.9}$$

$$= 4.44 \text{ kcal/kg}$$

Total heat drop in a stage,

$$(\Delta h)_{\text{stage}} = \Delta h_f + \Delta h_m$$

$$= 6.76 + 4.44 = \mathbf{11.2\ kcal/kg.} \quad \textbf{(Ans.)}$$

(*ii*) Degree of reaction, R_d :

$$R_d = \frac{\Delta h_m}{\Delta h_m + \Delta h_f} = \frac{4.44}{4.44 + 6.76}$$

$$= \mathbf{0.396.} \quad \textbf{(Ans.)}$$

(*iii*) Stage efficiency, η_{stage} :

Work done per kg of steam

$$= \frac{C_{bl} \times C_w}{gJ} = \frac{145 \times 281}{9.81 \times 427} = 9.726 \text{ kcal}$$

$$\therefore \quad \eta_{\text{stage}} = \frac{\text{Work done per kg of steam}}{\text{Total heat drop in a stage}}$$

$$= \frac{9.726}{11.2} = \mathbf{0.868 \ \ or \ 86.8\%.} \quad \textbf{(Ans.)}$$

3.20. STEAM CONDENSERS

3.20.1. Introduction

*A **steam condenser** is a device or an appliance in which steam condenses and heat released by steam is absorbed by water*. It serves the following *purposes :*

1. It *maintains a very low back pressure* on the exhaust side of the piston of the steam engine or turbine. Consequently, the steam expands to a greater extent which results in an *increase in available heat energy* for converting into mechanical work. The shaded area in Fig. 3.117. (*i.e.*, area 44′5′5) shows the increase in work obtained by fitting a condenser to a non-condensing engine. *The thermal efficiency of a condensing unit therefore is higher than that of non-condensing unit for the same available steam.*

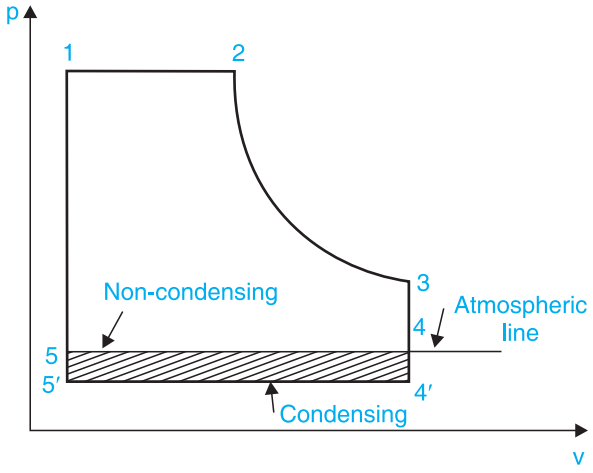


Fig. 3.117

2. It supplies to the boiler pure and hot feed water as the condensed steam which is discharged from the condenser and collected in a hot well, can be used as feed water for the boiler.

3.20.2. Vacuum

***Vacuum** is sub-atmospheric pressure.* It is measured as the pressure depression below atmospheric. The condensation of steam in a closed vessel produces a partial vacuum by reason of the great reduction in the volume of the low pressure steam or vapour. The back pressure in steam engine or steam turbine can be lowered from 0.013 to 0.2 bar abs. or even less. Since the steam engines are intermittent flow machines and as such cannot take the advantage of a very low vacuum, therefore, for most steam engines the exhaust pressure is about 0.2 to 0.28 bar abs. On the other hand, in steam turbines, which are continuous flow machines, the back pressure may be about 0.025 bar abs.

3.20.3. Organs of a Steam Condensing Plant

A steam condensing plant mainly consists of the following *organs / elements* :

1. Condenser (to condense the steam).
2. Supply of cooling (or injection) water.
3. Wet air pump (to remove the condensed steam, the air and uncondensed water vapour and gases from the condenser ; separate pumps may be used to deal with air and condensate).
4. Hot well (where the condensate can be discharged and from which the boiler feed water is taken).
5. Arrangement for recooling the cooling water in case surface condenser is employed.

3.20.4. Classification of Condensers

Mainly, condensers are of two types : (1) Jet condensers, (2) Surface condensers.

In ***jet condensers,*** *the exhaust steam and water come in direct contact with each other* and temperature of the condensate is the same as that of cooling water leaving the condenser. The cooling water is usually sprayed into the exhaust steam to cause rapid condensation.

In ***surface condensers,*** *the exhaust steam and water do not come into direct contact.* The steam passes over the outer surface of tubes through which a supply of cooling water is maintained. There may be single-pass or double-pass. In single-pass condensers, the water flows in one direction only through all the tubes, while in two-pass condenser the water flows in one direction through the tubes and returns through the remainder.

A jet condenser is simpler and cheaper than a surface condenser. It should be installed when the cooling water is cheaply and easily made suitable for boiler feed or when a cheap source of boiler and feed water is available. *A surface condenser is most commonly used because the condensate obtained is not thrown as a waste but returned to the boiler.*

3.20.5. Jet Condensers

These condensers may be classified as :

(*a*) Parallel-flow type

(*b*) Counter-flow type

(*c*) Ejector type.

Parallel flow and counter flow condensers are further sub-divided into two types : (*i*) Low level type (*ii*) High level type.

In *parallel-flow type* of condenser, both the exhaust steam and cooling water find their entry at the top of the condenser and then flow downwards and condensate and water are finally collected at the bottom.

In *counter-flow type,* the steam and cooling water enter the condenser from opposite directions. Generally, the exhaust steam travels in upward direction and meet the cooling water which flows downwards.

Low level jet condenser (Parallel-flow) :

In Fig. 3.118 is shown a line sketch of a low level parallel-flow condenser. The exhaust steam is entering the condenser from the top and cold water is being sprayed on its way. The baffle plate provided in it ensures the proper mixing of the steam and cooling water. An extraction pump at the bottom discharges the condensate to the hot well from where it may be fed to the boiler if the cooling water being used is free from impurities. A separate dry pump may be incorporated to maintain proper vacuum.

Low level jet condenser (Counter-flow) :

Refer to Fig. 3.119. *L, M* and *N* are the perforated trays which break up water into jets. The steam moving upwards comes in contact with water and gets condensed. The condensate and water mixture is sent to the hot well by means of an extraction pump and the air is removed by an air suction pump provided at the top of the condenser.

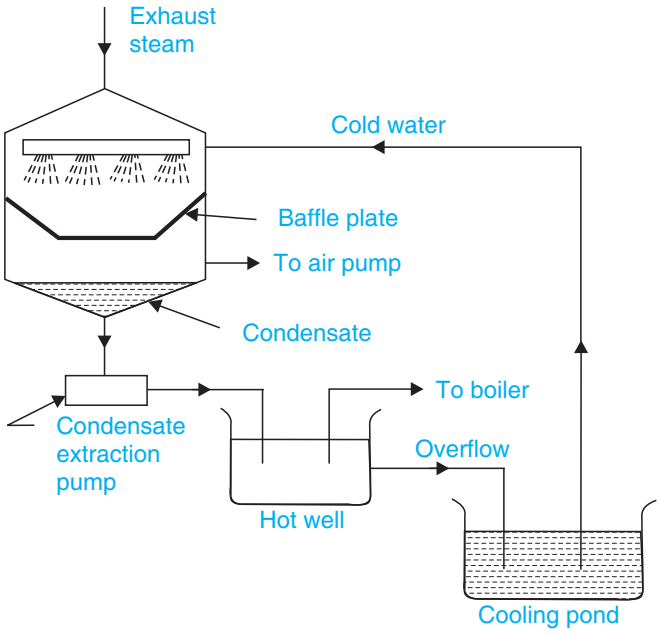


Fig. 3.118. Low level jet condenser (Parallel flow).

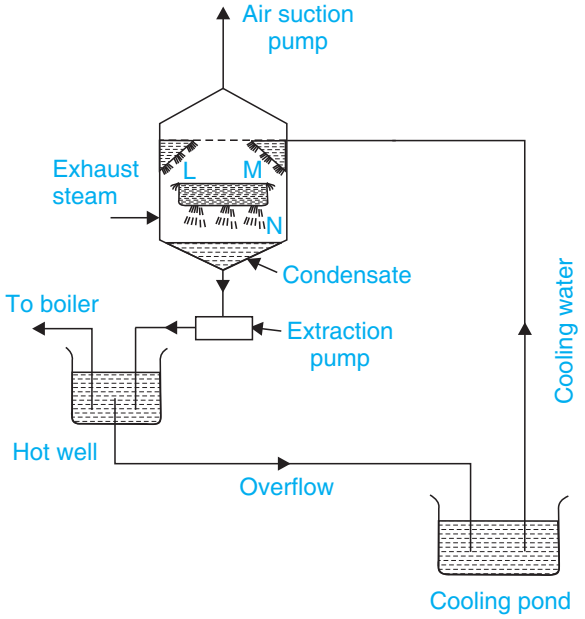


Fig. 3.119. Low level jet condenser (Counter flow).

High level jet condenser (Counter-flow type) :

In Fig. 3.120 is shown a high level counter-flow jet condenser. It is also called *barometric condenser.* In this case the shell is placed at a height about 10.363 metres above hot well and thus the necessity of providing an extraction pump can be obviated. However provision of own injection pump has to be made if water under pressure is not available.

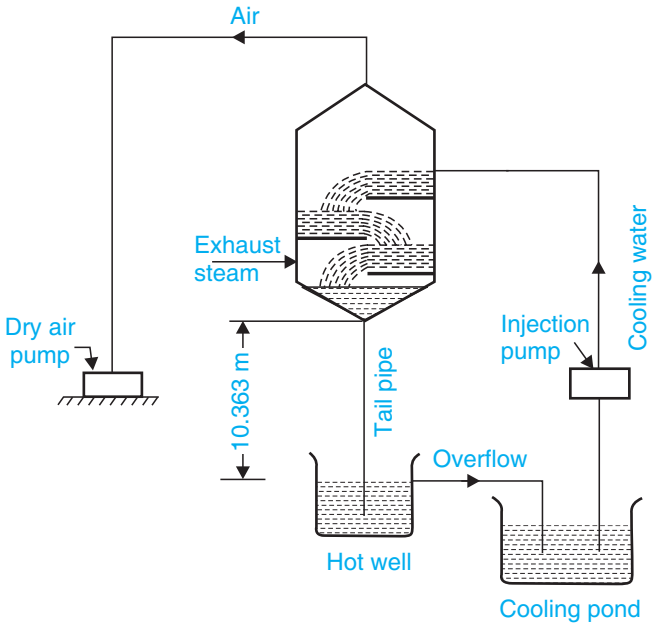


Fig. 3.120. High level jet condenser (Counter flow).

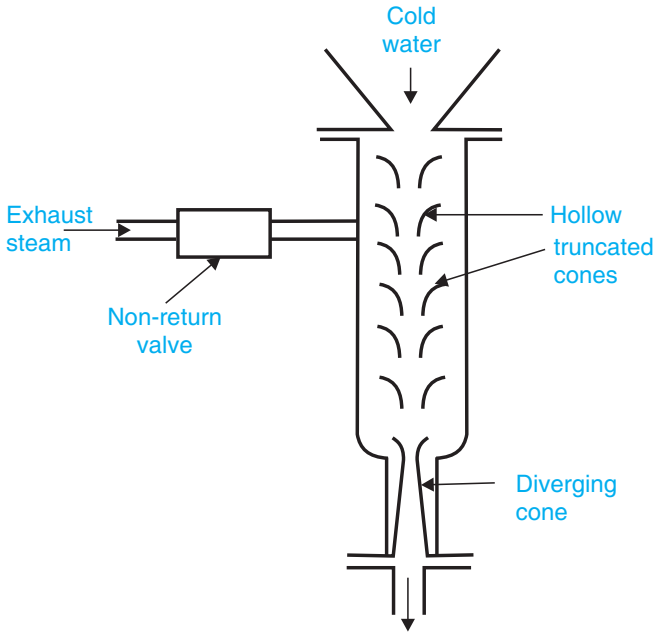


Fig. 3.121. Ejector condenser.

Ejector condenser :

Fig. 3.121 shows the schematic sketch of an ejector condenser. Here the exhaust steam and cooling water mix in hollow truncated cones. The cold water having a head of about 6 metres flow down through the number of cones and as it moves its velocity increases and drop in pressure results. Due to this decreased pressure exhaust steam along with associated air is drawn through the truncated cones and finally lead to diverging cone. In the diverging cone, a portion of kinetic energy gets converted into pressure energy which is more than the atmospheric so that condensate consisting of condensed steam, cooling water and air is discharged into the hot well. The exhaust steam inlet is provided with a non-return valve which does not allow the water from hot well to rush back to the engine in case a failure of cooling water supply to condenser.

3.20.6. Surface Condensers

Most condensers are generally classified on the direction of flow of condensate, the arrangement of the tubing and the position of the condensate extraction pump. The following is the main classification of surface condensers :

(*i*) Down flow type (*ii*) Central flow type
(*iii*) Inverted flow type (*iv*) Regenerative type
(*v*) Evaporative type.

(*i*) Down flow type

In Fig. 3.122 is shown a *down flow type* of surface condenser. It consists of a shell which is generally of cylindrical shape ; though other types are also used. It has cover plates at the ends and furnished with number of parallel brass tubes. A baffle plate partitions the water box into two sections. The cooling water enters the shell at the lower half section and after travelling through the upper half section comes out through the outlet. The exhaust steam entering shell from the top flows down over the tubes and gets condensed and is finally removed by an extraction pump. Due to the fact that steam flows in a direction right angle to the direction of flow of water, it is also called *cross-surface condenser*.

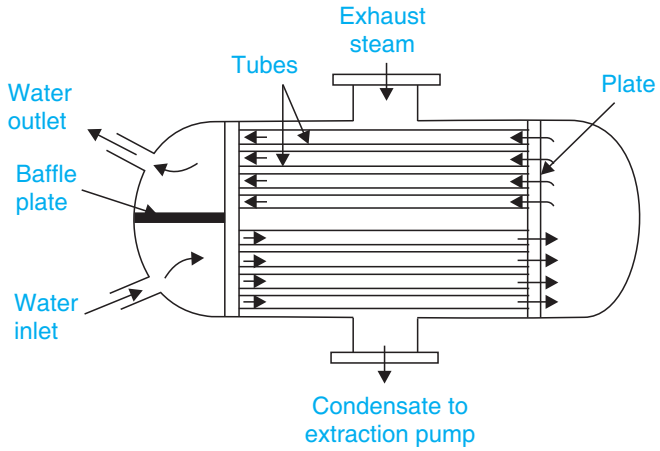


Fig. 3.122. Down flow type.

(*ii*) Central flow type

Refer to Fig. 3.123. In this type of condenser, the suction pipe of the air extraction pump is located in the centre of the tubes which results in radial flow of the steam. The better contact between the outer surface of the tubes and steam is ensured, due to large passages the pressure drop of steam is reduced.

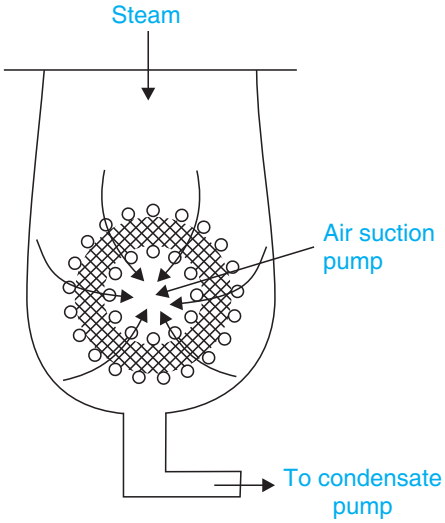


Fig. 3.123. Central flow type.

(*iii*) Inverted flow type

This types of condenser has the air suction at the top, the steam after entering at the bottom rises up and

then agains flows down to the bottom of the condenser, by following a path near the outer surface of the condenser. The condensate extraction pump is at the bottom.

(*iv*) Regenerative type

This type is applied to condensers adopting a regenerative method of heating of the condensate. After leaving the tube nest, the condensate is passed through the entering exhaust steam from the steam engine or turbine thus raising the temperature of the condensate, for use as feed water for the boiler.

(*v*) Evaporative type

Fig. 3.124 shows the schematic sketch of an evaporative condenser. The underlying principle of this condenser is that when a limited quantity of water is available, its quantity needed to condense the steam can be reduced by *causing the circulating water to evaporate under a small partial pressure*.

The exhaust steam enters at the top through gilled pipes. The water pump sprays water on the pipes and descending water condenses the steam. The water which is not evaporated falls into the open tank (cooling pond) under the condenser from which it can be drawn by circulating water pump and used over again. The evaporative condenser is placed in open air and finds its application in *small size plants*.

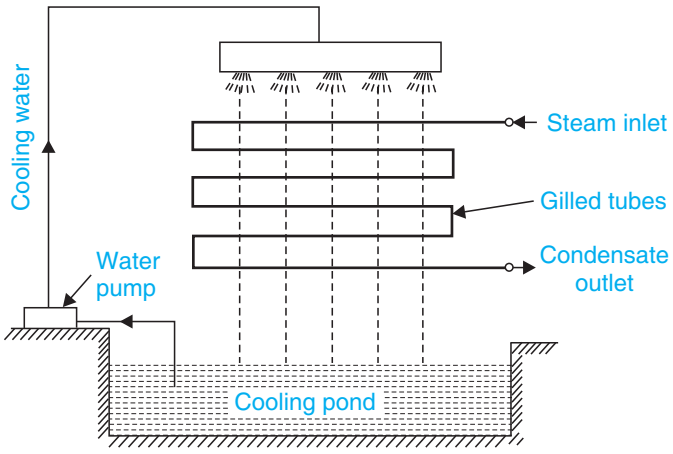


Fig. 3.124. Evaporative condenser.

Advantages of surface condenser :

1. Slightly better vacuum can be obtained.
2. There is no need to treat the condensate chemically before being supplied to the boiler.
3. High vacuum (about 73.5 cm Hg) can be obtained. This increases the thermal efficiency of the plant.
4. Condensate can be reused for boiler feed water.
5. Low pumping power required.
6. Less chances of losing vacuum as the drop in vacuum has got no effect on water supply.
7. Cooling water of even poor quality can be used because the cooling water does not come in direct contact with steam.

Disadvantages :

1. High initial cost.
2. Requires large floor area.
3. High maintenance cost.
4. More head is necessary in order to obtain sufficient head on hot well pump.
5. Proper cleaning of cooling water is necessary, otherwise it creates the problem of accumulation of dust inside the condenser tubes.

3.20.7. Reasons for Inefficiency in Surface Condensers

The *various reasons for inefficiency in surface condensers* are discussed below :

1. The pressure inside the condenser is less than atmospheric, and in order to obtain the maximum work from unit mass of steam, the pressure should be as low as possible. The pressure in the condenser also depends upon the amount of air. Owing to high vacuum pressure in the condenser it is impossible to prevent air from leaking in through the joints thereby increasing the pressure in the condenser and thus limiting the amount of work done by unit mass of steam in the engine or turbine. Air leakage also results in lowering the partial pressure of steam and temperature. This means that *latent heat increases* and therefore *more cooling water* is required and the undercooling of the condensate is likely to be more severe with a resulting lower overall efficiency.
2. One of the main causes of poor performance in surface condensers is the pressure drop which occurs as the steam flows over the tubes ; this pressure drop, by increasing the volume of the steam, tends to destroy the vacuum. The decrease in vacuum results in less amount of work done by unit mass of steam.
3. The heat conduction is through the brass tube walls. This conduction of heat is not perfect and results in less efficiency.
4. On examining the heat balance sheets of steam engine plants, it will be found that more than one-half of the heat supplied by fuel is rejected to the condenser cooling water ; this is chief loss of steam plant and is the cause of its low overall efficiency.

5. Steam entering the condenser with high resistance.
6. Circulating water passing through the condenser with high friction and at a velocity not consistent with high efficiency.
7. Undercooling of condensate.
8. Air extraction from hottest section and with comparatively large amount of water vapour.

3.20.8. Comparison Between Jet and Surface Condensers

S. No.	Jet condenser	Surface condenser
1.	Low manufacturing cost.	High manufacturing cost.
2.	Lower up keep.	Higher up keep.
3.	Requires small floor space.	Requires large floor space.
4.	The condensate cannot be used as feed water in the boilers unless the cooling water is free from impurities.	Condensate can be reused as feed water as it does not mix with the cooling water.
5.	More auxiliary power required.	Less auxiliary power needed.

3.20.9. Selection of Condenser

The selection of condenser depends on the following conditions :

1. The first cost. The first cost of jet condenser may be about one-fourth than that of an equivalent surface condenser.

2. The maintenance cost. The maintenance cost of jet condensers is lower than that of surface condensers.

3. The space available. The amount of floor space and the head room available are not actually the deciding factors. Surface condensers require more floor space than the jet condensers.

4. The quantity of cooling water. The quantity, quality and source of cooling water are the important considerations in the selection of the condenser where the water supply is limited, an artificial cooling system can be installed. For artificial cooling the cooling ponds and cooling towers are used.

5. The type of boiler feed-water available. This is an important factor in the selection of condenser. The surface condenser recovers the distilled condensate for boiler feed-water whereas in case of jet-condenser it is not.

3.20.10. Sources of Air in Condensers

The main sources of air found in condensers are given below :

1. There is a leakage of air from atmosphere at the joints of the parts which are internally under a pressure less than that of atmosphere. The quantity of air that leaks in can be reduced to a great extent if design and making of the vacuum joints are undertaken carefully.
2. Air is also accompanied with steam from the boiler into which it enters dissolved in feed water. The quantity of air depends upon the treatment which the feed water receives before it enters the boiler. However, the amount of air which enters through this source is relatively small.
3. In jet condensers, a little quantity of air accompanies the injection water (in which it is dissolved).

Notes. (*i*) In jet condensers, the quantity of air dissolved in injection water is about 0.5 kg/10000 kg of water.

(*ii*) In surface condensers of reciprocating steam engines, the air leakage is about 15 kg/10000 kg of steam whereas in surface condensers of well designed and properly maintained steam turbine plants the air leakage is about 5 kg/10000 kg of steam.

3.20.11. Effects of Air Leakage in Condenser

The following are the effects of air leakage in a condenser :

1. Lowered thermal efficiency. The leakage air in the condenser results in increased back-pressure on the primem over which means there is loss of heat drop and consequently thermal efficiency of steam power plant is lowered.

2. Increased requirement of cooling water. The leaked air in the condenser lowers the partial pressure of steam which means a lowered saturation temperature of steam. As the saturation temperature of steam lowers, its latent heat increases. So it will require increased amount of cooling water for increased latent heat.

3. Reduced heat transfer. Air has poor thermal conductivity. Hence leaked air reduces the rate of heat transfer from the vapour, and consequently it requires surface of the tubes of a surface condenser to be increased for a given condenser capacity.

4. Corrosion. The presence of air in the condenser increases the corrosive action.

3.20.12. Method for Obtaining Maximum Vacuum in Condensers

Following are some of the methods used to obtain *maximum possible vacuum in condensers used in modern steam power plants*.

1. Air pump. Air pumps are provided to maintain a desired vacuum in the condenser by extracting the air and other non-condensable gases. They are usually

classified as : (*a*) ***Wet air pumps*** which remove a *mixture of condensate and non-condensable gases*. (*b*) ***Dry air pump*** which removes the *air only*.

2. Steam air ejector. When a wet air pump (also called extraction pump) is employed then use is made of steam air ejectors to remove air from the mixture. The operation of the ejector consists in utilising the viscous drag of a high velocity steam jet for the ejection of air and other non-condensable gases from a chamber ; it is chiefly used for exhausting the air from steam condensers. In the case of ejectors used for steam plants where a high vacuum pressure is maintained in the condenser, it is necessary to use two, or perhaps three ejectors in series to obtain maximum vacuum.

3. De-aerated feed water. The de-aeration of feed water helps both in maintaining better vacuum in the condenser and controlling corrosion of the steel shell and piping of the steam power plant.

4. Air tight joints. The various joints of the steam power plant are rendered air-tight by suitable packing materials etc. at the joints of piping etc. and these are maintained as such by proper inspection from time to time.

3.20.13. Vacuum Measurement

The term *vacuum* in case of a condenser means *pressure below atmospheric pressure*. It is generally expressed in mm of mercury. The vacuum is measured by means of a vacuum gauge (Fig. 3.125). Usually for calculation purpose the vacuum gauge reading is corrected to standard barometric reading 760 mm as follows.

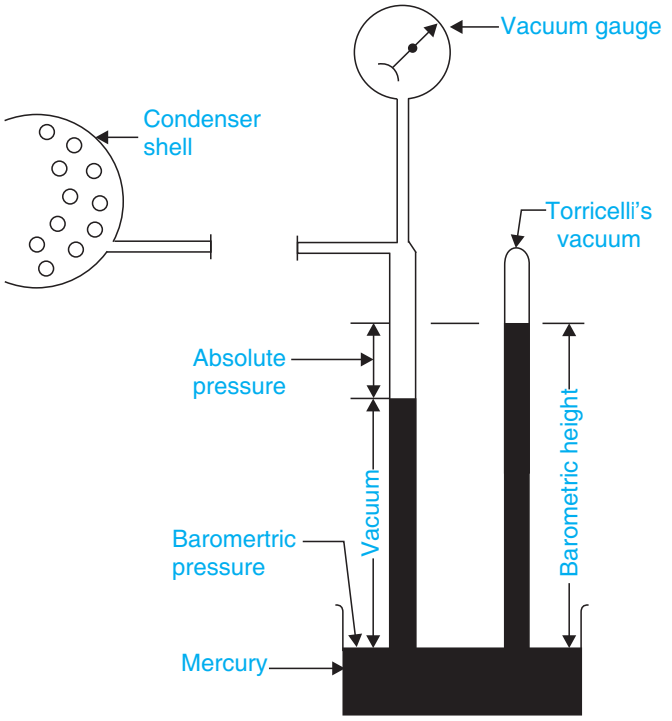


Fig. 3.125. Measurement of vacuum.

Corrected vacuum in mm of Hg
= (760 – Absolute pressure in mm of Hg)
= 760 – (Actual barometric height – Actual vacuum)

Also, 760 mm of Hg = 1.01325 bar

$$\therefore \quad \text{mm of Hg} = \frac{1.01325}{760} = 0.001333 \text{ bar}$$

3.20.14. Vacuum Efficiency

It is defined as the ratio of the actual vacuum to the maximum obtainable vacuum. The latter vacuum is obtained when there is only steam and no air is present in the condenser.

Vacuum efficiency

$$= \frac{\text{Actual vacuum}}{\text{Maximum obtainable vacuum}}$$

$$= \frac{\text{Actual vacuum}}{\text{Barometer pressure} - \text{Absolute pressure of steam}} \quad ...(3.73)$$

Note. In case of the absolute pressure of steam corresponding to the temperature of condensate being equal to the absolute pressure in the condenser, the efficiency would be 100%. Actually some quantity of air is also present in the condenser which may leak in and be accompanied by the entering steam. The vacuum efficiency, therefore, depends on the amount of air removed by the air pump from the condenser.

3.20.15. Condenser Efficiency

It is defined *as the ratio of the difference between the outlet and inlet temperatures of cooling water to the difference between the temperature corresponding to the vacuum in the condenser and inlet temperature of cooling water, i.e.,*

Condenser efficiency

$$= \frac{\text{Rise in temperature of cooling water}}{\left[\begin{array}{c}\text{Temp. corresponding to vacuum} \\ \text{in the condenser}\end{array}\right] - \left[\begin{array}{c}\text{Inlet temp. of} \\ \text{cooling water}\end{array}\right]}$$

or,

$$= \frac{\text{Rise in temperature of cooling water}}{\left[\begin{array}{c}\text{Temp. corresponding to the absolute} \\ \text{pressure in the condenser}\end{array}\right] - \left[\begin{array}{c}\text{Inlet temp. of} \\ \text{cooling water}\end{array}\right]} \quad ...(3.74)$$

3.20.16. Determination of Mass of Cooling Water

Let, m_w = Mass of cooling water required in kg/h,
m_s = Mass of steam condensed in kg/h,

t_s = Saturation temperature of steam corresponding to the condenser vacuum in °C,
t_c = Temperature of the condensate leaving the condenser,
t_{w_1} = Temperature of cooling water at inlet in °C,
t_{w_2} = Temperature of cooling water at outlet in °C,
c_{pw} = Specific heat of water at constant pressure,
x = Dryness fraction of steam entering the condenser, and
h_{fg} = Latent heat of 1 kg of steam entering the condenser.

Now, heat lost by steam

$$= m_s[xh_{fg_2} + c_{pw}(t_s - t_c)] \text{ kJ/kg}$$

and heat gained by water = $m_w \times c_{pw}(t_{w_2} - t_{w_1})$

If all heat lost by steam is gained by cooling water, then

$$m_s[x\,h_{f_g} + c_{pw}(t_s - t_c)] = m_w \times c_{pw}(t_{w_2} - t_{w_1})$$

$$\therefore \quad m_w = \frac{m_s[xh_{fg} + c_{pw}(t_s - t_c)]}{c_{pw}(t_{w_2} - t_{w_1})} \text{ kg/h} \qquad ...(3.75)$$

Eqn. (3.75) applies to *surface condenser only*.

In a jet condenser, since cooling water and steam mix together, therefore the condensate temperature will be same as that of outlet temperature of cooling water (*i.e.*, $t_c = t_{w_2}$). Thus quantity of cooling water, m_w in case of jet condenser is found by the following expression :

$$m_w = \frac{m_s[xh_{fg} + c_{pw}(t_s - t_{w_2})]}{c_{pw}(t_{w_2} - t_{w_1})} \text{ kg/h} \qquad ...(3.76)$$

[In MKS unit, the value of c_{pw} is taken as unity]

3.20.17. Heat Transmission Through Walls of Tubes of a Surface Condenser

In case of surface condenser, *the rate of heat transmission varies approximately with square root of the water velocity in tubes*. It thus follows that an increase of heat flow could be obtained by increasing the velocity of flow of water ; but this, in turn, would require a larger amount of energy to circulate the water on account of the corresponding increase in resistance. The following formula is sometimes used for calculating the rate of heat transmission through the walls of the tubes.

Let m_s = Mass of steam used in kg/h,
h = Total heat of 1 kg of steam entering the condenser,
t_m = Mean temperature difference causing heat flow across the tube surface in °C,
t_{w_1} = Temperature of entering cooling water in °C,
t_{w_2} = Temperature of leaving cooling water in °C,
t_s = Temperature of entering steam in °C,
t_c = Temperature of condensate when leaving in °C,
h_{fc} = Total heat of condensate when leaving,
A = Total surface area of condenser tubes in m^2, and
K = Heat transmission coefficient.

(The value of K must be obtained experimentally for the tubes used and for the cooling water velocity in the tubes ; it is a function of both of these factors).

Then, $$K = \frac{m_s(h - h_{fc})}{t_w A} \qquad ...(3.77)$$

where $$t_m = \frac{(t_c - t_{w_1}) - (t_s - t_{w_2})}{\log_e \dfrac{t_c - t_{w_1}}{t_s - t_{w_2}}} \qquad ...(3.78)$$

This equation is due to Grashof and gives approximate result only. It does not hold for all types of surface condensers and modifications of the equation have been made to suite particular types. Eqn. (3.78) may be applied to the *contra-flow* conditions.

If the pressure drop in the condenser is nil, $t_s = t_c$ then eqn. (3.78) may be written as

$$t_m = -\frac{t_{w_2} - t_{w_1}}{\log_e \dfrac{(t_s - t_{w_1})}{(t_s - t_{w_2})}} \qquad ...(3.79)$$

For a *cross-flow* condition,

$$t_m = \frac{(t_{w_2} - t_{w_1})}{\log_e \left[\dfrac{d}{d - \left(\dfrac{t_{w_2} - t_{w_1}}{t_s - t_c}\right) \log_e \left(\dfrac{t_s - t_{w_1}}{t_s - t_{w_2}}\right)} \right]} \qquad ...(3.80)$$

where 'd' is diameter of condenser tubes.

If the value of the heat transmission coefficient K is known and the value of t_m obtained from eqns. (3.78), (3.79), or (3.80), the necessary area of the heating surface of the tubes can now be obtained from eqn. (3.77).

3.20.18. Methods of Cleaning Condenser Tubes

In surface condensers, leaky tube ends and fouling of tubes both inside and outside may give troubles. These troubles are indicated by gradually falling vacuum. This could be offset by increasing the speed of the air as well as increasing the speed of circulating pumps. However, *for better efficiency the tubes must be cleaned.* The cleaning should be thorough.

The inside of the condenser may be usually cleaned with a hose pipe using ordinary city supply of water. A nozzle is fitted to the hose end so that the jet of water may penetrate deep into the condenser. If the water fails to clean out the tubes, soft rubber plugs may be shot through the

tubes under air or water pressure. Fig. 3.126 shows the various types of plugs used for cleaning of the condenser tubes.

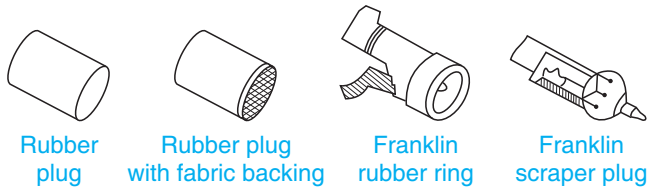


Fig. 3.126. Plugs used for cleaning condenser tubes.

Where water is moderately poor or muddy a built-in tube cleaning equipment may also be used.

Once the life of condenser tube (average 5 years and 15 years in exceptional cases) is finished, the tubes must be replaced.

3.21. COOLING PONDS AND COOLING TOWERS

3.21.1. Introduction

Even in today's many efficient steam plants at least half the energy input must be rejected as unavailable in the steam-turbine exhaust. *The main steam condenser performs the dual function of removing this rejected energy from the plant cycle and keeping the turbine back pressure at the lowest possible level*. The rejected energy inevitably must be returned to the atmosphere. The main condenser does this by transferring the latent heat of the exhaust steam to water exposed to the atmosphere. This water we call circulating, or cooling, water. The cooling water requirement in an open system is about 50 times the flow of steam to the condenser. Even with closed cooling system using cooling towers, the requirement for cooling water is also considerably large as 5 to 8 kg/kWh. This means a 1000 MW station will require about 100 thousand tons of circulating water per day even with the use of cooling towers. Thus the source of cooling water chosen should be able to supply the required quantity of cooling water. The cooling water supply is made by the following sources :

1. River or sea.
2. Cooling ponds.
3. Spray ponds.
4. Cooling towers.

3.21.2. River or Sea

When the power station situated on the bank of a river or lake or other natural source of water, the condenser water supply can be obtained directly from there, the water being discharged to the waste or back to the source (Fig. 3.127).

However, it is not always possible to locate central stations near the source of supply and it becomes necessary to use the same water over and over again by cooling it in a suitable device. Such devices as commonly employed in power stations are the *cooling ponds* and *cooling towers*. Sometimes a combination of natural supply and artificial cooling may be adopted.

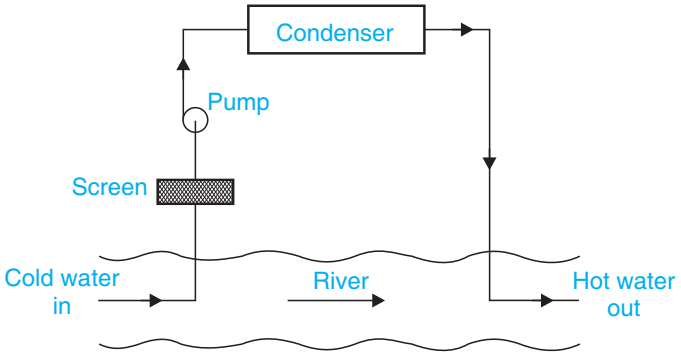


Fig. 3.127. River water cooling system.

3.21.3. Cooling Ponds

The cooling ponds are the simplest of the device for recooling of the cooling water. A cooling pond consists of a large, shallow pool into which the hot water is allowed to come in contact with the atmospheric air. Fig. 3.128 shows a *non-directed flow* naturally cooling pond and Fig. 3.129 illustrates a *directed flow* natural cooling pond. Its cooling effect is more than the non-directed flow pond as water comes in contact with air at lower temperature.

In a cooling pond no spray or other cooling device is employed thus keeping the operating expenses quite low. The cooling pond is suitable where sufficient supply of circulating water is not available. In case the amount of cooling water to be cooled is very large, as in the case of big power plants, the cooling ponds will have to be made very large thus making it prohibitive. For large power plants therefore, spray ponds should be used. The depth of cooling pond should be around one metre.

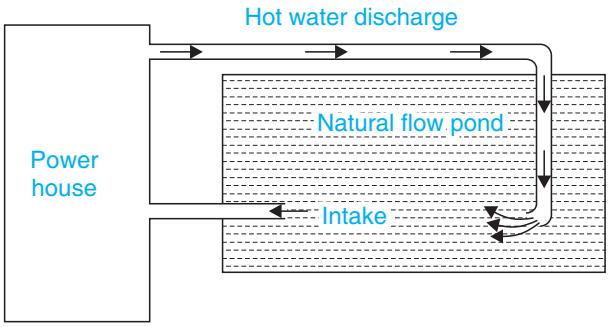


Fig. 3.128. Non-directed flow natural cooling pond.

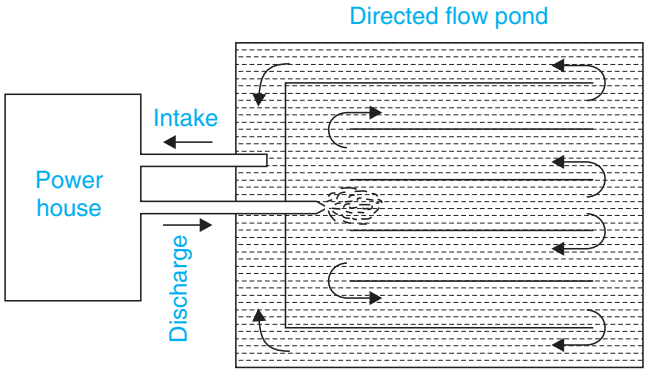


Fig. 3.129. Directed flow natural cooling pond.

3.21.4. Spray Ponds

Refer to Fig. 3.130. In this system warm water received from the condenser is sprayed through the nozzles over a pond of large area and cooling effect is mainly due to *evaporation* from the surface of water. In this system sufficient amount of water is lost by evaporation and windage.

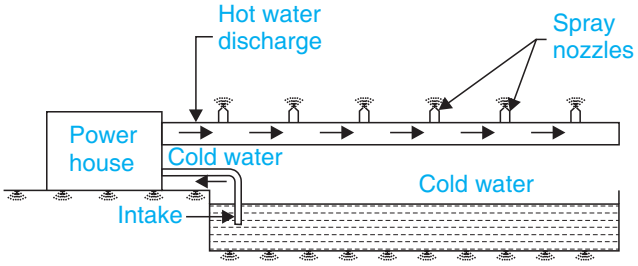


Fig. 3.130. Spray pond.

The spacing of the nozzles in a spray pond depends upon the design and size of the nozzles. Centrifugal nozzles of 50 mm size are usually spaced about 3 metres from centre to centre but the nozzles of large size may be set proportionally farther apart. Nozzles may be mounted in groups of four or five.

Disadvantages of cooling and spray ponds

1. A considerably large area required for cooling.
2. High spray losses (due to evaporation and windage).
3. No control over the temperature of cooled water.
4. Low cooling efficiency (as compared with cooling tower).

3.21.5. Cooling Towers

In power plants the hot water from condenser is cooled in cooling tower, so that it can be reused in condenser for condensation of steam. *In a cooling tower water is made to trickle down drop by drop so that it comes in contact with the air moving in the opposite direction. As a result of this some water is evaporated and is taken away with air. In evaporation the heat is taken away from the bulk of water, which is thus cooled.*

Factors affecting cooling of water in a cooling tower are :

1. Temperature of air.
2. Humidity of air.
3. Temperature of hot air.
4. Size and height of tower.
5. Velocity of air entering tower.
6. Accessibility of air to all parts of tower.
7. Degree of uniformity in descending water.
8. Arrangement of plates in tower.

Cooling towers may be *classified*, according to the *material* of which these are made, as follows :

(*a*) Timber,

(*b*) Concrete (Ferro-concrete, multideck concrete hyperbolic) and

(*c*) Steel duct type.

(*a*) Timber towers. Timber towers are rarely used due to the following disadvantages :

(*i*) Due to exposure to sun, wind, water, etc., timber rots easily.

(*ii*) Short life.

(*iii*) High maintenance charges.

(*iv*) The design generally does not facilitate proper circulation of air.

(*v*) Limited cooling capacity.

(*b*) Concrete towers. The concrete towers possess the following *advantages* :

(*i*) Large capacity sometimes of the order of 5×10^3 m^3/h.

(*ii*) Improved draft and air circulation.

(*iii*) Increased stability under air pressure.

(*iv*) Low maintenance.

(*c*) Steel duct type. Duct type cooling towers are rarely in case of modern power plants owing to their small capacity.

The cooling towers may also be *classified* as follows :

1. Natural draught cooling towers
2. Mechanical draught cooling towers :
   (*i*) Forced draught cooling towers
   (*ii*) Induced draught cooling towers.

1. Natural draught cooling tower. In this type of tower, the hot water from the condenser is pumped to the troughs and nozzles situated near the bottom. Troughs spray the water falls in the form of droplets into a pond situated at the bottom of the tower. The air enters the cooling tower from air openings provided near the base, rises upward and takes up the heat of falling water. A

concrete hyperbolic cooling tower is shown in Fig. 3.131. This tower has the following *advantages* over mechanical towers :

(*i*) Low operating and maintenance cost.

(*ii*) It gives more or less trouble free operation.

(*iii*) Considerable less ground area required.

(*iv*) The towers may be as high as 125 m and 100 m in diameter at the base with the capability of withstanding winds of very high speed. These structures are more or less self-supported structures.

(*v*) The enlarged top of the tower allows water to fall out of suspension.

The main *drawbacks* of this tower are listed below :

(*i*) High initial cost.

(*ii*) Its performance varies with the seasonal changes in DBT (dry bulb temperature) and R.H. (relative humidity) of air.

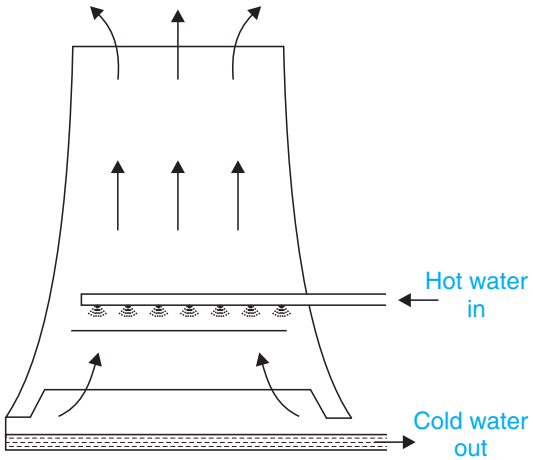


Fig. 3.131. Hyperbolic cooling tower.

While initial cost may be higher, the saving in fan power, longer life and less maintenance always favour for this type of tower. It is also more favourable over mechanical draught cooling towers as central station size increases.

2. Mechanical draught cooling towers. In these towers the draught of air for cooling the tower is produced mechanically by means of *propeller fans*. These towers are usually built in cells or units, the capacity depending upon the number of cells used.

Fig. 3.132 shows a *forced draught cooling tower*. It is similar to natural draught tower as far as interior construction is concerned, but the sides of the tower are closed and form an air and water tight structure, except for fan openings at the base for the inlet of fresh air, and the outlet at the top for the exit of air and vapours. There are hoods at the base projecting from the main portion of the tower where the fans are placed for forcing the air, into the tower.

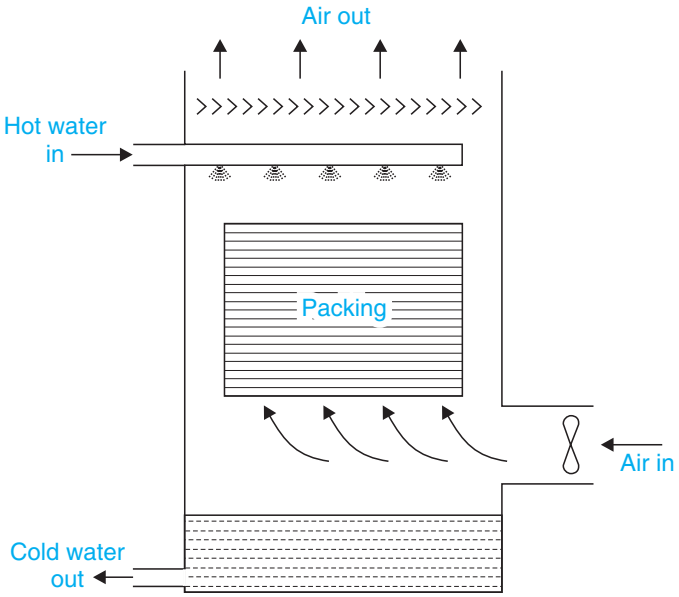


Fig. 3.132. Forced draught cooling tower.

Fig. 3.133 shows an *induced draught cooling tower*. In these towers, the fans are placed at the top of the tower and they draw the air in through louvers extending all around the tower at its base.

Comparison of forced and induced draught towers

Forced Draught Cooling Towers

Advantages :

1. More efficient (than induced draught).
2. No problem of fan blade erosion (as it handles dry air only).
3. More safe.
4. The vibration and noise are minimum.

Disadvantages :

1. The fan size is limited to 4 metres.
2. Power requirement high (approximately double that of induced draught system for the same capacity).
3. In the cold weather, ice is formed on nearby equipments and buildings or in the fan housing itself. The frost in the fan outlet can break the fan blades.

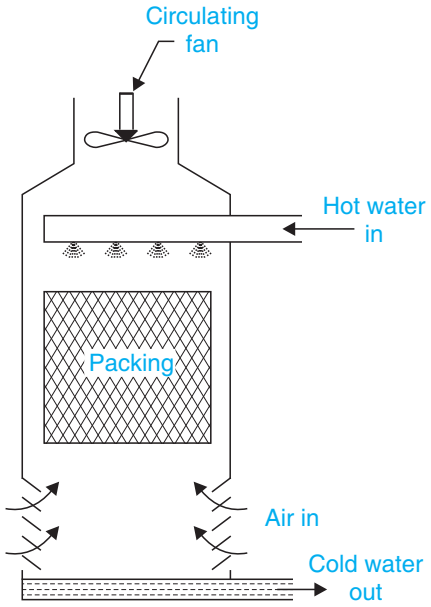


Fig. 3.133. Induced draught cooling tower.

Induced Draught Cooling Towers

Advantages :

1. The coldest water comes in contact with the driest air and warmest water comes in contact with the most humid air.
2. In this tower, the recirculation is seldom a problem.
3. Lower first cost (due to the reduced pump capacity and smaller length of water pipes).
4. Less space required.
5. This tower is capable of cooling through a wide range.

Disadvantages :

1. The air velocities through the packings are unevenly distributed and it has very little movement near the walls and centre of the tower.
2. Higher H.P. motor is required to drive the fan comparatively. This is due to the fact that the static pressure loss is higher as restricted area at base tends to choke off the flow of higher velocity air.

Comparison between Natural and Mechanical Draught Towers

Mechanical Draught Towers

Advantages :

1. These towers require a small land area and can be built at most locations.
2. The fans give a good control over the air flow and thus the water temperature.
3. Less costly to install than natural draught towers.

Disadvantages :

1. Fan power requirements and maintenance costs make them more expensive to operate.
2. Local fogging and icing may occur in winter season.

3.21.6. Dry Cooling Towers

The necessity of using dry cooling towers has been felt due to the following reasons :

(*i*) *Natural water resources* can be used for dissipating heat in power plants but there are some limitations to do so, as discussed earlier. Moreover there are *potential thermal pollution problems in this system.*

(*ii*) In *evaporative cooling system* (cooling towers) due to continuous evaporation of water, the concentration of impurities goes on increasing and so the disposal of tower blow down may become a serious problem at some sites. Besides this make up water for tower use is limited in some areas.

Thus the use of dry cooling towers in power plants in the only alternative. The *dry system rejects the heat directly to the atmosphere which is the largest heat sink available.*

Following are two basic types of closed cooling water systems for power plants utilising dry cooling principle.

1. Direct system
2. Indirect system.

1. Direct System. Refer to Fig. 3.134. In direct system the exhaust steam from the turbine is passed on to the cooling coils where it is condensed directly by *means of air*. Cooling coils constitute air cooled condenser. This system has the disadvantage that *large ducts are needed to convey the exhaust steam to the exchanger coils, to minimise the pressure drop*. This places a practical limit on the size of the unit. This system is limited to maximum generator unit sizes of 200 MW to 300 MW.

2. Indirect System. Refer to Fig. 3.135. In this case, the exhaust steam is condensed in a spray condenser by means of circulating water. The major part of the water from the condenser flows back to the cooling coils and an amount equal to the exhaust steam from the turbine is directed back to the boiler feed water circuit. Some energy recovery is possible by using hydraulic turbine (T) to drive the circulating water pumps. This system is applicable to all large unit sizes.

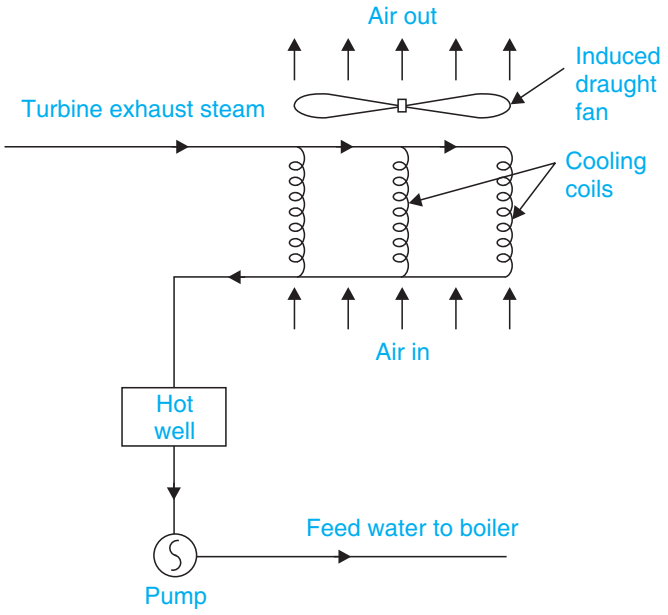


Fig. 3.134. Direct system.

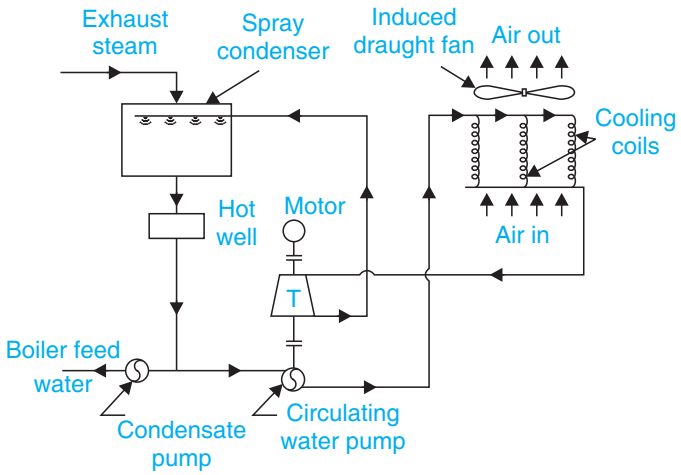


Fig. 3.135. Indirect system.

Advantages of dry cooling system :

1. It solves the problem of thermal pollution of water and as the circulating water does not come into direct contact with the cooling air, there is no evaporative loss of water as in wet type tower.

2. This system eliminates water supply as a significant plant site selection factor. Power plants can be sited closer to the load centre.

3. There is minimum air pollution.

4. From environmental view point, the dry towers offer several desirable features *e.g. no fog, no blowdown treatment, no windage loss of water, no evaporative loss of water* and *no thermal discharge to water source*.

Disadvantages :

1. Their performance is limited by dry bulb temperature and so turbine exhaust temperatures are much higher resulting in a substantial loss of turbine efficiency, most critical in warm climates.

2. Due to low heat transfer co-efficient, dry cooling towers require enormous volumes of air large surface areas and are less effective at high natural air temperatures.

3.21.7. Maintenance of Cooling Towers

The regular maintenance of cooling towers is very essential to achieve the desired cooling and to reduce the depreciation costs. The maintenance of cooling towers includes the following :

1. The fans, motors housings etc. should be inspected from time to time.

2. Motor bearings should be greased and gear boxes oiled. Any unusual noise or vibrations in them should be corrected immediately.

3. At least once in a year motor's gear boxes should be checked for structural weakness.

4. The circulating water should be tested for hardness and should be kept free from impurities to avoid scale formations and to avoid corrosive action of water.

5. The water spraying nozzles should be inspected regularly for clogging.

Example 3.24. *In a surface condenser a section of the tubes near to the air pump suction is screened off so that the air is cooled to a temperature below that of the condensate, separate extraction pumps being provided to deal with air and condensate respectively. 5448 kg of steam are condensed per hour and the air leakage is 4.54 kg / h. The temperature of the exhaust steam is 31°C, the temperature of the condensate is 27°C, and the temperature at the air pump suction is 21.1°C. Assuming a constant vacuum throughout the condenser, find :*

(i) The mass of steam condensed per hour in the air cooler ;

(ii) The volume of air in m^3 / h to be dealt with by the air pump ;

(iii) The percentage reduction in necessary air pump capacity following the cooling of the air.

Solution. From steam tables, pressure of steam at 31°C,

$$p_s = 0.045 \text{ bar abs.}$$

and partial pressure of steam at air pump suction at 21.1°C,

$$p_s = 0.025 \text{ bar abs.}$$

Partial pressure of air,

$$p_a = 0.045 - 0.025 = 0.02 \text{ bar abs.}$$

Also, at air pump suction ;

$$T = 21.1 + 273 = 294.1 \text{ K}$$

(*i*) Using characteristic equation of gas for 4.54 kg of air,

$$p_a V = mRT$$

$$V = \frac{mRT}{10^4 p_a} = \frac{4.54 \times 287 \times 294.1}{0.02 \times 10^5}$$

$= 191.6$ m³/h.

As per Dalton's law this is also the volume of the steam mixed with air at the air pump suction.

Specific volume of steam at partial pressure of 0.025 bar = 54.25 m³/kg

∴ *Mass of steam at air pump suction / h*

$$= \frac{191.6}{54.25} = \mathbf{3.53\ kg.}\quad \textbf{(Ans.)}$$

(*ii*) **Volume of air/h to be dealt**

$= \mathbf{191.6\ m^3/h.}$ **(Ans.)**

(*iii*) Temperature at the pump *without air cooling*,

$T = 27 + 273 = 300$ K.

Partial pressure of steam at 27°C

= 0.0357 bar (From steam tables).

Then, partial pressure of air

= 0.045 – 0.0357 bar = 0.0093 bar

Again, using the characteristic gas equation to 4.54 kg of air at partial pressure of 0.0093 bar,

$$V = \frac{mRT}{p_a} = \frac{4.54 \times 287 \times 300}{0.0093 \times 10^5}$$

$= 420.3$ m³/h.

Percentage reduction in air pump capacity due to air cooling

$$= \frac{420.3 - 191.6}{420.3}$$

$= \mathbf{0.544\ or\ 54.4\%.}$ **(Ans.)**

☞ **Example 3.25.** *A surface condenser deals with 13625 kg of steam per hour at a pressure of 0.09 bar. The steam enters 0.85 dry and the temperature at the condensate and air extraction pipes is 36°C. The air leakage amounts to 7.26 kg / hour. Determine (i) the surface required if the average heat transmission rate is 3.97 kJ / cm² per second ; (ii) the cylinder diameter for the dry air pump, if it is to be single-acting at 60 r.p.m. with a stroke to bore ratio of 1.25 and volumetric efficiency of 0.85.*

Solution. Corresponding to 0.09 bar (from steam tables)

$h_f = 183.3$ kJ/kg, $h_{fg} = 2397.7$ kJ/kg

Heat extracted/sec. from steam

$$= \frac{13625}{3600}\ [(h_f + x h_{fg}) - h_{f_1}]$$

$$= \frac{13625}{3600}\ [(183.3 + 0.85 \times 2397.7) - 4.184 \times 36]$$

$= 3.785\ [(183.3 + 2038) - 150.62]$

$= 7837.5$ kJ/s.

(*i*) **Surface required**

$$= \frac{7837.5}{3.97} = \mathbf{1974.18\ cm^2.}\quad \textbf{(Ans.)}$$

(*ii*) Quantity of air leakage/min. into the condenser

$$= \frac{7.26}{60} = 0.121\ \text{kg}$$

Partial pressure of steam at 36°C (from steam tables)

$p_s = 0.0595$ bar

But, $p = p_a + p_s = 0.09$ bar

∴ $p_a = 0.09 - 0.0595 = 0.0305$ bar

Using characteristic gas equation,

$$p_a V = mRT$$

$$0.0305 \times 10^5 \times V = 0.121 \times 287 \times (273 + 36)$$

or $$V = \frac{0.121 \times 287 \times 309}{0.0305 \times 10^5} = 3.52\ \text{m}^3$$

Capacity of air pump/min

$$= \frac{3.52}{0.85} = 4.14\ \text{m}^3 \text{ or } 4.14 \times 10^6\ \text{cm}^3$$

Capacity of the pump/stroke

$$= \frac{4.14 \times 10^6}{60} = 69000\ \text{cm}^3$$

Also, $\pi/4 \times d^2 \times 1.25 \times d = 69000$

where d is the **diameter of cylinder for dry air pump**

or $$d^3 = \frac{69000 \times 4}{\pi \times 1.25} = 70282.8$$

or $d \simeq \mathbf{41.3\ cm.}$ **(Ans.)**

☞ **Example 3.26.** *A surface condenser deals with 13,000 kg of steam per hour. The leakage air in the system amounts to 1 kg per 2700 kg of steam. The vacuum in the air pump suction is 705 mm of mercury (barometer 760 mm of Hg) and temperature is 34.6°C.*

Determine the discharging capacity of the wet air pump which removes both air and condensate in m³ per minute, taking the volumetric efficiency of the pump as 90%.

If the air pump is single-acting and runs at 60 r.p.m. and piston stroke is 1.25 times the diameter of the pump, find the dimensions of the wet air pump.

Solution. From steam tables, corresponding to 34.6°C,

$p_s = 0.055$ bar

The combined pressure of steam and air in the condenser,

$p = 760 - 705 = 55$ mm of Hg

$= 55 \times 0.001333 = 0.0733$ bar

Partial pressure of air,

$p_a = p - p_s$

$= 0.0733 - 0.055 = 0.0183$ bar

$$\left(\because\ 1\ \text{mm of Hg} = \frac{1.01325}{760} = 0.001333\ \text{bar}\right)$$

Mass of air leakage in the condenser/min.,

$$m_a = \frac{13000}{2700 \times 60} = 0.0802\ \text{kg.}$$

Volume of air leakage in the condenser/min.,

$$V_a = \frac{m_a R T_a}{p_a} = \frac{0.0802 \times 287 \times (34.6 + 273)}{0.0183 \times 10^5}$$
$$= 3.869 \text{ m}^3$$

Mass of steam condensed/min.,

$$m_s = \frac{13000}{60} \text{ kg}$$

Volume of condensate/min.

$$= \frac{13000}{60 \times 1000} = 0.2167 \text{ m}^3$$

[$\because$ Density of water = 1000 kg/m^3]

$\therefore$ Volume of mixture (air + condensate) actually discharged/min.

$$= 3.869 + 0.2167 = 4.0857 \text{ m}^3$$

$\therefore$ **Discharging capacity of the air pump/min.**

$$= 4.0857 \times \frac{100}{90} = \mathbf{4.539\ m^3} \quad \textbf{(Ans.)}$$

$\therefore$ Discharging capacity of the air pump/stroke

$$= \frac{4.539}{60} \times 10^6 = 75650 \text{ cm}^3$$

$\pi/4\ d^2 \times 1.25\ d = 75650$

[d = dia. of the cylinder for the pump]

$$\boldsymbol{d} = \left(\frac{75650 \times 4}{\pi \times 1.25}\right)^{1/3}$$
$$= \mathbf{42.55\ cm.} \quad \textbf{(Ans.)}$$

Piston stroke, $\boldsymbol{l} = 1.25\ d = 1.25 \times 42.55$
$= \mathbf{53.2\ cm.}$ **(Ans.)**

Example 3.27. *To check the leakage of air in a condenser, the following procedure is adopted. After ruming the plant to reach the steady conditions the steam supply to the condenser and the air and condensate pump are shut down, thus completely isolating the condenser. The temperature and vacuum readings are noted at shut down and also after a period of 10-minutes. They are 39°C and 685 mm Hg and 28°C and 480 mm Hg respectively. The barometer reads 750 mm Hg. The effective volume of the condenser is 1.5 m^3. Determine (i) quantity of air leakage into the condenser during the period of observation ; (ii) the quantity of water vapour condensed during the period.*

Solution. At shut down :

From steam tables, corresponding to t_s = 39°C :

$$p_s = 0.07 \text{ bar} = \frac{0.07}{0.001333} = 52.5 \text{ mm Hg}$$

and $v_g = 20.53$ m^3/kg

The combined pressure of steam and air in the condenser,

$$p = p_a + p_s = 750 - 685 = 65 \text{ mm Hg}$$

$\therefore$ $p_a = p - p_s = 65 - 52.5 = 12.5$ mm Hg
$= 12.5 \times 0.001333 = 0.0167$ bar

Now, mass of air in 1.5 m^3

$$m_a = \frac{p_a V_a}{R T_a} = \frac{0.0167 \times 10^5 \times 1.5}{287 \times (273 + 39)} = 0.028 \text{ kg}$$

and mass of steam in 1.5 m^3

$$m_s = \frac{1.5}{20.53} = 0.073 \text{ kg}$$

After 10 minutes, observed duration,

From steam tables, corresponding to t_s = 28°C

$$p_s = 0.0378 \text{ bar} = \frac{0.0378}{0.001333} = 28.36 \text{ mm Hg},$$

$v_g = 36.69$ m^3/kg

Total pressure in the condenser,

$p = 750 - 480 = 270$ mm Hg

$\therefore$ Air pressure,

$p_a = p - p_s = 270 - 28.36 = 241.64$ mm Hg
$= 241.64 \times 0.001333 = 0.322$ bar

Mass of air,

$$m_a = \frac{p_a V_a}{R T_a} = \frac{0.322 \times 10^5 \times 1.5}{287 \times (273 + 28)} = 0.559 \text{ kg.}$$

Mass of steam,

$$m_s = \frac{1.5}{36.69} = 0.0408 \text{ kg}$$

$\therefore$ **Air leakage** in 10 minutes period
$= (0.559 - 0.028) =$ **0.531 kg.** **(Ans.)**

and **steam condensed** in 10 minutes period
$= (0.073 - 0.0408) =$ **0.0322 kg.** **(Ans.)**

Example 3.28. *A jet condenser is required to condenser 5000 kg of steam per hour. 350 m^3 of injection water are used per hour. Initial temperature of the cooling water is 27°C. The volume of air at atmospheric pressure dissolved in injection water is 5% of the volume of water. The amount of air entering the condenser with steam is 1 kg for every 3500 kg of steam. The vacuum in the air pump suction is 686 mm. When the barometer records 760 mm and the temperature of the condensate is 34.6°C, determine the suction capacity of the air-pump in m^3/min to remove air and water from the condenser. Assume volumetric efficiency of pump as 85%.*

Solution. Total pressure in the condenser,

$p = p_a + p_s = (760 - 686) = 74$ mm Hg

$74 \times 0.001333 = 0.0986$ bar

Partial pressure of steam corresponding to 34.6°C = 0.055 bar (From steam tables)

$\therefore$ Partial pressure of air, $p_a = p - p_s$
$= 0.0986 - 0.055 = 0.0436$ bar

Mass of air entering per minute with steam

$$= \frac{5{,}000}{3500 \times 60} = 0.0238 \text{ kg}$$

Volume of air entering per minute with injection water

$$= \frac{350 \times 5}{100 \times 60} = 0.292 \text{ m}^3.$$

Mass of this volume of air

$$= \frac{p_a V_a}{RT_a} = \frac{1.01325 \times 10^5 \times 0.292}{287 \times (273 + 27)}$$

$$= 0.343 \text{ kg.}$$

Total weight of air entering the condenser per minute

$$= 0.0238 + 0.343 = 0.3668 \text{ kg}$$

Now, volume of this air at 0.045 bar and 34.6°C,

$$V = \frac{m_a RT_a}{p_a} = \frac{0.3668 \times 287 \times (273 + 34.6)}{0.0436 \times 10^5}$$

$$= 7.427 \text{ m}^3$$

Volume of condensate/min

$$= \frac{5000}{60 \times 1000} = 0.083 \text{ m}^3$$

Volume of injected water/min.

$$= \frac{350}{60} = 5.83 \text{ m}^3$$

Hence, total volume to be handled

$$= 7.427 + 0.083 + 5.83 = 13.34 \text{ m}^3$$

∴ Suction capacity of the air pump

$$= \frac{13.34}{0.85} = \mathbf{15.69\ m^3.} \quad \textbf{(Ans.)}$$

Example 3.29. *In a condenser air pump and water pump are separately installed. Steam enters the condenser at 41.5°C and the condensate is removed at 37.6°C. The quantity of air infiltrating into the condenser through various zones is 6 kg/h. Determine :*

(i) The volume of air handled by the air pump.

(ii) The quantity handled by a combined air and condensate pump at 39°C.

Make suitable assumptions and list all such assumptions.

Solution. Pressure of steam corresponding to 41.5°C = 0.08 bar.

Air pump suction point

Temperature = 37.6°C

Pressure (p_s) corresponding to 37.6°C = 0.065 bar

∴ Partial pressure of air

$$= 0.08 - 0.065 = 0.015 \text{ bar}$$

∴ *Volume of air,*

$$V_a = \frac{mRT}{p_a}$$

$$= \frac{6 \times 0.287 \times (273 + 37.6) \times 1000}{0.015 \times 10^5}$$

$$= \mathbf{356.57\ m^3/h.} \quad \textbf{(Ans.)}$$

Assumptions :

1. Pressure inside the condenser is uniform.

2. Air is removed at the same temperature as that of condensate.

3. The pressure due to air at the entry of steam is neglected.

If condensate and air are to be removed by the same pump, the air is to be removed at 39°C.

Partial pressure of steam at 39°C = 0.07 bar

∴ Partial pressure of air = 0.08 – 0.07 = 0.01 bar

∴ *Volume of air* $= \frac{6 \times 0.287 \times (273 + 39) \times 1000}{0.01 \times 10^5}$

$$= \mathbf{537.26\ m^3/h.} \quad \textbf{(Ans.)}$$

Example 3.30. *During a trial on a steam condenser, the following observations were recorded :*

Condenser vacuum 680 mm kg

Barometer reading 764 mm kg

Mean condenser temperature 36.2°C

Hot well temperature 30°C

Condensate formed per hour 1780 kg

Circulating cooling water inlet temperature 20°C

Circulating cooling water outlet temperature 32°C

Quantity of cooling water 1250 kg/min.

Determine :

(i) Condenser vacuum corrected to standard barometer.

(ii) Vacuum efficiency.

(iii) Undercooling of condensate.

(iv) Condenser efficiency.

(v) Condition of steam as it enters the condenser.

(vi) Mass of air present per kg of condensed steam.

Assume : R for air = 0.287 kJ/kg K

Specific heat of water = 4.186 kJ/kg K.

Solution. (i) Condenser vacuum corrected to standard barometer

= Standard barometric pressure – (barometric pressure – gauge pressure)

= 760 – (764 – 680) = 676 mm of Hg

But 1 mm of Hg = 1.333×10^{-3} bar

∴ 676 mm of Hg = $676 \times 1.333 \times 10^{-3}$

$$= \mathbf{0.9011\ bar.} \quad \textbf{(Ans.)}$$

(ii) Vacuum efficiency :

From steam tables saturation pressure corresponding to 36.2°C = 0.06 bar.

∴ *Vacuum efficiency*

$$= \frac{\text{Condenser vacuum}}{\text{Barometer reading} - \text{Pressure of steam}}$$

$$= \frac{680 \times 1.333 \times 10^{-3}}{764 \times 1.333 \times 10^{-3} - 0.06}$$

$$= \mathbf{0.9458 \text{ or } 94.58\%.} \quad \textbf{(Ans.)}$$

(iii) Undercooling of condensate :

= Condensate temperature – Hot well temperature

= 36.2 – 30 = **6.2°C.** **(Ans.)**

(iv) Condenser efficiency :

Absolute condenser pressure

= Barometric pressure – Vacuum reading

= 764 – 680 = 84 mm of Hg

= 84 × 1.333 × 10^{-3} = 0.1119 bar

Saturation temperature corresponding to 0.1119 bar (from steam tables) ≃ 48°C.

∴ *Condenser efficiency*

$$= \frac{\text{Actual cooling water temperature rise}}{\text{Maximum possible temperature rise}}$$

$$= \frac{32 - 20}{48 - 20} = 0.4286 = \mathbf{42.86\%.} \quad \textbf{(Ans.)}$$

(v) Condition of steam entering the condenser :

Absolute condenser pressure = 0.1119 bar.

For this pressure, h_f = 200.1 kJ/kg,

h_{fg} = 2387.2 kJ/kg

Enthalpy of condensate corresponding to hot well temperature of 30°C

= 125.75 kJ/kg.

Also, heat lost by steam = heat gained by water

$$m_s\,[(h_f + x\,h_{fg}) - h_{\text{hot-well}}] = m_w \times c_{pw} \times (t_{w_2} - t_{w_1})$$

$$= \frac{1780}{60}\,[(200.1 + x \times 2387.2) - 125.75]$$

$$= 1250 \times 4.186 \times (32 - 20)$$

$$(200.1 + x \times 2387.2) - 125.75 = 2116.5$$

Solving, $x = 0.855$

Hence, *condition of steam entering the condenser* = **0.855.** **(Ans.)**

(vi) Mass of air present :

Specific volume of steam at mean condensate temperature of 36.2°C

= 23.74 m^3/kg

Partial pressure of steam at 36.2°C = 0.06 bar

∴ Partial pressure of air

= 0.1119 – 0.06 = 0.0519 bar

∴ *Mass of air present per kg of uncondensed vapour,*

$$m_a = \frac{p_a V}{RT} = \frac{0.0519 \times 10^5 \times 23.74}{0.287 \times 1000 \times (273 + 36.2)}$$

$$= \mathbf{1.3884 \text{ kg.}} \quad \textbf{(Ans.)}$$

Example 3.31. *A primemover uses 15000 kg of steam per hour and develops 2450 kW. The steam is supplied at 30 bar and 350°C. The exhaust from the primemover is condensed at 725 mm Hg when barometer records 755 mm Hg. The condensate temperature from the condenser is 31°C and the rise of temperature of circulating water is from 8°C to 18°C. Determine : (i) The quality of steam entering the condenser, (ii) The quantity of circulating cooling water and the ratio of cooling.*

Assume that no air is present in the condenser and all mechanical drive losses are negligible.

Solution. Quantity of steam used, m_s = 15000 kg/h

Pressure of steam = 30 bar, 350°C

Vacuum reading = 725 mm Hg

Barometer reading = 755 mm Hg

Condensate temperature = 31°C

Rise of temperature of cooling water,

$$t_{w_2} - t_{w_1} = 18 - 8 = 10°C.$$

(i) Quality of steam entering the condenser, x :

Condenser pressure = 755 – 725 = 30 mm Hg

= 30 × 1.333 × 10^{-3}

= 0.0399 bar

From steam table :

At 0.0399 bar : h_f = 121.5 kJ/kg,

h_{fg} = 2432.9 kJ/kg

At 30 bar, 350°C : h_g = 3115.3 kJ/kg

The work done in the turbine = 2450 kW or kJ/s ...(*i*)

Enthalpy drop in the turbine/sec.

$$= \frac{15000}{3600}\,[3115.3 - (121.5 + x \times 2432.9)] \text{ kJ/s} \quad ...(ii)$$

Since mechanical drive losses are negligible, the expressions (*i*) and (*ii*) are equal.

$$\therefore \quad 2450 = \frac{15000}{3600}\,[3115.3 - (121.5 + x \times 2432.9)]$$

$$\text{or} \quad \frac{2450 \times 3600}{15000} = 3115.3 - 121.5 - x \times 2432.9$$

$$588 = 3115.3 - 121.5 - 2432.9x$$

$$\therefore \qquad x = \frac{3115.3 - 121.5 - 588}{2432.9} = \mathbf{0.988.} \quad \textbf{(Ans.)}$$

(*ii*) Quantity of circulating water, m_w :

Ratio of cooling :

Heat lost by condensing steam = Heat gained by cooling water

$$m_s\,[h_f + x\,h_{fg} - h_c] = m_w \times c_{pw} \times (t_{w_2} - t_{w_1})$$

or
$$m_w = \frac{m_s\,[h_f + x\,h_{fg} - h_c]}{c_{pw} \times (t_{w_2} - t_{w_1})}$$

$$= \frac{15000\,[121.5 + 0.988 \times 2432.9 - 4.186 \times 31]}{4.186 \times 10}$$

$$= \mathbf{858375\ kg/h.} \quad \textbf{(Ans.)}$$

[where c_{pw} = specific heat of water = 4.186 kJ/kg K]

$$\therefore \quad \textit{Ratio of cooling} = \frac{m_w}{m_s} = \frac{858375}{15000}$$

$$= \mathbf{57.225\ kg.} \quad \textbf{(Ans.)}$$

☞ **Example 3.32.** *A surface condenser is required to deal with 20000 kg of steam per hour, and the air leakage is estimated at 0.3 kg per 1000 kg of steam. The steam enters the condenser dry saturated at 38°C. The condensate is extracted at the lowest point of the condenser at a temperature of 36°C. The condensate loss is made up with water at 7°C. It is required to find the saving in condensate and the saving in heat supplied in the boiler, by fitting a separate air extraction pump which draws the air over an air cooler. Assume that the air leaves the cooler at 27°C. The pressure in the condenser can be assumed to remain constant.*

Solution. The mass of air per kg of steam at entry
= 0.3/1000 = 0.0003 kg

At 38°C : Saturation pressure = 0.06624 bar and
v_g = 21.63 m³/kg (From steam tables)

For 1 kg of steam, the volume is 21.63 m³, and this must be the volume occupied by 0.0003 kg of air when exerting its partial pressure,

i.e., Partial pressure of air

$$= \frac{m_a R_a T}{V}$$

$$= \frac{0.0003 \times 0.287 \times (273 + 38) \times 10^3}{21.63 \times 10^5}$$

$$= 1.2 \times 10^{-5} \text{ bar}$$

This is negligibly small and may be neglected.

Condensate extraction :

At 36°C : Saturation pressure
= 0.0594 bar, v_g = 23.97 m³/kg.

The total pressure in the condenser is 0.06624 bar, hence,

$$0.06624 = 0.0594 + p_a$$

$$\therefore \quad p_a = 0.00684 \text{ bar}$$

The mass of air removed per hour is

$$\frac{20000 \times 0.3}{1000} = 6 \text{ kg/h}$$

Hence the volume of air removed per hour is

$$\frac{mRT}{p} = \frac{6 \times 0.287 \times (273 + 36) \times 10^3}{0.00684 \times 10^5}$$

$$= 778 \text{ m}^3\text{/h}$$

The mass of steam associated with the air removed is therefore given by

$$\frac{778}{23.97} = 32.45 \text{ kg/h.}$$

Separate extraction :

At 27°C : Saturation pressure
= 0.03564 bar, v_g = 38.81 m³/kg

The air partial pressure
= 0.06624 – 0.03564 = 0.0306 bar

$\therefore$ The volume of air removed

$$= \frac{mRT}{p} = \frac{6 \times 0.287 \times (273 + 27) \times 10^3}{0.0306 \times 10^5}$$

$$= 168.9 \text{ m}^3\text{/h}$$

$\therefore$ Steam removed $= \frac{168.9}{38.81} = 4.35$ kg/h.

Hence, *the saving in condensate by using the separate extraction method*

$$= 32.45 - 4.35 = \mathbf{28.1\ kg/h.} \quad \textbf{(Ans.)}$$

The *saving in heat to be supplied in the boiler*

$$= 28.1 \times 4.186\ (36 - 7)$$

$$= \mathbf{3411\ kJ/h.} \quad \textbf{(Ans.)}$$

Example 3.33. *For the data of example 3.32, calculate :*

(*i*) *The percentage reduction in air pump capacity by using the separate extraction method.*

(*ii*) *If the temperature rise of cooling water is 5.5 K, calculate the mass flow of cooling water required.*

Solution. Capacity of air pump without air cooler

$$= 778 \text{ m}^3\text{/h}$$

Capacity of air pump with air cooler
= 168.9 m³/h.

$\therefore$ *Percentage reduction in capacity*

$$= \left(\frac{778 - 168.9}{778}\right) \times 100 = \mathbf{78.3\%.} \quad \textbf{(Ans.)}$$

Fig. 3.136 shows the system to be analysed. Let suffixes *s*, *a*, and *c* denote steam, air and condensate respectively.

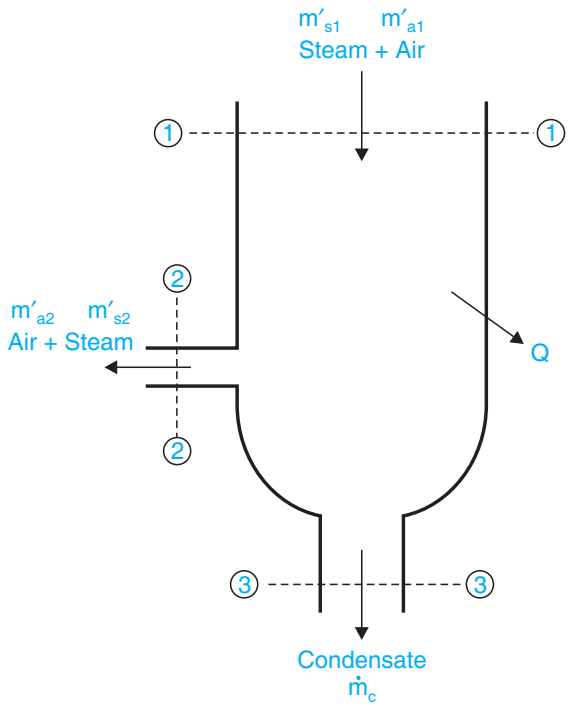


Fig. 3.136

Applying the steady flow energy equation and neglecting changes in kinetic energy, we have:

$$Q = (\dot{m}_{s_1} h_{s_1} + \dot{m}_{a_1} h_{a_1}) - (\dot{m}_{s_2} h_{s_2} + \dot{m}_{a_2} h_{a_2}) - \dot{m}_c h_c$$

$\dot{m}_{a_1} = \dot{m}_{a_2} = 6$ kg/h ; $\dot{m}_{s_2} = 4.35$ kg/h

$\dot{m}_c = 20000 - 4.35$
$= 20000$ kg/h approximately.

Also, $h_{a_1} - h_{a_2} = c_p (T_1 - T_2)$

$\therefore \quad Q = 20000 \times 2570.1 + 6 \times 1.005 (38 - 27) - 4.35 \times 2550.3 - 20000 \times 150.9$

[where $h_c = h_f$ at 36°C = 150.9 kJ/kg]

i.e. Heat rejected $= 48.37 \times 10^6$ kJ/h

The *mass of cooling water required* for a 5.5 K rise in temperature

$$= \frac{48.37 \times 10^6}{4.186 \times 5.5}$$

$= \mathbf{2.1 \times 10^6\ kg/h.}$ **(Ans.)**

☞ **Example 3.34.** *The following data relate to a two pass surface condenser :*

Steam condensed	*15400 kg/h*
Temperature of cooling water when it enters the condenser	*15°C*
Temperature of cooling water when it leaves the condenser	*30°C*
The vacuum in the condenser	*675 mm of Hg*
Barometer reading	*755 mm of Hg*
Temperature of the condensate	*32°C*
Quality of exhaust steam	*0.92*
Water velocity in the tubes	*2.6 m/s*
Outside diameter of the tubes	*2.8 cm*
Thickness of the tubes	*0.03 cm*
Heat transfer co-efficient (U)	*3.35 kJ/h/cm²/°C.*

Determine : (i) Area of the tube surface required.
(ii) Number of tubes.
(iii) Length of tubes.

Solution. Absolute pressure in the condenser
$= 750 - 675 = 75$ mm Hg
$= 75 \times 0.001333 = 0.1$ bar

From steam tables saturation temperature corresponding to 0.1 bar pressure is 45.8°C. (At 0.1 bar ; $h_f = 191.8$ kJ/kg ; $h_{fg} = 2392.8$ kJ/kg).

Mean temperature difference,

$$t_m = \frac{t_{w_2} - t_{w_1}}{\log_e \frac{(t_s - t_{w_1})}{(t_s - t_{w_2})}} = \frac{(30 - 15)}{\log_e \frac{(45.8 - 15)}{(45.8 - 30)}}$$

$$= \frac{15}{\log_e \frac{30.8}{15.8}} = 22.5°C$$

Heat extracted per kg of steam
$= (h_f + x h_{fg}) - 1 \times 4.184 \times 32$
$= (191.8 + 0.92 \times 2392.8) - 133.9$
$= 2259.3$ kJ/kg.

Now, heat lost by steam = heat gained by water

$15400 \times 2393.2 = m_w \times c_{pw} \times (t_{w_2} - t_{w_1})$
$= m_w \times 4.184 \times (30 - 15)$

$\therefore$ Mass of circulating water,

$$m_w = \frac{15400 \times 2259.3}{4.184 \times 15} = 554385 \text{ kg/h.}$$

(i) Area of tube surface required, A :

$$A = \frac{Q}{U t_m}$$

where, Q = Heat lost by steam or heat gained by water
$= m_w \times c_{pw} \times (t_{w_2} - t_{w_1})$
$= 554385 \times 4.184 \times (30 - 15)$
$= 34793202$ kJ/h
U = Heat transfer co-efficient
$= 3.35$ kJ/h/cm²/°C

$\therefore \quad A = \frac{34793202}{3.35 \times 22.5} = \mathbf{461601\ cm^2.}$ **(Ans.)**

(ii) Number of tubes :

Total water required/sec.

$$= \frac{m_w \times 1000}{3600}$$

$$= \frac{554385 \times 1000}{3600}$$

[$\because$ 1 kg occupies 1000 cm^3 volume]

$= 153996$ cm^3

Water required/sec./tube

$$= \frac{\pi}{4} \times (2.8 - 2 \times 0.03)^2 \times (2.6 \times 100)$$

$= 1533$ cm^3

$\therefore$ Number of tubes

$$= \frac{2 \times m_w \times 1000}{3600 \times 1533} = \frac{2 \times 554385 \times 1000}{3600 \times 1533}$$

$=$ **200.** **(Ans.)**

(*iii*) Length of tubes, l :

Surface area per tube $= \frac{A}{200} = \frac{461601}{200} = 2308$

i.e., $\pi \times d \times l = 2308$

$\pi \times 2.8 \times l = 2308$

$l =$ **262.4 cm.** **(Ans.)**

Example 3.35. *A steam condenser consists of 3000 brass tubes of 20 mm diameter. Cooling water enters the tubes at 20°C with a mean flow rate of 3000 kg/s. The heat transfer coefficient on the inner surface is 11270 W/m^2°C, and that for condensation on the outer surface is 15500 W/m^2°C. The steam condenses at 50°C, and the condenser load is 230 MW. The latent heat of steam is 2380 kJ/kg. Assuming counter flow arrangement, calculate the tube length per pass if two tube passes are used.*

Solution. *Given :* $N_p = 3000$ per pass ; $d = 20$ mm $= 0.02$ m ; $t_{c1} = 20$°C ; $\dot{m}_c = 3000$ kg/s ; $h_i = 11270$ W/m^2°C ; $h_o = 15500$ W/m^2°C, $t_{h1} = t_{h2} = 50$°C ; condenser load = 230 W (or 230×10^3 kW) ; $h_{fg} = 2380$ kJ/kg ; number of passes = 2.

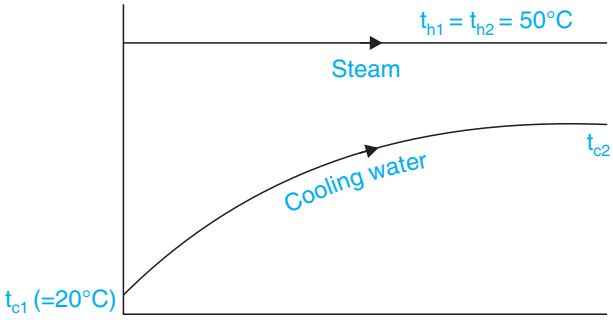


Fig. 3.137

Tube length per pass, L :

Assuming the tubes to be thin, the overall heat transfer coefficient :

$$U_o = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o}} = \frac{1}{\frac{1}{11270} + \frac{1}{15500}}$$

$= 6525.4$ W/m^2°C

Heat exchanger load

$= \dot{m}_c \, c_{pc} \, (t_{c2} - t_{c1})$

i.e., $230 \times 10^3 = 3000 \times 4.187 \, (t_{c2} - 20)$

$\therefore$ Water outlet temperature, $t_{c2} = 38.31$°C

Log-mean temperature difference,

$$\theta_m = \frac{\theta_1 - \theta_2}{\ln (\theta_1/\theta_2)} = \frac{(t_{h1} - t_{c1}) - (t_{h2} - t_{c2})}{\ln \left[\frac{t_{h1} - t_{c1}}{t_{h2} - t_{c2}} \right]}$$

$$= \frac{(50 - 20) - (50 - 38.31)}{\ln \left[\frac{50 - 20}{50 - 38.31} \right]} = \frac{18.31}{0.9425} = 19.43°\text{C}$$

Now, $Q = U_o A \theta_m$

$230 \times 10^6 = 6525.4 \times (\pi \, dL) \times (2N_p) \times 19.43$

$= 6525.4 \times (\pi \times 0.02 \times L) \times (2 \times 3000) \times 19.43$

$\therefore \quad L = \frac{230 \times 10^6}{6525.4 \times \pi \times 0.02 \times (2 \times 3000) \times 19.43}$

$=$ **4.812 m.** **(Ans.)**

Example 3.36. *A two-pass surface condenser is required to handle the exhaust from a turbine developing 15 MW with specific steam consumption of 5 kg/kWh. The condenser vacuum is 660 mm of Hg when the barometer reads 760 mm of Hg. The mean velocity of water is 3 m/s, water inlet temperature is 24°C. The condensate is saturated*

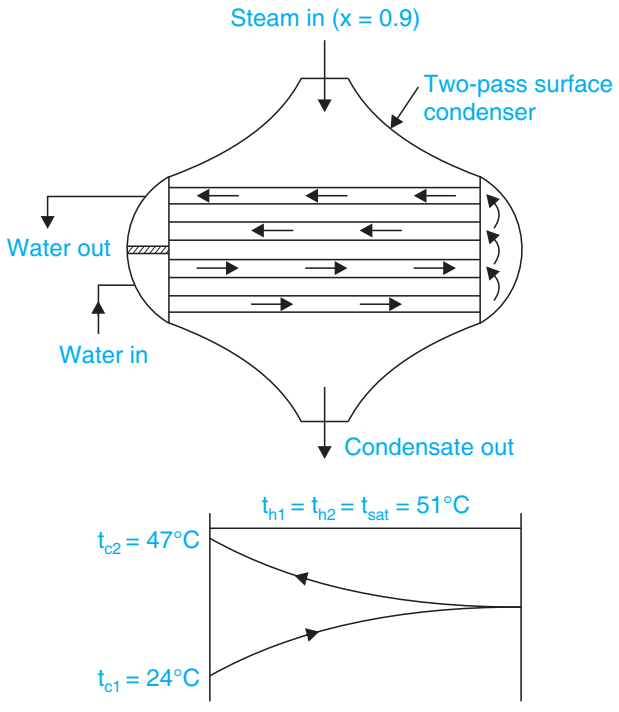


Fig. 3.138. A two-pass surface condenser.

water and outlet temperature of cooling water is 4°C less than the condensate temperature. The quality of exhaust steam is 0.9 dry. The overall heat transfer coefficient based on outer area of tubes is 4000 W/m²°C. The water tubes are 38.4 mm in outer diameter and 29.6 mm in inner diameter. Calculate the following :

(i) Mass of cooling water circulated in kg/min,

(ii) Condenser surface area,

(iii) Number of tubes required per pass, and

(iv) Tube length.

Solution. *Given :* $d_i = 29.6$ mm $= 0.0296$ m ; $d_o = 38.4$ mm $= 0.0384$ m ; $U = 4000$ W/m²°C ; $V = 3$ m/s ; $t_{c1} = 24$°C ; x (dryness fraction) $= 0.9$.

The pressure of the steam in the condenser,

$$p_s = \frac{760 - 660}{760} \times 1.01325 = 0.133 \text{ bar}$$

The properties of steam at $p_s = 0.133$ bar, from steam table, are :

$$t_{sat} = 51°C \text{ ; } h_{fg} = 2592 \text{ kJ/kg}$$

$$\therefore \quad t_{c_2} = 51 - 4 = 47°C$$

The steam condensed per minute,

$$\dot{m}_s \ (= \dot{m}_h) = \frac{(15 \times 1000) \times 5}{60} = 1250 \text{ kg/min}$$

(i) Mass of cooling water circulated per minute, $\dot{m}_w \ (= \dot{m}_c)$:

Heat lost by steam = Heat gained by water

$$\dot{m}_h \times (x \, . \, h_{f_g}) = \dot{m}_c \times c_{pc} \times (t_{c_2} - t_{c_1})$$

$$1250 \times (0.9 \times 2592) = \dot{m}_c \times 4.187 \ (47 - 24)$$

$$\therefore \quad \dot{m}_c \ (= \dot{m}_w) = \mathbf{30280 \text{ kg/min.}} \quad \textbf{(Ans.)}$$

(ii) Condenser surface area, A :

$$Q = \frac{\dot{m}_s \times (x \, . \, h_{f_g})}{60} = U A \, \theta_m \qquad ...(i)$$

where $\theta_m = \dfrac{\theta_1 - \theta_2}{\ln (\theta_1/\theta_2)} = \dfrac{(t_{h1} - t_{c1}) - (t_{h2} - t_{c2})}{\ln [(t_{h1} - t_{c1})/(t_{h2} - t_{c2})]}$

$$= \frac{(51 - 24) - (51 - 47)}{\ln [(51 - 24)/(51 - 47)]} = \frac{(27 - 4)}{\ln (27/4)} = 12.04°C$$

Substituting the values in eqn. (*i*), we get

$$\frac{1250}{60} \times (0.9 \times 2592 \times 10^3) = 4000 \times A \times 12.04$$

or $$A = \mathbf{1009.1 \text{ m}^2.} \quad \textbf{(Ans.)}$$

(iii) Number of tubes required per pass, N_p :

$$\dot{m}_w = \left(\frac{\pi}{4} d_i^2 \times V \times \rho \right) \times N_p$$

$$\frac{30280}{60} = \frac{\pi}{4} \times (0.0296)^2 \times 3 \times 1000 \times N_p$$

or $$N_p = \frac{30280 \times 4}{60 \times \pi \times (0.0296)^2 \times 3 \times 1000}$$

$$= 244.46 \text{ say } \mathbf{245} \quad \textbf{(Ans.)}$$

(Total number of tubes required,

$$N = 2N_p = 2 \times 245 = 490)$$

(iv) Tube length, L :

$$A = (\pi \, d_o \, L) \times (2N_p)$$

$$1009.1 = \pi \times 0.0384 \times L \times (2 \times 245)$$

$$L = \frac{1009.1}{\pi \times 0.0384 \times 2 \times 245} \simeq \mathbf{17.1 \text{ m}} \quad \textbf{(Ans.)}$$

3.22. FEED WATER TREATMENT

For steam power plants water is one of the most important raw materials. In most of the cases, water used for steam power plants contains impurities which must be treated before use. All natural waters-even rain, snow, hail, treated municipal supplies contain impurities in one form or the other.

3.22.1. Classification of Impurities in Water

The impurities in water may be classified as follows :

1. Visible impurities

(*i*) *Microbiological growth.* Presence of micro-organisms is always undesirable as they may produce *clogging troubles*.

(*ii*) *Turbidity and sediments. Turbidity* is the suspended insoluble matter whereas *sediments* are the coarse particles which settle down in stationary water, both are objectionable.

2. Dissolved gases

(*i*) Carbon dioxide (*ii*) Oxygen

(*iii*) Nitrogen (*iv*) Methane

(*v*) Hydrogen sulphide.

3. Minerals and salts

(*i*) Iron and manganese

(*ii*) Sodium and potassium salts

(*iii*) Flourides

(*iv*) Silica.

4. Mineral acids. Their presence in water is always undesirable as it may result in the chemical reaction with the boiler material.

5. Hardness. The salts of calcium and magnesium as bicarbonates, chlorides, sulphates etc. are mainly responsible for the formation of a *very hard surface which resists heat transfer and clogs the passages in pipes*. Presence of these salts is known as hardness.

3.22.2. Troubles Caused by the Impurities in Water

The impurities in water may cause one or more of the following troubles :

1. Scale formation 2. Corrosion
3. Carryover 4. Embrittlement.

1. Scale formation. The *formation of scale reduces heat transfer* and *simultaneously raises the temperature of the metal wall*. When temperature of boiler tube material reaches 450°C to 500°C, there is a serious danger of *overheating* and consequently *rupture of boiler plates*. The *scaling results from the decrease of solubility of some salt with increase of temperature*. It is formed by crystallisation of scale-forming salts from a locally super-saturated layer of water lying on the heating surface. This forms an incrustation at the point of evaporation. Scale is due to mainly the salts of *calcium* and *magnesium* as also to a certain extent the salts of *silicates. Calcium sulphate* is essentially responsible for the formation of scale.

The scale chokes the flow in the piping system and thus requires increased pressure to maintain water delivery. The accumulation of scale may become so thick that the temperature drop from gas to water is through the scale only. This will result in *overheating, blistering* and *rupturing*. When scale is formed, tubes are cleaned with electric-powered rotary brushes and cutters are pushed through the tubes during boiler overhaul.

2. Corrosion. *The corrosion is the eating away process of boiler metal.* Corrosion in power-plant equipment produces pits, grooves and cracks or a general wastage of the wall material. Allowed to continue, *corrosion ultimately makes metal parts fail.*

The corrosion is caused by an acid or low pH in addition to the presence of *dissolve oxygen and carbon dioxide* in the boiler feed water. The presence of oxygen is mostly responsible for corrosion among all other factors. Oxygen generally enters a closed system through make-up condenser leakage and condensate pump packings. The *carbon dioxide* is next to oxygen which is responsible for corrosion, it comes out of bicarbonates on heating and it combines with water to form weak acid known as carbonic acid. This acid slowly reacts with iron and other metals to form their bicarbonates. The new bicarbonates of metals formed are decomposed by heat once more and carbon dioxide is again liberated. This gas again unites with water to form carbonic acid and the cycle is repeated.

The corrosion can be controlled by adding alkali salts to neutralise acids in water and raise the pH value (it is the logarithm of the reciprocal of hydrogen ion concentration). The effect of CO_2 is neutralised by the addition of ammonia for neutralising amines in water. This is necessary because CO_2 lowers the pH of the boiler feed water. The effect of oxygen is reduced only by removing the oxygen from water. The corrosion of metal surfaces can be prevented by applying protecting coating of amines to the internal surfaces of boilers and economisers.

3. Carryover. Water solids carried over in the steam leaving a boiler drum are called *"carry-over". Foaming* or *priming* of the boiler water forms the carry-over. In *"foaming", bubles form on the water surface and may fill the drum steam space. Excessive amounts of sodium alkalinity,* or *finaly divided calcium phosphate, or oil may cause foaming. "Priming" refers to the vigorous and periodic surging of water in the boiler drum and throws water slugs into the leaving steam.* This may be *caused by excessive steaming rate, too high or fluctuating a water level, and improper boiler-water circulation.* Carryover may originate from mechanical or chemical causes.

The following detrimental results are caused by the carry-over. The water droplets carrying solids evaporate and build deposits in the valves, superheaters, and piping and even in the turbine or engine.

(*i*) *Superheater deposits reduce heat transfer and raise the tube-metal temperatures.*

(*ii*) *Deposits on turbine blade reduce efficiency and capacity and may unbalance the rotor.*

(*iii*) *Deposits forming on governing valves raise a serious hazard.*

Foaming and *priming* can be checked by taking the following prrecautions :

1. Valves not to be opened suddenly to maximum.
2. Water level in the boiler should be at its minimum possible level.
3. The boiler water should not contain oil, soap and other suspended impurities.

4. Embrittlement. *The caustic embrittlement is the weakening of boiler steel as a result of inner crystalline cracks.* Presence of certain concentration of sodium hydroxide causes embrittlement.

The following *three conditions contribute to embrittlement :*

(*i*) Slow boiler-water leaks through cracks or seams vapourises to leave behind a built-up of salts.

(*ii*) The metal must be stressed by cold working during fabrication, or riveting, or from expansion and contraction.

(*iii*) The concentrated water in a crack must have chemical properties that will attack the metal.

This defect is not very common but very important. It affects the drum and its presence cannot be traced so easily.

To *measure embrittlement, a detector is installed in the boiler* where boiler water will circulate over it continuously, as in a continuous blowdown line.

Some of the methods to *control embrittlement* are listed below :

1. Elimination of free sodium hydroxide from boiler water.

2. Maintenance of a definite ratio of sodium nitrate to sodium hydroxide.

3. Using waste sulphite liquor.

3.22.3. Methods of Feed Water Treatment

The different treatments adopted to remove the various impurities are enumerated and discussed as follows :

1. Mechanical treatment

(*i*) Sedimentation (*ii*) Coagulation

(*iii*) Filteration (*iv*) Interior painting.

2. Thermal treatment

(*i*) Deaeration

(*ii*) Distillation by evaporators.

3. Chemical treatment

(*i*) Cold lime-soda softening process

(*ii*) Hot lime-soda softening process

(*iii*) Lime-phosphate softening process

(*iv*) Ion exchange process which may be sodium zeolite process or hydrogen zeolite process.

4. Demineralisation

5. Blow down

(*i*) Hot lime-soda and hot zeolite process

(*ii*) Adding acid to control alkalinity and *vice versa*.

1. Mechanical Treatment

(*i*) Sedimentation. In this process the water is allowed to stand at stand-still in big tanks so that solid matter settles down. The water at a very low velocity will also have the same process. These solid matters settled down could be removed from the bottom either periodically or continuously. Clear water is then drained out from the tank surface.

(*ii*) Coagulation. Coagulation of minute colloidal suspensions make them settle out easily. Adding a coagulation like aluminium sulphate or sodium aluminate improves the sedimentation or filtration process. A reaction between these salts and alkalinity in the water forms a gelatinuous material which makes small particles adhere to each other, forming larger particles that settle out or filter out more easily.

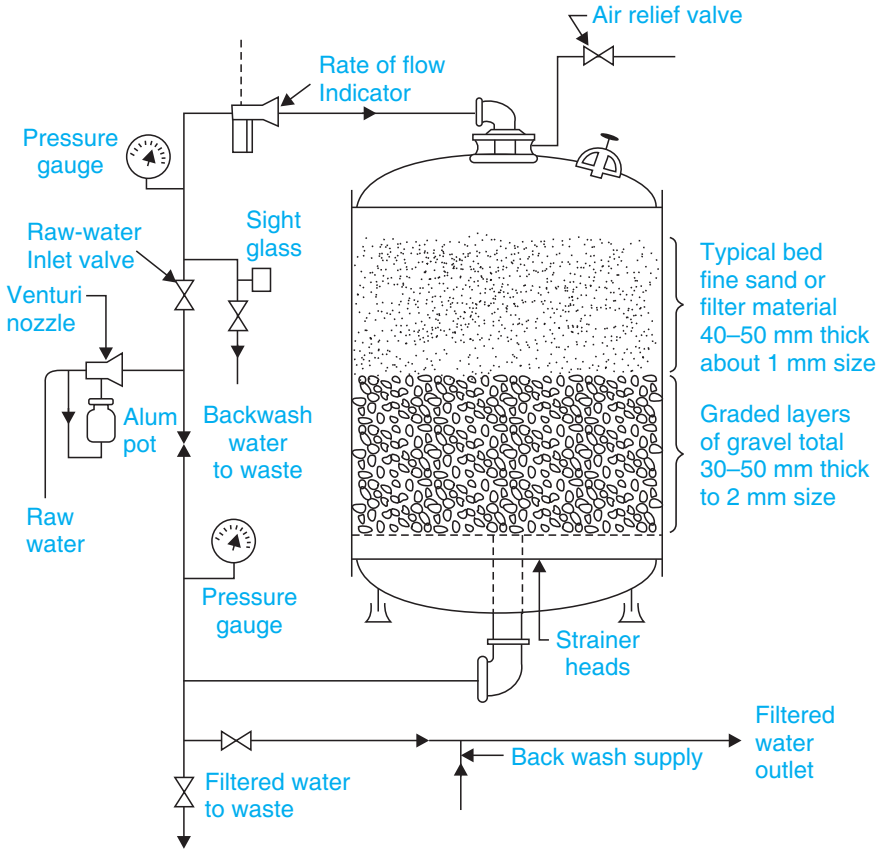


Fig. 3.139. Pressure filter.

(iii) Filtration. The suspended matter which cannot be removed during sedimentation are removed with the help of filtration. The water is allowed to pass through a bed of fine sand or graded sand and then a layer of gravels etc. as shown in Fig. 3.139. The suspended matter adheres to the filter material leaving the water clear as it drains from the bottom. The beds must be backwashed periodically to remove the dirt that collects in the voids of the filter material.

In case of pressure filter (Fig. 3.139) the water is forced through the filter by means of a pump whereas in gravity filter the water flows by gravity.

2. Thermal Treatment

(i) Deaeration. The *process of removing dissolved oxygen is known as* ***deaeration.*** This is done in deaerating heaters. If water is heated to a temperature of about 110°C with subsequent agitation, the dissolved oxygen is expelled.

Fig. 3.140 shows a *tray type deaerating heater*. In this heater feed water after passing through the vent condenser is sprayed upwards in the spray pipe. Water falls in the form of uniform showers over the heating trays and air separating trays and finally gets collected in the storage space. Steam enters the heater through a nozzle fitted in the side of heater shell. The entire space between the shell and tray compartment gets filled with steam. The steam makes its way downwards through the perforations

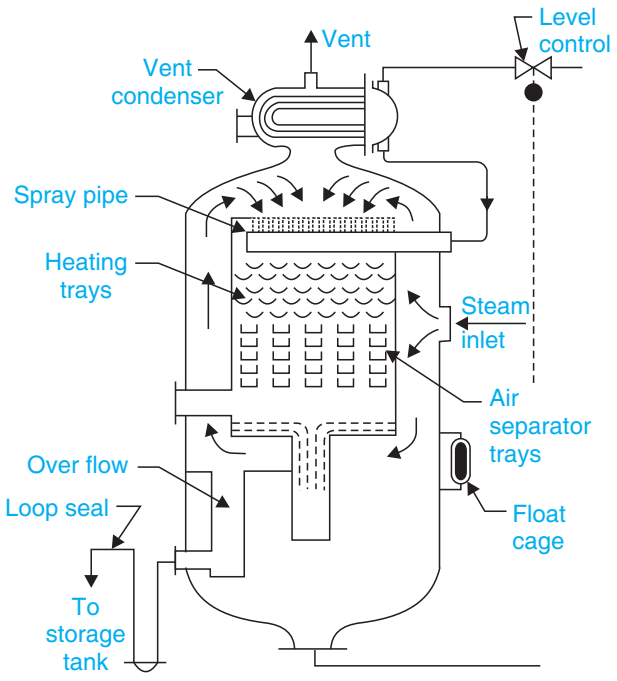


Fig. 3.140. Tray type deaerating heater.

in the top plate of tray compartment. While flowing downward the steam comes in contact with the falling water. Most of the steam condenses in between the spray and heating trays. From the bottom of heating trays, the remaining steam and separated gases such as oxygen etc. flow to the vent condenser. The steam used for heating may be main turbine bled steam or may be from other sources. Storage tank with controls help to add make up water when needed to maintain the feed water level.

(ii) Distillation by evaporators. An evaporator's function is to produce from raw water, vapour that can be condensed to distilled water for boiler feed make-up. In some cases the use of evaporators is required where the make-up water percentage is small say upto 4 per cent. In case of regenerative cycle, the evaporator is quite useful as the steam used for evaporation is being used in feed water itself. It has the advantage of requiring lesser or very little blow down of deconcentration in the boiler. An evaporator system may be *single effect* where steam is produced from one evaporator or *multiple effect* in which steam is produced from several evaporators in series. They may also be classified as *film type, flash type* and *submerged tube type*.

3. Chemical Treatment

Lime-soda softening process. This process uses calcium hydroxide (lime) and sodium carbonate (soda ash), to remove dissolved calcium and magnesium salt, by precipitating them. This may be done by either a *cold process* or *hot process*. The processes use these types of reactions :

$$Mg(HCO_3)_2 + 2Ca(OH_2) = Mg(OH)_2 \downarrow + 2CaCO_3 \downarrow + 2H_2O \quad ...(3.81)$$

$$MgCl_2 + Ca(OH)_2 = Mg(OH)_2 \downarrow + CaCl_2 \quad ...(3.82)$$

$$CaCl_2 + Na_2CO_3 = CaCO_3 \downarrow + 2NaCl \quad ...(3.83)$$

$$CaSO_4 + Na_2CO_3 = CaCO_3 \downarrow + Na_2SO_4 \quad ...(3.84)$$

The arrows show the molecule precipited from the solution.

Eqn. (3.81) : *All the carbonate hardness is precipitated out, leaving pure water*.

Eqns. (3.82) to (3.84) : *The non-carbonte hardness precipitates, to be replaced by soluble sodium salts*.

The magnesium hydroxide [$Mg(OH)_2$] acts as a coagulant and has the property of absorbing soluble silica from solution. The original matter hardness usually is not completely removed in hot process softner (used in power plants) because of the chemical cost. Even when some excess chemicals are used, the effluent hardness will range from 10 to 30 ppm (parts per million).

Hot-process phosphate softening uses trisodium phosphate and caustic sode to precipitate and remove calcium and magnesium hardness. The reactions are as follows :

$$3Ca(HCO_3)_2 + 6NaOH = 3CaCO_3 \downarrow + 3Na_2CO_3 + 6H_2O \quad ...(3.85)$$

$$3CaCO_3 + 2Na_3PO_4 = Ca_3(PO_4)_2 \downarrow + 2Na_2CO_3 \quad ...(3.86)$$

$$Mg(HCO_3)_2 + 4NaOH = Mg(OH)_2 \downarrow + 2Na_2CO_3 + 2H_2 \quad ...(3.87)$$

$$3CaSO_4 + 2Na_3PO_4 = Ca_3(PO_4)_2 \downarrow + 3Na_2SO_4 \quad ...(3.88)$$

Phosphates also remove silica compounds, which are troublesome in high pressure boilers. Phosphate chemicals cost more than lime-soda.

Ion Exchange Processes

(*i*) **Sodium zeolite process.** The zeolites are solid materials of a sandy texture. They remove various ions from the water replacing them with other ions of like charge. In case of sodium zeolite, the reactions are as follows :

$$Ca(HCO_3)_2 + Na_2Z = CaZ + 2NaHCO_3 \quad ...(3.89)$$

$$CaSO_4 + Na_2Z = CaZ + Na_2SO_4 \quad ...(3.90)$$

$$CaCl_2 + Na_2Z = CaZ + 2NaCl \quad ...(3.91)$$

(Z is the symbol used for zeolite).

Fig. 3.141 shows a typical zeolite softener. It consists of a shell holding a bed of active sodium zeolite supported by layers of graded gravel lying over a water distribution and collection system. *Zeolites almost completely remove hardness but do not reduce alkalinity or total solids*. Turbid water does not react well with zeolite sands. They do not remove silica and may even add it. The exhaustion capacity of the zeolite bed should be known, because regeneration should be started as soon as the exhaustion starts.

First back washing should be done by passing a strong current of water upwards. A measured quantity of common salt solution should then be injected in the softner. The salt reacts with the zeolite thus removing calcium and magnesium in the form of soluble chlorides. After salt rinse zeolite filter is ready to be used again. The equation of this reaction is :

$$CaZ + 2NaCl = Na_2Z + CaCl_2 \quad ...(3.92)$$

$$MgZ + 2NaCl = Na_2Z + MgCl_2 \quad ...(3.93)$$

The entire regeneration period should not consume more than 3 to 4 minutes.

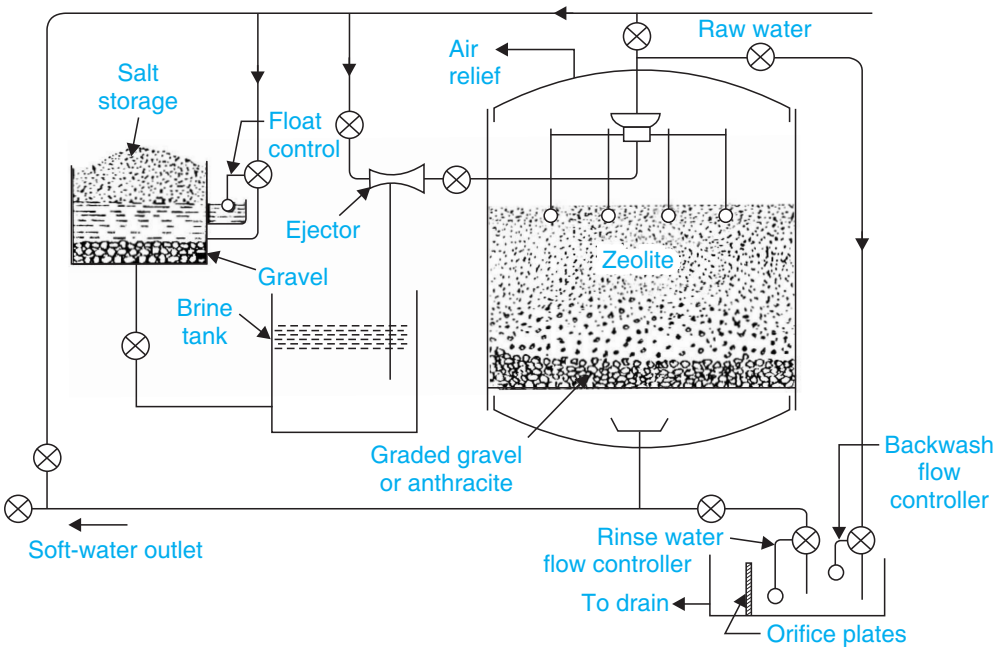


Fig. 3.141. Sodium zeolite softner.

(*ii*) **Hydrogen-zeolite process.** Non-silicious material can be used to exchange the hydrogen ions for cations as calcium and magnesium. The synthetic zeolites developed are sulphonated coal and polystyrene resins which withstand acid and when regenerated with acid could be used to exchange hydrogen for the metals of salt in solution.

The equations for reactions are :

$$Ca(HCO_3)_2 + H_2Z = CaZ + 2H_2CO_3 \quad ...(3.94)$$

$$CaSO_4 + H_2Z = CaZ + H_2SO_4 \quad ...(3.95)$$

$$CaCl_2 + H_2Z = CaZ + 2HCl \quad ...(3.96)$$

$$CaZ + H_2SO_4 = H_2Z + CaSO_4$$

...in case of regeneration (3.96)

The main merit of this process is that *the water high in carbonates including sodium carbonate or bicarbonate can be softened easily without replacing the water with some other salt.*

4. Demineralisation. The mineral content of water may be removed by evaporation or by series of cation and anion exchangers to produce essentially distilled water. *Demineralisation is often the most economical method of producing make-up water for high-pressure boilers.* Fig. 3.142 shows a series process for demineralisation. A simple demineraliser would use only the first two units.

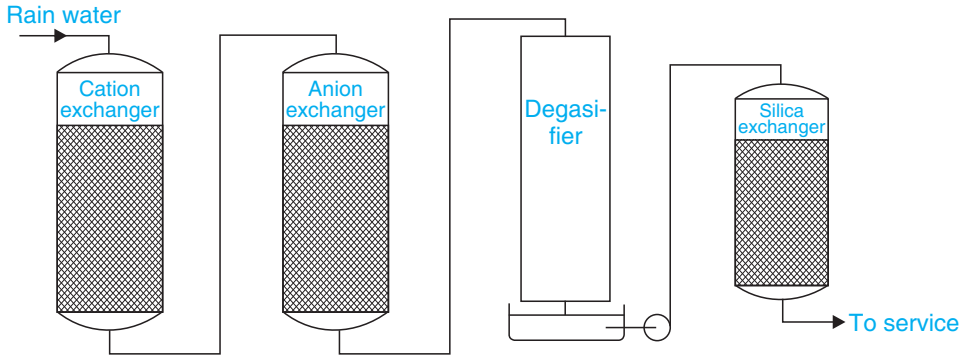


Fig. 3.142. Demineralising process.

Strong-base anion-exchange material absorbs weak acids (silica types) as well as strong acids. Weak-base anion exchange materials are most efficient for removing chlorides, sulphates and nitrates.

5. Blow down. There may be some dissolved solids in the water entering the boiler. As the water gets evaporated the concentration of these solids goes on increasing. Beyond a certain limit of concentration, these solids may cause foaming and priming. The concentration of these solids can be reduced by drawing off some of the quantity of the boiler water from the bottom of boiler drain. This is called *blowing down* and *discharged water is known as* ***blow down.***

3.22.4. pH Value of Water

pH value of water is the logarithm of the reciprocal of hydrogen ion concentration. It is number from 0 to 14 with 7 indicating neutral water.

A sample of water having pH value *less than 7 indicates acidity* of water and the samples having value *more than 7 are alkaline*. Acidic or alkaline nature of a sample depends upon whether the hydrogen or hydroxyl ions predominate. In a mixture of bases and water, hydroxyl ions result. Hydrogen ions make a solution acidic whereas hydroxyl ions make it alkaline. When a sample contains one (OH) ion for every (H) ion, the acid effect of one balances the alkaline effect of the other. Result is a neutral solution with a pH value of 7.0.

pH value of a sample of water can be easily determined by a pH meter. A pH meter is essentially a comparator which compares sample colour with that of many standards to determine the value.

3.23. PIPING SYSTEM

Many fluids such as steam, water, oil, gas, air etc. are used in power plants. These fluids must be completely controlled–co-ordinated. The piping system can be divided into following categories :

1. Steam piping : For main auxiliary, reheat, bleed, exhaust and process steam.

2. Water piping : For condensate, feed-water, raw water etc.

3. Blow off piping : For boiler, evaporator and feed treatment.

4. Others : Including service water, fuel, lubricating oil, compressed air, soot blowing, fire protecting, chemical feed etc.

The pipes employed for different purposes have different specifications. Mostly the pipes used are for *steam* and *water*. Standards for different classification of piping have been laid down for the pipes working under different temperatures and pressures.

The pipes may be broadly divided into various categories as *low pressure pipes, medium pressure pipes* and *high pressure pipes* at high temperature. The temperature of the fluid in the pipes plays an important role specially at higher pressures.

3.23.1. Requirements of Steam Piping System

The piping system used for carrying the steam must fulfil the following *requirements* :

1. Maximum reliability.
2. Should be of necessary size to carry the required flow of fluids.
3. Must withstand the pressure to which it is subjected.

4. It should be possible to carry out inspection and maintenance on any section of the plant without the need for complete shut-down.
5. The pipes should be made in longest possible lengths to reduce the number of joints.
6. Should be able to withstand the temperature and expansion caused due to the temperature changes.
7. The piping supports, anchors and joints should be in accessible positions so that inspection is possible throughout the life of the plant.
8. The pipe should run as direct and straight as possible.
9. The piping system should ensure an efficient drainage of all pipes.
10. To reduce the erection time the template pipes should be as few as possible.
11. Steam piping system should be installed in such a way that the horizontal runs should slope in the direction of steam flow.

3.23.2. Materials used for Pipes

The materials for steam piping fall into following three general classes :

1. Wrought iron
2. Cast iron
3. Steel.

1. Wrought iron. Wrought iron pipe is used where *corrosive conditions* exist especially in hot water lines, underground piping and special plumbing installation.

2. Cast iron. Cast iron pipes are also used for low pressure. It is used for water services upto a pressure of 15 kgf/cm^2 or for gas, drain piping etc. *Steam pipes do not use cast iron*.

3. Steel. Steel pipes are being widely used having different percentage of metals in the alloy of steel depending upon the purpose for which they are used.

— For '*steam pipes*' of high temperature *alloy steels are used*.

— For temperature above 450°C alloy steel containing *chromium, vanadium, molybdenum* and *nickel* is used. *Chromium improves corrosion and oxidation resistance. Nickel adds toughness to the materials. Molybdenum improves creep strength.*

— *Stainless steel* is also used in a number of modern power plants where the pressures and temperatures of steam are quite high.

— *Pipe of large size carrying very high pressure and temperature steam is made by turning and boring solid forgings.*

3.23.3. Insulation of Steam Piping

Insulating hot pipes not only conserves heat but also avoids an uncomfortable overheated atmosphere in the vicinity of pipe. The insulating material used for steam pipes should possess the following properties :

1. Should possess high *insulating-efficiency* $\left(= \frac{\text{bare surface loss} - \text{insulated loss}}{\text{bare surface loss}}\right)$.
2. Should not be too costly.
3. Should be easily moulded and applied.
4. Should not be affected by moisture.
5. Should have high mechanical strength.
6. Should be able to withstand high temperature.
7. Should not cause corrosion of pipes if chemically decomposed.
8. Should not overload the pipe by its dead weight.

3.23.4. Steam Pipe Fittings

These are used to assemble piping system and make connections. The various fittings which are in common use are elbows, bends, tees, crosses, plugs and reducers. In Fig. 3.143 are shown the various fittings. The material used for fittings depends on service as regard pressure and temperature.

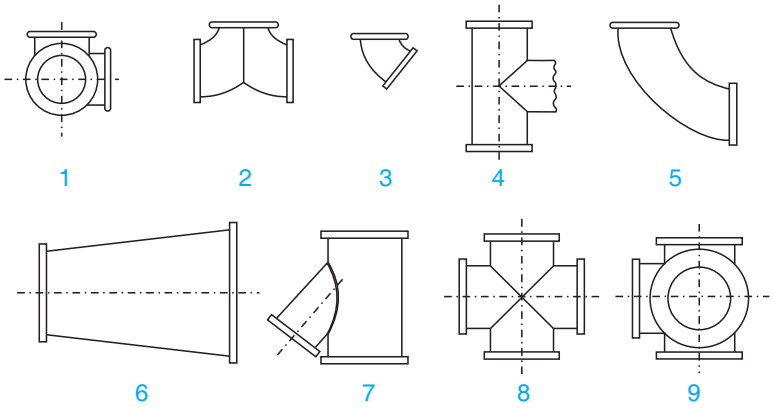


Fig. 3.143. Steam pipe fittings.

3.23.5. Pipe Expansion Bends

As the forces produced by expansion are practically irresitible, the pipe is invariably allowed to expand and its movement is prevented from unduly stressing the fittings and connections by providing (*i*) suitable bends, (*ii*) expansion joints.

Fig. 3.144 shows the standard expansion bends.

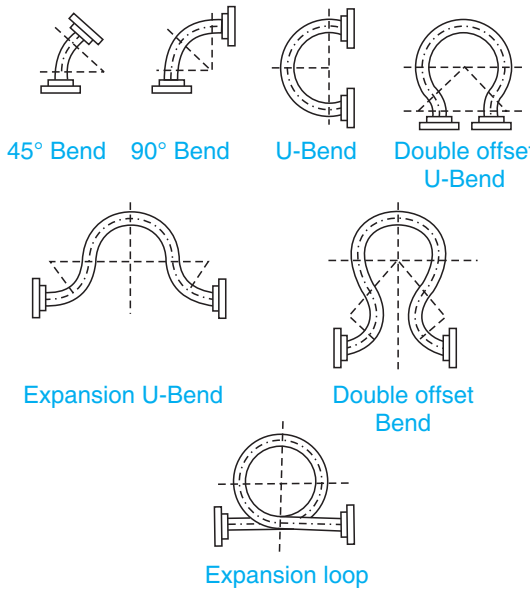


Fig. 3.144. Pipe expansion bends.

Expansion joints provide flexibility to the piping system by permitting relative motion between pipe sections. They compensate for changes in dimensions due to temperature variations. These joints being flexible, can isolate vibration and can allow the ground settling if used underground. Most of the joints permit considerable axial movement.

Fig. 3.145 shows the expansion joint.

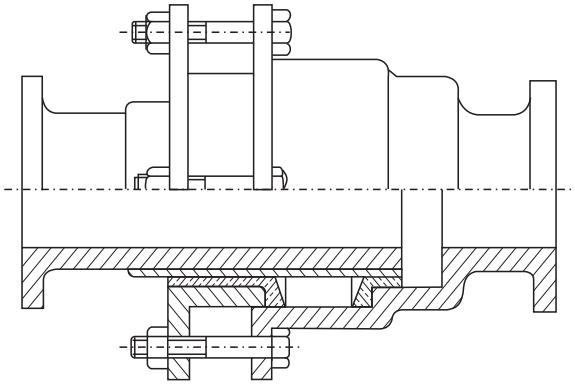


Fig. 3.145. Expansion joint.

Screwed, welded and socket and spigot joints are shown in Figs. 3.146, 3.147 and 3.148 respectively.

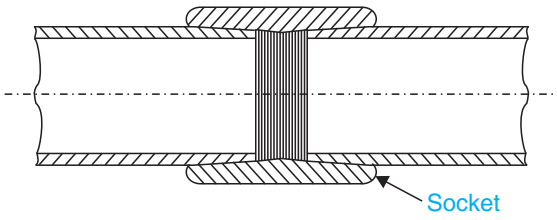


Fig. 3.146. Screwed joint.

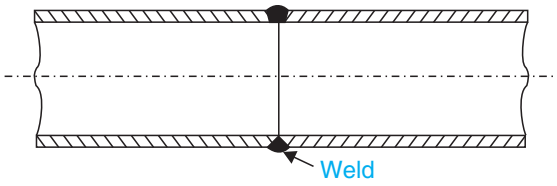


Fig. 3.147. Welded joint.

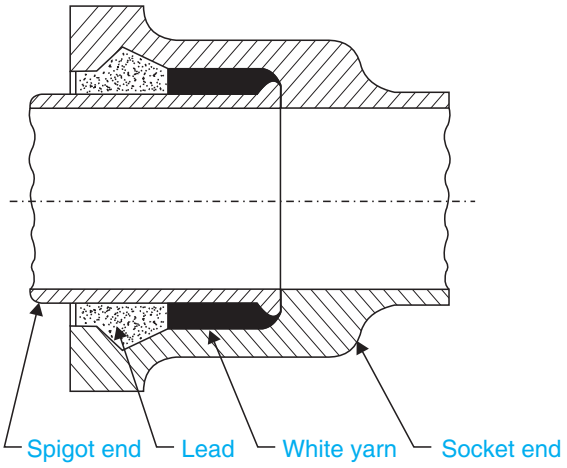


Fig. 3.148. Socket and spigot joint.

3.24. ADVANTAGES AND DISADVANTAGES OF STEAM POWER PLANTS

Advantages of Steam Power Plants :

1. They can respond to rapidly changing loads without difficulty.
2. A portion of the steam generated can be used as a process steam in different industries.
3. Can be located very conveniently near the load centre.
4. As these plants can be set up near the industry transmission costs are reduced.
5. Steam engines and turbines can work under 25 per cent of overload continuously.
6. Fuel used is cheaper.
7. Less space is required in comparison with that for hydroelectric plants.

8. Cheaper in production cost in comparison with that of diesel power stations.

9. Cheaper in initial cost in comparison with that of diesel power stations.

Disadvantages :

1. Maintenance and operating costs are high.

2. The cost of plant increases with increase in temperature and pressure.

3. Long time required for erection and putting into action.

4. A large quantity of water is required.

5. Great difficulty experienced in coal handling.

6. The plant efficiency decreases rapidly below about 75 per cent load.

7. Presence of troubles due to smoke and heat in the plant.

3.25. MISCELLANEOUS

3.25.1. Plant Arrangement

Fig. 3.149 shows the typical arrangement of various equipment used in steam power plant. The following factors should be taken into consideration while installing various components :

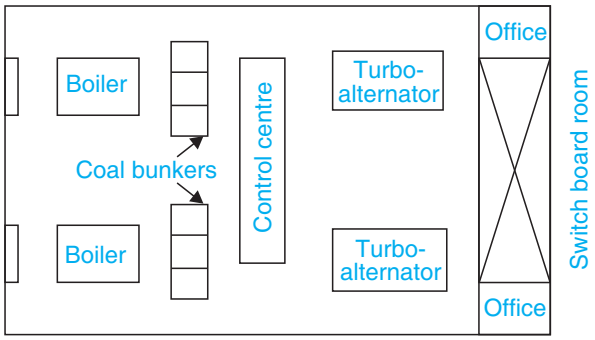


Fig. 3.149. Plant arrangement.

1. Similar items such as turbines, boilers, transformers, bunker bays and other mechanical and electrical components—to be arranged in parallel lines.

Individual boiler, turbo-generator etc.—to be arranged at right angles rows.

2. The chimneys should be installed independent of station building. Each chimney may serve two or more boilers.

3. The following components should be located behind the boiler house :

(*i*) Main flue

(*ii*) Draught fans

(*iii*) Outdoor precipitators.

4. The unit transformers and outdoor generator should be located in front of the turbine house.

5. Coal supply to bunkers, circulating water supply and lifting equipment should be properly placed.

Fig. 3.150 shows a **typical layout/schematic arrangement of a steam power plant,** the stepwise description of which is as follows :

— The coal is fed (from the bunker) to stoker hopper and then on the travelling grate stoker. Ash from the grate falls into the ash hopper from where it can be disposed off periodically.

— Forced draught fan supplies the air underneath the stoker *via* air *preheater*. The preheater is a tubular type heat exchanger with flue gases passing through the tubes and air flowing around the tubes. In air preheater, some heat of the outgoing gases is utilised to increase the temperature of air which promotes better combustion in the furnace.

— The flue gases pass on their heat to *boiler tubes* and *superheater* and then move into a *dust collector*. From here, the flue gases move on to the *economiser* where some of their heat is utilised to increase the temperature of the feed water before it is fed into the boiler. Therefore the flue gases travel through the air preheater, induced draught fan to the chimney.

— From the economiser the feed water is discharged to the boiler drum. The water flows through the water tubes due to natural circulation. Forced circulation can also be done with the help of pumps.

— The steam generated then flows through the superheater tubes into steam header. From here the steam enters the steam turbine through a pipe.

— Steam expands in the turbine and work done is utilised to run a hydrogen cooled generator.

— Bled steam for feed water heating in feed water heaters is extracted from the turbine at three points.

— The exhaust steam flows into a surface type condenser where it is condensed by means of cooling water. There is a cooling tower to recool this circulating water.

— The condensate is first heated in open or closed type feed heater and then enters the boiler drum *via* the economiser.

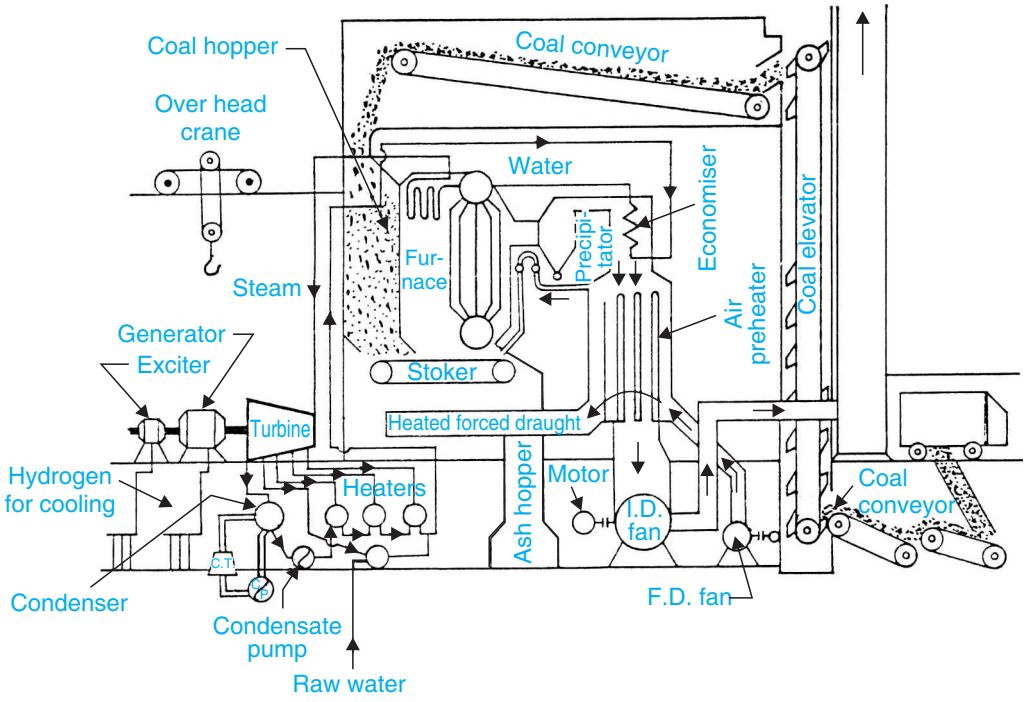


Fig. 3.150. Typical layout/schematic arrangement of a steam power plant.

3.25.2. Useful Life of Steam Power Plant Components

Approximate useful life of some of the components of a steam power plant is given below :

Components	*Life (years)*
1. Water tube boiler	20
2. Coal and ash machinery	10 to 20
3. Steam turbines	15 to 20
4. Steam condensers	20
5. Turbo-generators	10 to 20
6. Feed water heater	30
7. Pumps	15 to 20
8. Transformers	15 to 20
9. Motors	20
10. Air compressors	20 to 25
11. Buildings	50

3.25.3. Steam Power Plant Pumps

The pumps used in a steam power plant are classified as follows :

1. Reciprocating
   (*i*) Direct acting (*ii*) Power
2. Rotary
   (*i*) Vane (*ii*) Screw
   (*iii*) Gear (*iv*) Lobe
3. Centrifugal
   (*i*) Volute (*ii*) Diffuser
   (*iii*) Axial flow (*iv*) Mixed flow

The above mentioned pumps are used for the following services :

(*i*) Boiler feed
(*ii*) Circulating water
(*iii*) Evaporator feed
(*iv*) Condensate
(*v*) Well water
(*vi*) Ash sluicing
(*vii*) Fuel oil.

3.25.4. Cost of Steam Power Plant

A typical subdivision of investment cost of steam power station is as follows :

Components	*Investment cost*
1. Building etc.	25%
2. Boiler Plant	18%
3. Turbo-generators and condensers	25%
4. Fuel handling	6%
5. Switch yard, switching and wiring	16%
6. Piping	5%
7. Miscellaneous	5%

3.25.5. Comparison of Various Types of Power Plants

S. No.	Particulars	Steam power plants	Hydroelectric power plants	Diesel power plants	Nuclear power plants
1.	*Site*	Located near load centres but other factors water supply, land cost, transportation facilities are to be kept in view. Location of steam power plant is somewhat flexible as compared with that of hydro-plants.	The site should be such that sufficient area, huge quantity of water at a sufficient head, cheap and rocky land and transportation facilities should be available. These plants are usually at a far off distance from the load centres.	Can be installed anywhere.	Located near the load centre.
2.	*Initial cost*	*Low* as compared to hydroelectric and atomic power plants.	*High* as compared to steam power plant on account of large amount of excavation work and heavy cost of transportation of the plant and machinery.	Initial cost is the *minimum*.	The capital cost is *very high* as compared to all other types of power plants on account of heavy cost of nuclear reactors and heavy cost of erection as highly specialised and expert engineers are required for its erection work.
3.	*Fuel transportation cost*	*High,* especially when the power plants are away from the coal mines and has no railway siding.	*Nil* (as no fuel is required).	Higher than that of atomic power plant but lower than that for steam power plants.	Very low (since quantity of fuel required is very small).
4.	*Operating cost*	Very high as compared to hydro-plants and atomic power plants but low as compared to diesel power plant.	Practically nil (since no fuel is required for the operation of the plant).	Very high as compared to all other types of power plants.	Very low as compared to all other types of power plants except that of hydroelectric plants.
5.	*Maintenance cost*	Higher as compared with that of hydro-plants and diesel power plants (because large operating staff and more skilled engineers are required).	Maintenance cost is comparatively low (because few skilled engineers and small operating staff is required).	Maintenance cost is comparatively lower (because lesser operating and supervising staff is required).	Maintenance cost is comparatively higher (because skilled and well trained staff is required for its operation and maintenance).
6.	*Limit of source of power*	Source of fuel *i.e., coal* reserve all over the world is considered to be fixed and therefore coal mines are being exhausted and time may come when all of these might get exhausted.	Source of power *i.e., water* in case of hydro-plants is not dependable because it depends upon the rainfall which is at the whim of nature.	Source of fuel *i.e., diesel* is not available in plenty.	The source of power is unlimited since large deposits of fissionable materials all over the world are available.
7.	*Transmission and distribution cost.*	Low (because short transmission lines are required).	*Very high* (because long transmission lines are required).	Transmission cost is *nil* and distribution cost is also *very small*.	*Very low*.
8.	*Reliability*	Less reliable.	More reliable.	Less reliable.	Reliable.

9.	*Simplicity and cleanliness*	Atmosphere is polluted by fumes and residues of pulverised fuels.	Most simple and clean.	Simple and cleaner than steam plants and atomic power plants.	The handling of atomic power plant is quite complicated as radiation hazards are involved in it. Special outfits are designed and explored by the operating staff.
10.	*Field of application*	Most economical if sited near coal mines and by the side of river or canal.	Most economical where water source is available at a sufficient head.	These plants are installed to supply power is emergency.	Where neither water nor coal as a source of power is available, as in Rajasthan these plants are more feasible and adopted.

3.25.6. Thermal Power Stations in India

Some of the thermal power stations installed in the country or under the process of installation are as follows :

S. No.	State	Name of power station	Capacity (MW)
1.	Andhra Pradesh	Kothagndam	240
2.	Assam	Gauhati	40
3.	Bihar	(*i*) Barauni	140
		(*ii*) Bokaro	225
		(*iii*) Patratu	400
4.	Delhi	(*i*) Rajghat and I.P. thermal power station	350
		(*ii*) Badarpur	300
5.	Gujarat	(*i*) Dhuvaran	530
		(*ii*) Ukai	240
6.	Haryana	(*i*) Faridabad	200
		(*ii*) Panipat	220
7.	Madhya Pradesh	(*i*) Kobra	420
		(*ii*) Satpura	300
		(*iii*) Amarkantak	180
8.	Maharashtra	(*i*) Nagpur (Koradi)	480
		(*ii*) Nasik	280
		(*iii*) Paras	90
9.	Odisha	Talcher	254
10.	Tamil Nadu	(*i*) Neyveli	600
		(*ii*) Eunore	450
11.	Uttar Pradesh	(*i*) Harduaganj	540
		(*ii*) Obra	550
12.	West Bengal	(*i*) Santaldih	480
		(*ii*) Chandrapur	420
		(*iii*) Bandel	330
		(*iv*) Durgapur	290

3.25.7. Indian Boilers Act

For steam boilers Government of India enforced an Act known as Indian Boilers Act, 1923. This Act came in force from 1st January, 1924 (and later on ended in 1953). Some of the sections of the Act are given below :

1. Definition. *Accident*. Accident means an explosion of a boiler or steam pipe or any damage to a boiler or steam pipe which is calculated to weaken the strength thereof so as to render it liable to explode.

Boiler. Boiler means any closed vessel exceeding 22.75 litres in capacity which is used expressly for generating steam under pressure and includes any mounting or other fitting attached to such vessel which is wholly or partly under pressure when steam is shut off.

Economiser. Economiser means any part of a feed pipe that is wholly or partly exposed to the action of flue gases for the purpose of recovery of waste heat.

Feed pipe. Feed pipe means any pipe or connected fitting wholly or partly under pressure through which feed water passes directly to a boiler and which does not form an integral part thereof.

Owner. Owner includes any person using a boiler as agent of the owner thereof and any person using a boiler which he has hired or obtained on load from the owner thereof.

Steam pipe. Steam pipe means any pipe through which steam passes from a boiler to a primemover to other user or both, if :

(*i*) the pressure at which steam passes from a boiler through such pipe exceeds 3.5 kilograms per square centimetre above atmospheric pressure ; or

(*ii*) such pipe exceeds 254 millimetres in internal diameter and includes in either case any connected fitting of a steam pipe.

"Structural alterations, addition or renewal" shall not be deemed to include any renewal or replacement or a petty nature when the part or fitting used for replacement is not inferior in strength, efficiency or otherwise to the replaced part or fitting.

To enforce this Act effectively, the State Governments employ Chief Inspector, Deputy Chief Inspectors and Inspectors.

2. Prohibition of use of unregistered boilers. No owner of a boiler shall use the boiler or permit it to be used :

(*a*) unless it has been registered in accordance with the provisions of this Act ;

(*b*) unless a certificate or provisional order authorising use of the boiler is for the time being in force under this Act.

(*c*) in the case of any boiler which has been transferred from one State to another until the transfer has been reported in the prescribed manner ;

(*d*) at a pressure higher than the maximum pressure recorded in such certificate or provisional order.

3. Registration. (*i*) The owner of any boiler which is not registered under the provisions of this Act may apply to the Inspector to have the boiler registered. Every such application shall be accompanied by the prescribed fee.

(*ii*) On receipt of an application under sub-section (*a*), the Inspector shall fix a date, within thirty days or such shorter period as may be prescribed from the date of the receipt, for the examination of the boiler and shall give the owner thereof not less than ten days' notice of the date so fixed.

(*iii*) On the said date the Inspector shall proceed to measure and examine the boiler and to determine in the prescribed manner the maximum pressure, if any, at which such boiler may be used, and shall report the result of the examination to the Chief Inspector in the prescribed form.

(*iv*) The Chief Inspector, on receipt of the report, may register the boiler and assign a register number thereto either forthwith or after satisfying himself that any structural alteration, addition or renewal which he may deem necessary has been made in or to the boiler or any steam pipe attached thereto, or (*b*) refuse to register the boiler :

Provided that where the Chief Inspector refuses to register a boiler, he shall forthwith communicate his refusal to the owner of the boiler together with the reason therefore.

(*v*) The Chief Inspector shall, on registering the boiler order the issue to the owner of a certificate in the prescribed form authorising the use of the boiler for a period not exceeding such maximum pressure as he thinks fit, and as is in accordance with the regulations made under this Act :

Provided that a certificate issued under this sub-section in respect of an economiser (or of an unfired boiler which forms an integral part of a processing plant in which steam is generated solely by the use of oil, asphalt or bitumen as a heating medium) may authorise its use for a period not exceeding 24 months.

(*vi*) The Inspector shall forthwith convey to the owner of boiler the orders of the Chief Inspector and shall in accordance therewith issue to the owner any certificate of which the issue has been ordered, and where the boiler has been registered, the owner shall within the prescribed period cause the register number to be permanently marked there on the prescribed manner.

4. Renewal of Certificate. (*i*) A certificate authorising the user of a boiler shall cease to be in force :

(*a*) on the expiry of the period for which it was granted ; or

(*b*) when any accident occurs to the boiler ; or

(*c*) when the boiler is moved : the boiler not being a vertical boiler, the heating surface of which is less than 18.58 sq. m or a portable or vehicular boiler ;

(*d*) when any structural alteration, addition or renewal is made in or to the boiler ; or

(*e*) if the Chief Inspector in any particular case so directs, when any structural alteration, addition or renewal is made in or to any steam pipe attached to the boiler ; or

(*f*) on the communication to the owner of the boiler of an order of the Chief Inspector or Inspectors prohibiting its use on the ground that it or any steam pipe attached thereto is in a dangerous condition.

(*ii*) Where an order is made under clause (*f*) of the sub-section (*i*), the grounds on which the order is made shall be communicated to the owner with the order.

(*iii*) When a certificate ceases to be in force, the owner of the boiler may apply to the Inspector for a renewal thereof for such period not exceeding 12 months as he may specify in the application ;

Provided that where the certificate relates to an economiser, the application for its renewal may be for a period not exceeding 24 months.

(*iv*) An application under sub-section (*iii*) shall be accompanied by the prescribed fee and, on receipt thereof, the Inspector shall fix a date, within 30 days or such shorter period as may be prescribed from the date of the receipt, for the examination of the boiler and shall give the owner thereof not less than 10 days' notice of the date so fixed ;

Provided that, where the certificate has ceased to be in force owing to the making of any structural alteration, addition or renewal, the Chief Inspector may dispense with the payment of any fee.

(*v*) On the said date the Inspector shall examine the boiler in the prescribed manner and if he is satisfied that the boiler and the steam pipe or steam pipes attached thereto are in good condition shall issue a renewal certificate authorising the use of the boiler for such period not exceeding 12 months and at a pressure not exceeding such maximum pressure as he thinks fit and as in accordance with the regulations made under this Act :

Provided that a renewed certificate issued under this sub-section in respect of a economiser, may authorise its use for a period not exceeding 24 months :

Provided further that if the Inspector :

(*a*) proposes to issue any certificate ;

— having validity for a less period than the period entered in the application, or

— increasing or reducing the maximum pressure at which the boiler may be used, or

(*b*) proposes to order any structural alteration, addition or renewal to be made in or to the boiler or any steam-pipe attached thereto, or

(*c*) is of opinion that the boiler is not fit for use, the Inspector shall, within 48 hours of making the examination, inform the owner of the boiler in writing of his opinion and the reasons therefor, and shall forthwith report the case for orders to the Chief Inspector.

(*vi*) The Chief Inspector, on receipt of a report under sub-section (5), may, subject to the provisions of this Act and of the regulations made hereunder, order the renewal of the certificate in such terms and on such conditions, if any, as he thinks fit, or may refuse to renew it :

Provided that where the Chief Inspector refuses to renew a certificate, he shall forthwith communicate his refusal to the owner of the boiler, together with the reasons therefor.

(*vii*) Nothing in this section shall be deemed to prevent an owner of a boiler from applying for a renewal certificate therefor at any time during the currency of a certificate.

5. Provisional orders. Where the Inspector reports the case of any boiler to the Chief Inspector under above sections he may, if the boiler is not a boiler the use of which has been prohibited, grant to the owner thereof a provisional order in writing permitting the boiler to be used at a pressure not exceeding such maximum pressure as he thinks fit and as is in accordance with the regulations made under this Act pending the receipt of the order of the Chief Inspector. Such provisional order shall be cease to be in force :

(*i*) on the expiry of 6 months from the date on which it is granted, or

(*ii*) on receipt of the orders of the Chief Inspector.

6. Use of boiler pending grant of certificate. Notwithstanding anything hereinbefore contained, when the period of the certificate relating to a boiler has expired, the owner shall, provided that he has applied before the expiry of that period for a renewal of the certificate, be entitled to use the boiler at the maximum pressure entered in the former certificate pending the issue of orders on the application.

7. Revocation of certificate of provisional order. The Chief Inspector may at any time withdraw or revoke any certificate or provisional order on the report of an Inspector or otherwise :

(*i*) if there is reason to believe that the certificate or provisional order has been fraudulently obtained or has been granted erroneously or without sufficient examination ; or

(*ii*) if the boiler in respect of which it has been granted has sustained injury or has ceased to be in good condition ; or

(*iii*) where the State Government has made rules requiring that boilers shall be in charge of persons holding, if the boiler is in charge of a person not holding the certificate required by such rules ; or

(*iv*) where no such rules have been made, if the boiler is in charge of a person who is not, having regard to the condition of the boiler, in the opinion of the Chief Inspector competent to have charge thereof :

Provided that where the Chief Inspector withdraws or revokes a certificate or provisional order on the ground specified in clause (*iv*), he shall communicate to the owner of the boiler his reasons in writing for the withdrawal of revocation, and the order shall not take effect until the expiry of thirty days from the receipt of such communication.

8. Alterations and renewals to boilers. No structural alteration, addition or renewal shall be made in or to any boiler registered under this Act unless such alterations, additions or renewals have been sanctioned in writing by the Chief Inspector.

9. Alterations and renewals to steam pipes. Before the owner of any boiler registered under this Act makes any structural alteration, addition or renewal in or to any steam pipe attached to the boiler, he shall transmit to the Chief Inspector a report in writing of his intention, and shall send therewith such particulars of the proposed alteration, addition or renewal as may be prescribed.

10. Duty of the owner at examination. (*i*) On any date fixed under this Act for the examination of the boiler, the owner thereof shall be bound :

(*a*) to afford to the Inspector all reasonable facilities for the examination and all such information as may reasonably be required of him ;

(*b*) to have the boiler properly prepared and ready for examination in the prescribed manner ; and

(*c*) in the case of an application for the registration of a boiler, to provide such drawings, specifications, certificates and other particulars as may be prescribed.

(*ii*) If the owner fails, without reasonable cause, to comply with the provisions of the sub-section (*i*), the Inspector shall refuse to make the examination and shall report the case to the Chief Inspector who shall, unless sufficient cause to the contrary is shown, require the owner to file a fresh application, and may forbid him to use the boiler notwithstanding any thing contained in section (F).

11. Production of certificates, etc. The owner of any boiler who holds a certificate or provisional order relating thereto shall, at all reasonable times during the period for which the certificate or order is in force, be bound to produce the same when called upon to do so by a District Magistrate, Commissioner of Police or Magistrate of the first class having jurisdiction in the area in which the boiler is, for the time being, or by the Chief Inspector or by any Inspector appointed under the Indian Factories Act, or by any person specially authorised in writing by a District Magistrate or Commissioner of Police.

12. Transfer of certificate, etc. If any person becomes the owner of a boiler during the period for which a certificate or provisional order relating thereto is in force, the preceding owner shall be bound to make over to him the certificate or provisional order.

13. Power of entry. An Inspector may, for the purpose of inspecting or examining a boiler or any steam pipe attached there to or of seeing that any provision of this Act or of any regulation or rule made hereunder has been or is being observed, at all reasonable times, enter any place or building within the limits of the area for which he has been appointed in which he has reason to believe that a boiler is in use.

14. Report of accidents. (*i*) If any accident occurs to a boiler or steam pipe, the owner or person incharge thereof shall, within 24 hours of the accident, report the same in writing to the Inspector. Every such report shall contain a true description of the nature of the accident and of the injury, if any, caused thereby to the boiler or to the steam pipe or to any person and shall be in sufficient detail to enable the Inspector to judge the gravity of the accident.

(*ii*) Every person shall be bound to answer truly to the best of his knowledge and ability every question put to him in writing by the Inspector as to the cause, nature or extent of his accident.

15. Minor Penalties. Any owner of a boiler who refuses or without reasonable excuse neglects :

(*i*) to surrender a provisional order as required,

(*ii*) to produce a certificate or provisional order when duly called upon to do so,

(*iii*) to make over to the new owner of a boiler a certificate or provisional order as required shall be punishable with fine which may extend to one hundred rupees.

16. Penalties for illegal use of boiler. Any owner of a boiler who, in any case in which a certificate or provisional order is required for the use of the boiler under this Act, uses the boiler either without any such certificate or provisional order being in force or at a higher pressure than that allowed thereby, shall be punishable with fine which may extend to ₹ 500 and, in the case of a continuing offence, with an additional fine which may extend to one hundred rupees for each day after the first day in regard to which he is convicted of having persisted in the offence.

17. Other Penalties. Any person who

(*i*) uses or permits to be used a boiler of which he is the owner and which has been transferred from one State to another without such transfer having been reported as required ;

(*ii*) being the owner of a boiler fails to cause the register number allotted to the boiler under this Act to be marked on the boiler as required ;

(*iii*) makes any structural alteration, addition or renewal in or to a boiler without first obtaining the sanction of the Chief Inspector when so required, or to a steam pipe without first informing the Chief Inspector when so required ;

(*iv*) fails to report an accident to a boiler or steam pipe when so required.

(*v*) tampers with a safety valve of a boiler so as to render it inoperative at the maximum pressure at which the use of the boiler is authorised under this Act.

18. Penalty for tampering with registered mark. (*i*) Whoever removes, alters, defaces, renders invisible or otherwise tampers with the register number marked on a boiler in accordance with the provision of this

Act or any Act repealed hereby, shall be punishable with fine which may extend to five hundred rupees.

(*ii*) Whoever fraudulently marks upon a boiler a register number which has not been allotted to it under this Act or any Act repealed hereby, shall be punishable with imprisonment which may extend to 2 years, or with fine, or with both.

ADDITIONAL / TYPICAL EXAMPLES

Example 3.37. *The following data relate to a regenerative steam power plant generating 22500 kW energy, the alternator directly coupled to steam turbine :*

Condition of steam supplied to the steam turbine ... *60 bar, 450°C*

Condenser vacuum ... *707.5 mm*

Pressure at which steam is bled from the steam turbine ... *3 bar*

Turbine efficiency of each portion of expansion ... *87 per cent*

Boiler efficiency ... *86 per cent*

Alternator efficiency ... *94 per cent*

Mechanical efficiency from turbine to generator ... *97 per cent*

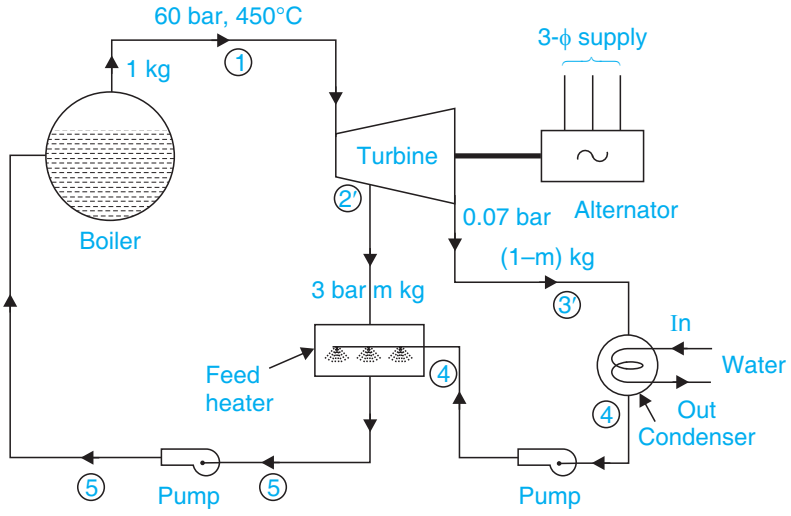
Neglecting the pump work in calculating the input to the boiler, determine :

(*i*) *The steam bled per kg of steam supplied to the turbine.*

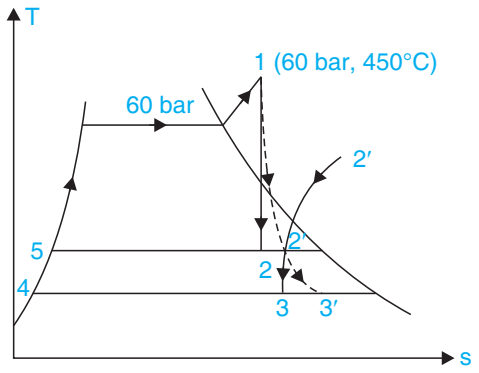
(*ii*) *The steam generated per hour if the 9 per cent of the generator output is used to run the pumps.*

(*iii*) *The overall efficiency of the plant.*

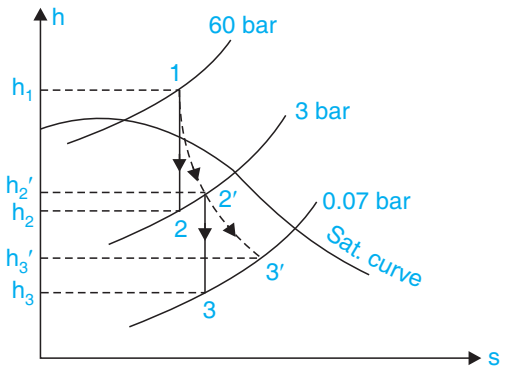
Solution. The schematic arrangement of the steam power plant is shown in Fig. 3.151 (*a*), while the conditions of the fluid passing through the components are represented on *T-s* and *h-s* diagrams as shown in Fig. 3.151 (*b*) and (*c*). The conditions of the fluid entering and leaving the pump are shown by the same point as the rise in temperature due to pump work is neglected.



(a) Schematic arrangement of the steam power plant



(b) T-s diagram (Neglecting pump work)



(c) h-s diagram

Fig. 3.151

Given : Power generated = 22500 kW ;

$p_1 = 60$ bar ; $t_1 = 450°C$; $p_2 (= p_2') = 3$ bar ;

$$p_3 (= p_3') = \frac{760 - 707.5}{760} \times 1.013$$

$= 0.07$ bar ; $\eta_{\text{turbine (each portion)}} = 87\%$;

$\eta_{\text{boiler}} = 86\%$; $\eta_{\text{alt.}} = 94\%$, $\eta_{\text{mech.}} = 97\%$

- Locate point 1 corresponding to the conditions : $p_1 = 60$ bar ; $t_1 = 450°C$ on the *h-s* chart *(Mollier chart)*.

  From *h-s* chart ; we find : $h_1 = 3300$ kJ/kg.

- Draw vertical line through point 1 till it cuts the 3 bar pressure line, then locate point 2.

  $\therefore \quad h_2 = 2607$ kJ/kg

  Now, $\eta_{\text{turbine}} = 0.87 = \dfrac{h_1 - h_2'}{h_1 - h_2}$

  or $0.87 = \dfrac{3300 - h_2'}{3300 - 2607}$

  $\therefore \quad h_2' = 2697$ kJ/kg

- Locate the point 2 on the *h-s* chart as enthalpy and pressure are known and then draw a vertical line through the point 2 till it cuts the 0.07 bar pressure line and then locate the point 3.

  $\therefore \quad h_3 = 2165$ kJ/kg

  Again, $\eta_{\text{turbine}} = 0.87 = \dfrac{h_2' - h_3'}{h_2' - h_3}$

  or $0.87 = \dfrac{2697 - h_3'}{2697 - 2165}$

  $\therefore \quad h_3' = 2234$ kJ/kg

From steam tables, corresponding to pressures 3 bar and 0.02 bar, the saturated liquid heats at points 4 and 5 are :

$$h_{f4} = 163.4 \text{ kJ/kg} ; h_{f5} = 561.4 \text{ kJ/kg}$$

(*i*) The steam bled per kg of steam supplied to the turbine, m :

Considering the *energy balance for feed heater* we have ;

$$m(h_2' - h_{f5}) = (1 - m)(h_{f5} - h_{f4})$$

or $m(2697 - 561.4) = (1 - m)(561.4 - 163.4)$

or $2135.6\, m = 398 (1 - m)$

$\therefore \quad m =$ **0.157 kJ/kg of steam generated.** **(Ans.)**

(*ii*) Steam generated per hour :

Work developed per kg of steam in the turbine

$$= 1(h_1 - h_2') + (1 - m)(h_2' - h_3')$$

$$= (3300 - 2697) + (1 - 0.157)(2697 - 2234)$$

$= 993.3$ kJ/kg

Actual work developed by the turbine

$$= \frac{22500}{\eta_{\text{alt.}} \times \eta_{\text{mech.}}} = \frac{22500}{0.94 \times 0.97}$$

$= 24676.5$ kW

$\therefore$ Steam generated per hour

$$= \frac{24676.5}{993.3} \times \frac{3600}{1000} \text{ tonnes/h}$$

$=$ **89.43 tonnes/h.** **(Ans.)**

(*iii*) The overall efficiency of the plant, η_{overall} :

Net power available deducting pump power

$= 22500 (1 - 0.09) = 20475$ kW

Heat supplied in the boiler

$$= \frac{89.43 \times 1000 (h_1 - h_{f5})}{0.86} \text{ kJ/h}$$

$$= \frac{89.43 \times 1000 (3300 - 561.4)}{0.86 \times 3600} \text{ kW}$$

$= 79106.3$ kW

$$\therefore \quad \eta_{\text{overall}} = \frac{\text{Net power available}}{\text{Heat supplied by the boiler}}$$

$$= \frac{20475}{79106.3}$$

$=$ **0.2588** or **25.88%.** **(Ans.)**

Example 3.38. *A steam power plant of 110 MW capacity is equipped with regenerative as well as reheat arrangement. The steam is supplied at 80 bar and 55°C of superheat. The steam is extracted at 7 bar for feed heating and remaining steam is reheated to 350°C, and then expanded to 0.4 bar in the L.P. stage. Assume indirect type of feed heaters. Determine :*

(i) The ratio of steam bled to steam generated,

(ii) The boiler generating capacity in tonnes of steam / hour, and

(iii) Thermal efficiency of the cycle.

Assume no losses and ideal processes of expansion.

Solution. The schematic arrangement of the plant is shown in Fig. 3.152 (*a*) and the processes are represented on *h-s* chart in Fig. 3.152 (*b*).

Given : Capacity of plant = 110 MW ;

$t_1 = 350°C$ *i.e.*, t_s at 80 bar $\simeq 295°C + 55°C = 350°C$

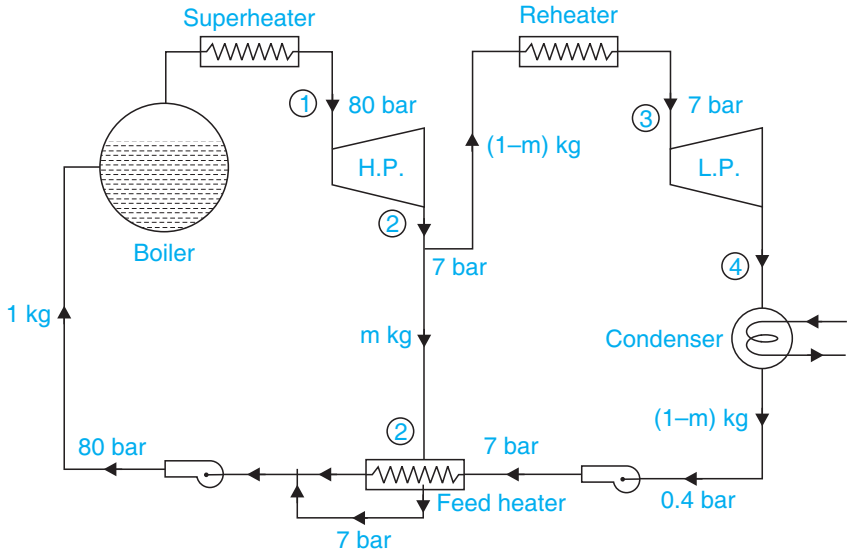
$p_2 = p_3 = 7$ bar ; $t_3 = 350°C$; $p_4 = 0.4$ bar

- Locate point 1 corresponding to the condition $p_1 = 80$ bar and $t_1 = 350°C$, on the *h-s* chart.
- Locate point 2 by drawing vertical line through point 1 till it cuts the 7 bar pressure line.
- Locate point 3 as the cross point of 7 bar and 350°C temperature line.
- Locate point 4 by drawing vertical line through the point 3 till it cuts the 0.4 bar pressure line.

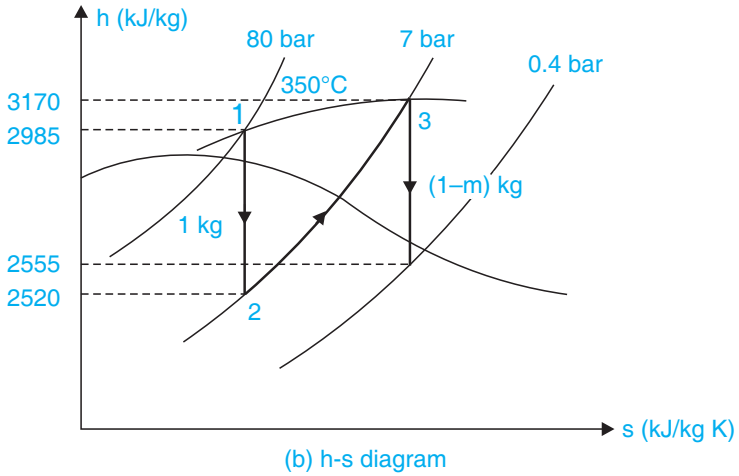
From *h-s* chart, we find :

$h_1 = 2985$ kJ/kg ; $h_2 = 2520$ kJ/kg ;

$h_3 = 3170$ kJ/kg ; $h_4 = 2555$ kJ/kg.



(a) Schematic arrangement of the plant



(b) h-s diagram

Fig. 3.152

Also, from steam tables, we have :

h_{f2} (at 7 bar) = 697.1 kJ/kg ; h_{f4} (at 0.4 bar) = 317.7 kJ/kg

(*i*) The ratio of steam bled to steam generated :

Consider energy/heat balance of feed heater :

Heat lost by m kg of steam = Heat gained by $(1 - m)$ kg of condensed steam

$$m(h_2 - h_{f2}) = (1 - m)(h_{f2} - h_{f4})$$

$$m(2520 - 697.1) = (1 - m)(697.1 - 317.7)$$

$$1822.9\, m = (1 - m) \times 379.4$$

$$\therefore \quad m = 0.172 \text{ kg}$$

i.e., Amount of steam bled per kg of steam supplied to the turbine = 0.172 kg

$$\therefore \quad \frac{\text{Steam generated}}{\text{Steam bled}} = \frac{1}{0.172}$$

$$= \mathbf{5.814.} \quad \textbf{(Ans.)}$$

(*ii*) The boiler generating capacity :

If m_s is the mass of steam supplied to the power plant per second, then the work developed is given by :

$$m_s(h_1 - h_2) + m_s(1 - m)(h_3 - h_4) = 110 \times 10^3$$

or $$m_s(2985 - 2520) + m_s(1 - 0.172)(3170 - 2555) = 110 \times 10^3$$

or $$m_s(465 + 509.22) = 110 \times 10^3$$

$$\therefore \quad m_s = \mathbf{112.91 \text{ kg/s or } 406.48 \text{ tonnes/hour}} \quad \textbf{(Ans.)}$$

(*iii*) Thermal efficiency of the cycle, η_{thermal} :

$$\eta_{\text{thermal}} = \frac{\text{Output / kg of steam}}{\text{Input / kg of steam}}$$

$$= \frac{(h_1 - h_2) + (1 - m)(h_3 - h_4)}{(h_1 - h_{f_2}) + (1 - m)(h_3 - h_2)}$$

$$= \frac{(2985 - 2520) + (1 - 0.172)}{(3170 - 2555)}$$

$$= \frac{(2985 - 697.1) + (1 - 0.172)}{(3170 - 2520)}$$

$$= \frac{974.22}{2826.1}$$

$$= \mathbf{0.3447} \quad \text{or} \quad \mathbf{34.47\%}. \quad \textbf{(Ans.)}$$

Example 3.39. *A steam power plant equipped with regenerative as well as reheat arrangement is supplied with steam to the H.P. turbine at 80 bar 470°C. For feed heating, a part of steam is extracted at 7 bar and remainder of the steam is reheated to 350°C in a reheater and then expanded in L.P. turbine down to 0.035 bar. Determine :*

(i) Amount of steam bled-off for feed heating,

(ii) Amount of steam supplied to L.P. turbine,

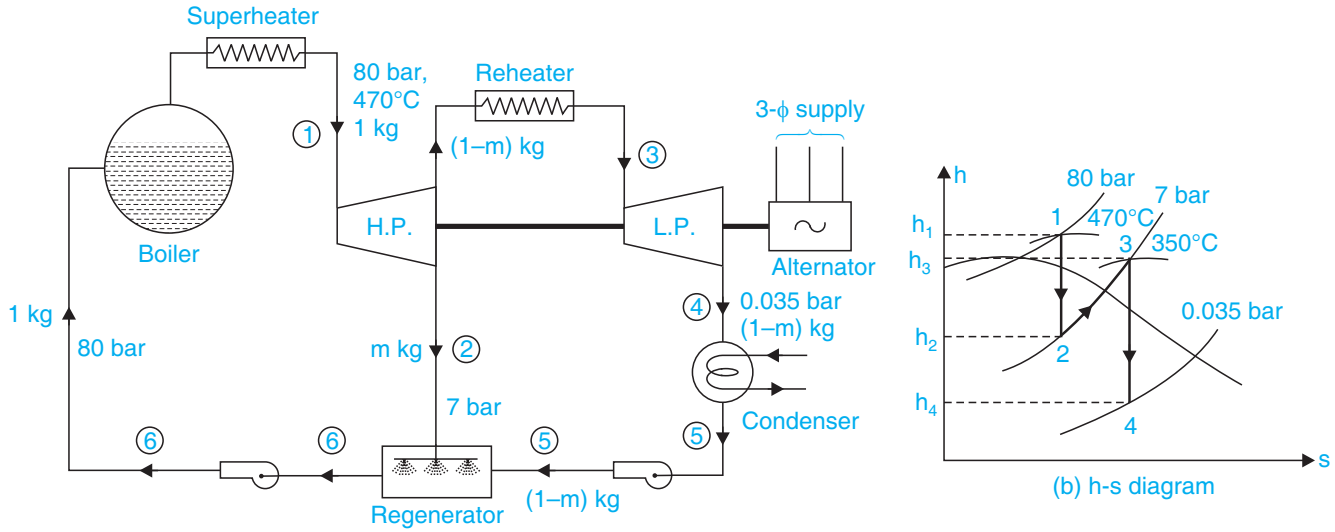
(iii) Heat supplied in the boiler and reheater,

(iv) Cycle efficiency, and

(v) Power developed by the system.

The steam supplied by the boiler is 50 kg/s. **(B.U.)**

Solution. The schematic arrangement is the steam power plant of shown in Fig. 3.153 (*a*) and the processes are represented on *h-s* diagram as shown in Fig. 3.153 (*b*).



(a) Schematic arrangement of the steam power plant

Fig. 3.153

From *h-s* chart and steam tables, we have enthalpies at different points as follows :

$h_1 = 3315$ kJ/kg ; $h_2 = 2716$ kJ/kg
$h_3 = 3165$ kJ/kg ; $h_4 = 2236$ kJ/kg } From *h-s* chart

$h_{f6} = h_{f2} = 697.1$ kJ/kg ;
$h_{f5} = h_{f4} = 101.9$ kJ/kg } From steam table.

(*i*) Amount of steam bled off for feed heating :

Considering *energy balance at regenerator, we have :*

Heat lost by steam = Heat gained by water

$$m(h_2 - h_{f6}) = (1 - m)(h_{f6} - h_{f5})$$

or $$m(h_2 - h_{f2}) = (1 - m)(h_{f2} - h_{f4})$$

$$[\because \quad h_{f6} = h_{f2} \; ; \; h_{f5} = h_{f4}]$$

or $$m(2716 - 697.1) = (1 - m)(697.1 - 111.9)$$

or $$2018.9\, m = 585.2\,(1 - m)$$

$$\therefore \quad m = 0.225 \text{ g of steam supplied}$$

Hence amount of **steam bled off is 22.5% of steam generated by the boiler.** **(Ans.)**

(*ii*) Amount of steam supplied to L.P. turbine :

Amount of steam supplied to L.P. turbine

$= 100 - 22.5$

$=$ **77.5% of the steam generated by the boiler.** **(Ans.)**

(*iii*) Heat supplied in the boiler and reheater :

Heat supplied in the *boiler* per kg of steam generated

$$= h_1 - h_{f6} = 3315 - 697.1$$

$$= \mathbf{2617.9\ kJ/kg.} \quad \textbf{(Ans.)} \quad (\because \quad h_{f6} = h_{f2})$$

Heat supplied in the *reheater* per kg of steam generated

$$= (1 - m)(h_3 - h_2)$$

$$= (1 - 0.225)(3165 - 2716)$$

$$= \mathbf{347.97\ kJ/kg.} \quad \textbf{(Ans.)}$$

Total amount of heat supplied by the boiler and reheater per kg of steam generated,

$$Q_s = 2617.9 + 347.97 = 2965.87 \text{ kJ/kg}$$

(iv) Cycle efficiency, η_{cycle} :

Amount of work done by per kg of steam generated by the boiler,

$$W = 1(h_1 - h_2) + (1 - m)(h_3 - h_4),$$

Neglecting pump work

$$= (3315 - 2716) + (1 - 0.225)(3165 - 2236)$$
$$\simeq 1319 \text{ kJ/kg}$$

$$\therefore \quad \eta_{cycle} = \frac{W}{Q_s} = \frac{1319}{2965.87}$$
$$= \mathbf{0.4447 \quad or \quad 44.47\%} \quad \textbf{(Ans.)}$$

(v) Power developed by the system :

Power developed by the system

$$= m_s \times W = 50 \times 1319 \text{ kJ/s} = \frac{50 \times 1319}{1000}$$
$$= \mathbf{65.95 \text{ MW}} \quad \textbf{(Ans.)}$$

Example 3.40. *A steam power plant operates on ideal Rankine cycle using reheater and regenerative feed water heaters. It has one open feed heater. Steam is supplied at 150 bar and 600°C. The condenser pressure is 0.1 bar. Some steam is extracted from the turbine at 40 bar for closed feed water heater and remaining steam is reduced at 40 bar to 600°C. Extracted steam is completely condensed in this closed feed water heater and is pumped to 150 bar before mixing with the feed water heater. Steam for the open feed water heater is bled from L.P. turbine at 5 bar. Determine :*

(i) Fraction of steam extracted from the turbines at each bled heater, and

(ii) Thermal efficiency of the system.

Draw the line diagram of the components and represent the cycle on T-s diagram. **(P.U.)**

Solution. The arrangement of the components is shown in Fig. 3.154 (*a*) and the processes are represented on *T-s* diagram as shown in Fig. 3.154 (*b*).

From *h-s* chart and steam tables we have enthalpies at different points as follows :

$h_1 = 3578$ kJ/kg ; $h_2 = 3140$ kJ/kg ;
$h_3 = 3678$ kJ/kg ; $h_4 = 3000$ kJ/kg ;
$h_5 = 2330$ kJ/kg ; From *h-s* chart

h_{f1} (at 150 bar) = 1611 kJ/kg
h_{f2} (at 40 bar) = 1087.4 kJ/kg ;
h_{f4} (at 5 bar) = 640.1 kJ/kg ;
$h_{f5} = h_{f6}$ (at 0.1 bar) = 191.8 kJ/kg
Steam tables

(i) Fraction of steam extracted from the turbines at each bled heater m_1, m_2 :

Considering *energy balance for closed feed heater,* we have :

$$m_1(h_2 - h_{f2}) = (1 - m_1)(h_{f2} - h_{f4})$$
$$m_1(3140 - 1087.4) = (1 - m_1)(1087.4 - 640.1)$$

or, $$2052.6\, m_1 = (1 - m_1) \times 447.3$$

$\therefore$ $\mathbf{m_1 = 0.179}$ **kg/kg of steam supplied by the boiler.** **(Ans.)**

Considering *energy balance for open feed heater,* we have :

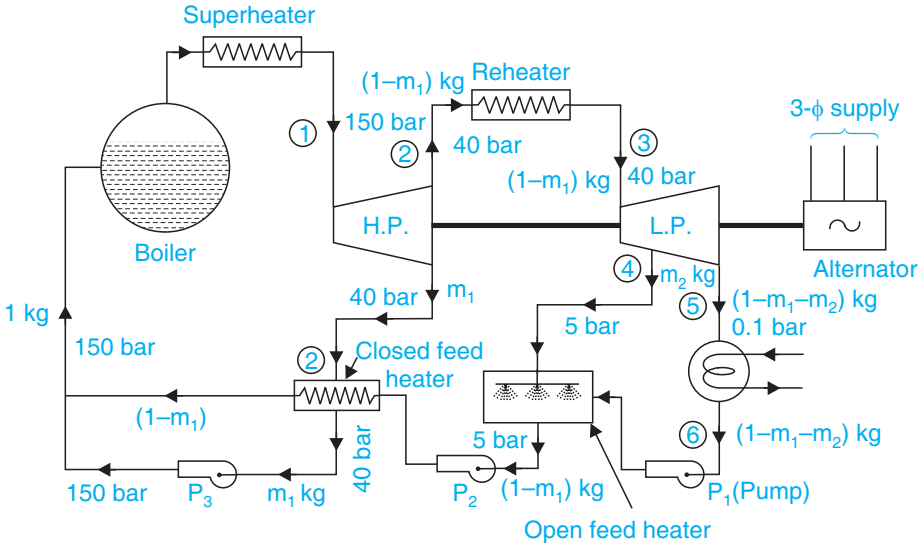
$$m_2(h_4 - h_{f4}) = (1 - m_1 - m_2)(h_{f4} - h_{f6})$$

or, $$m_2(h_4 - h_{f4}) = (1 - m_1 - m_2)(h_{f4} - h_{f5}) \quad (\because \ h_{f6} = h_{f5})$$

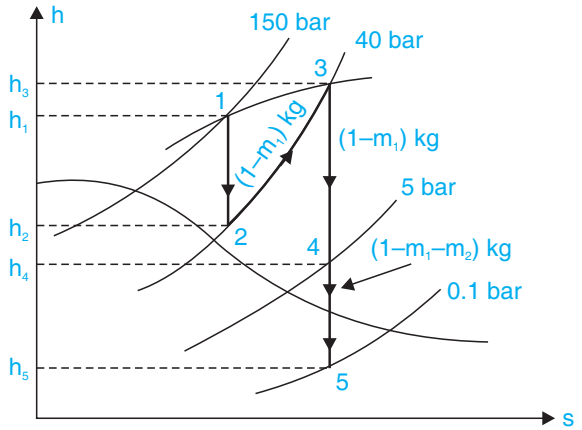
or, $$m_2(3000 - 640.1) = (1 - 0.179 - m_2)(640.1 - 191.8)$$

or, $$2359.9\, m_2 = (0.821 - m_2) \times 448.3$$
$$= 368.05 - 448.3\, m_2$$

$\therefore$ $\mathbf{m_2 = 0.131}$ **kg/kg of steam supplied by boiler.** **(Ans.)**



(a) Schematic arrangement of the steam power plant



(b) h-s diagram

Fig. 3.154

(ii) Thermal efficiency of the system, $\eta_{thermal}$:

Total work done per kg of steam supplied by the boiler

$$= 1 \times (h_1 - h_2) + (1 - m_1)(h_3 - h_4) + (1 - m_1 - m_2)(h_4 - h_5)$$
$$= (3578 - 3140) + (1 - 0.179)(3678 - 3000) + (1 - 0.179 - 0.131)(3000 - 2330)$$
$$= 438 + 556.64 + 462.3 = 1456.94 \text{ kJ/kg}$$

Work done by the pump P_1

$$W_{P1} = v_{w1}(1 - m_1 - m_2)(5 - 0.1) \times 10^5 \times 10^{-3} \text{ kJ/kg}$$
$$= \frac{1}{1000}(1 - 0.179 - 0.131)(5 - 0.1) \times 10^5 \times 10^{-3} = 0.338 \text{ kJ/kg}$$

$$\left[\text{Taking } v_{w1} = v_{w2} = v_{w3} = \frac{1}{1000} \text{ m}^3/\text{kg}\right]$$

Work done by the pump P_2,

$$W_{P2} = v_{w2}(1 - m_1)(150 - 5) \times 10^5 \times 10^{-3} \text{ kJ/kg}$$
$$= \frac{1}{1000}(1 - 0.179)(150 - 5) \times 10^5 \times 10^{-3}$$
$$= 11.9 \text{ kJ/kg}$$

Work done by pump P_3,

$$W_{P3} = v_{w3} \times m_1 \times (150 - 40) \times 10^5 \times 10^{-3}$$
$$= \frac{1}{1000} \times 0.179\,(150 - 40) \times 10^5 \times 10^{-3}$$
$$= 1.97 \text{ kJ/kg}$$

Total pump work

$$= W_{P1} + W_{P2} + W_{P3}$$
$$= 0.338 + 11.9 + 1.97$$
$$= 14.21 \text{ kJ/kg of steam supplied by boiler}$$

$\therefore$ Net work done by the turbine per kg of steam supplied by the boiler,

$$W_{net} = 1456.94 - 14.21 = 1442.73 \text{ kJ/kg}$$

Heat of feed water extering the boiler

$$= (1 - m_1) \times 1611 + m_1 \times 1611$$
$$= 1611 \text{ kJ/kg}$$

Heat supplied by the boiler per kg of steam,

$$Q_{s1} = h_1 - 1610 = 3578 - 1610 = 1968 \text{ kJ/kg}$$
$$Q_{s2} = \text{Heat supplied in the reheater}$$
$$= (1 - m_1)(h_3 - h_2)$$
$$= (1 - 0.179)(3678 - 3140)$$
$$= 441.7 \text{ kJ/kg of steam supplied by the boiler}$$

Q_{st} (Total heat supplied)

$$= Q_{s1} + Q_{s2} = 1968 + 441.7 = 2409.7 \text{ kJ/kg}$$

$$\therefore \eta_{thermal} = \frac{W_{net}}{Q_{st}} = \frac{1442.73}{2409.7}$$
$$= \mathbf{0.5987} \quad \text{or} \quad \mathbf{59.87\%}. \quad \textbf{(Ans.)}$$

Example 3.41. *Steam at 70 bar and 450°C is supplied to a steam turbine. After expanding to 25 bar in high pressure stages, it is reheated to 420°C at the constant pressure. Next ; it is expanded in intermediate pressure stages to an appropriate minimum pressure such that part of the steam bled at this pressure heats the feed water to a temperature of 180°C. The remaining steam expands from this pressure to a condenser pressure of 0.07 bar in the low pressure stage. The isentropic efficiency of H.P. stage is 78.5%, while that of the intermediate and L.P. stages is 83% each. From the above data, determine :*

(i) The minimum pressure at which bleeding is necessary.

(ii) The quantity of steam bled per kg of flow at the turbine inlet.

(iii) The cycle efficiency.

Neglect pump work. **(Roorkee University)**

Solution. The schematic arrangement of the plant is shown in Fig. 3.155 (*a*) and the processes are represented on *T-s* and *h-s* diagrams as shown in Fig. 3.155 (*b*) and (*c*) respectively.

(i) The minimum pressure at which bleeding is necessary :

It would be assumed that the feed water heater is an open heater. Feed water is heated to 180°C. So p_{sat} at 180°C $\simeq$ 10 bar is the pressure at which the heater operates.

Thus, *the pressure at which bleeding is necessary is* **10 bar.** **(Ans.)**

From the *h-s* chart (Mollier chart), we have :

$$h_1 = 3285 \text{ kJ/kg} ; h_2 = 2980 \text{ kJ/kg} ;$$
$$h_3 = 3280 \text{ kJ/kg} ; h_4 = 3030 \text{ kJ/kg}$$
$$h_3 - h_4' = 0.83(h_3 - h_4) = 0.83(3280 - 3030)$$
$$= 207.5 \text{ kJ/kg}$$
$$\therefore \quad h_4' = h_3 - 207.5 = 3280 - 207.5$$
$$= 3072.5 \text{ kJ/kg}$$

$h_5 = 2210$ kJ/kg

$h_4' - h_5' = 0.83(h_4' - h_5) = 0.83(3072.5 - 2210)$

$\simeq 715.9$ kJ/kg

$\therefore \quad h_5' = h_4' - 715.9 = 3072.5 - 715.9$

$= 2356.6$ kJ/kg

From steam tables, we have :

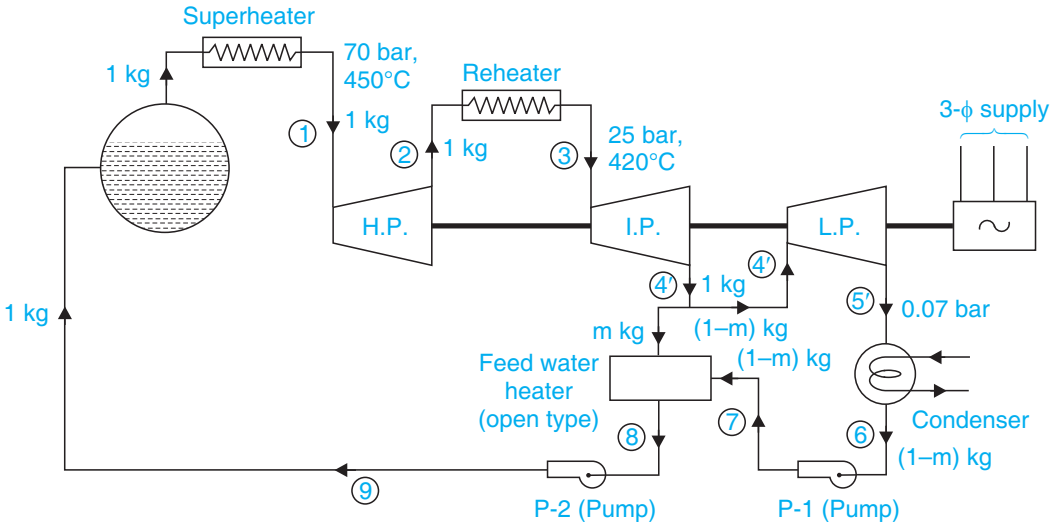
$h_{f6} = 163.4$ kJ/kg ; $h_{f8} = 762.6$ kJ/kg

$h_1 - h_2' = 0.785(h_1 - h_2) = 0.785(3285 - 2980)$

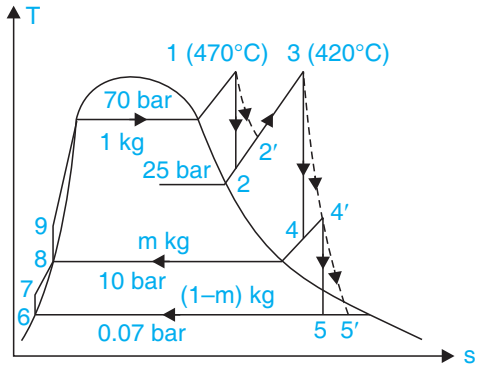
$= 239.4$ kJ/kg

$\therefore \quad h_2' = h_1 - 239.4 = 3285 - 239.4$

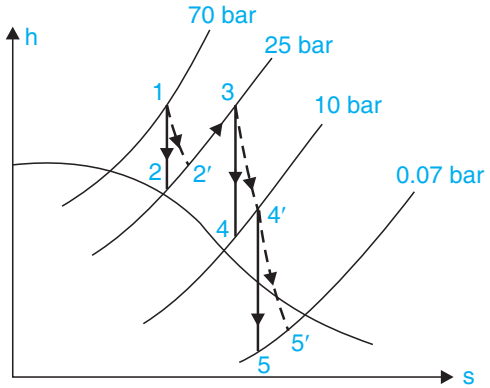
$= 3045.6$ kJ/kg



(a) Schematic arrangement of the plant



(b) T-s diagram



(c) h-s diagram (Pump work not shown)

Fig. 3.155

(*ii*) The quantity of steam bled per kg of flow at the turbine inlet, m :

Considering *energy balance for the feed water heater*, *we have :*

$$m \times h_4' + (1 - m)\, h_{f7} = 1 \times h_{f8}$$

$$m \times 3072.5 + (1 - m) \times 163.4 = 1 \times 762.6 \qquad (\because \quad h_{f7} = h_{f6})$$

$$3072.5\, m + 163.4 - 163.4\, m = 762.6$$

$$\therefore \quad m = \frac{(762.6 - 163.4)}{(3072.5 - 163.4)}$$

= 0.206 g of steam flow at turbine inlet. (Ans.)

(*iii*) Cycle efficiency, η_{cycle} :

$$\eta_{cycle} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{1(h_1 - h_2) + 1(h_3 - h_4) + (1 - m)(h_4' - h_5')}{(h_1 - h_{f8}) + (h_3 - h_2')}$$

$$= \frac{(3285 - 3045.6) + 207.5 + (1 - 0.206)(715.9)}{(3285 - 762.6) + (3280 - 3045.6)}$$

$$= \frac{1015.3}{2756.8}$$

$$= \mathbf{0.3683} \quad \text{or} \quad \mathbf{36.83\%}. \quad \textbf{(Ans.)}$$

Example 3.42. *A steam turbine plant developing 120 MW of electrical output is equipped with reheating and regenerative feed heating arrangement consisting of two feed heaters—one surface type on H.P. side and other direct contact typed on L.P. side. The steam conditions before the steam stop valve are 100 bar and 530°C. A pressure drop of 5 bar takes place due to throttling in valves.*

Steam exhausts from the H.P. turbine at 25 bar. A small quantity of steam is bled off at 25 bar for H.P. surface heater for feed heating and the remaining is reheated in a reheater to 550° C and the steam enters at 22 bar in L.P. turbine for further expansion. Another small quantity of steam is bled off at pressure 6 bar for the L.P heater and the rest of steam expands up to the back pressure of 0.05 bar. The drain from the H.P. heater is led to the L.P. heater and the combined feed from the L.P. heater is pumped to the high-pressure feed heater and finally to the boiler with the help of boiler feed pump.

The component efficiencies are: turbine efficiency 85%, pump efficiency 90%, generator efficiency 96%, boiler efficiency 90% and mechanical efficiency 95%. It may be assumed that the feed water is heated up to the saturation temperature at the prevailing pressure in feed heater. Work out the following :

(i) Sketch the feed heating system and show the process on T-s and h-s diagrams.

(ii) Amounts of steam bled off.

(iii) Overall thermal efficiency of turbo-alternator considering pump work.

(iv) Specific steam consumption is kg/kWh.

(AMIE)

Solution. *(i)* The *schematic arrangement* including feed heating system is shown in Fig. 3.156 (*a*), and *T-s* and *h-s* diagrams of the process are shown in Fig. 3.156 (*b*) and (*c*) respectively.

***(ii)* Amounts of bled off.** The enthalpies at various state points as read from *h-s* diagram/steam tables, in kJ/kg, are :

$h_1 = h_2 = 3460$ kJ/kg

$h_3 = 3050$, and

$\therefore \quad h_3' = 3460 - 0.85(3460 - 3050) = 3111.5$

$h_4 = 3385$

$h_5 = 3140$, and

$\therefore \quad h_5' = 3585 - 0.85(3585 - 3140) = 3207$

$h_6 = 2335$, and

$\therefore \quad h_6' = 3207 - 0.85\ (3207 - 2335) = 2466$

$h_7 = 137.8$ kJ/kg (h_f at 0.05 bar)

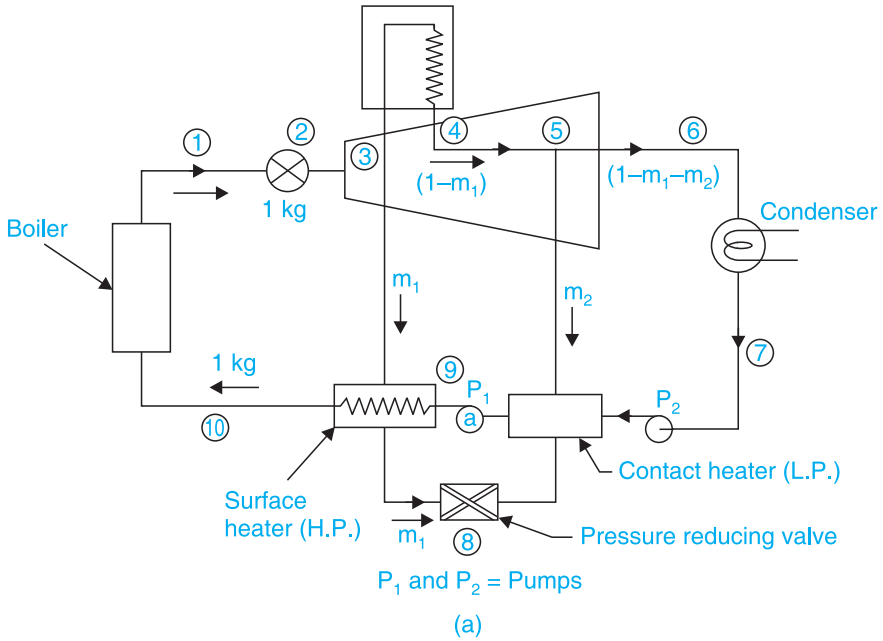
$h_8 = h_{10} = 962$ kJ/kg (h_f at 25 bar)

and, $h_9 = 670.4$ kJ/kg (h_f at 6 bar).

Enthalpy balance for ***surface heater :***

$m_1 h_3' + h_9 = m_1 h_8 + h_{10}$, neglecting pump work

or, $$m_1 = \frac{h_{10} - h_9}{h_3' - h_8} = \frac{962 - 670.4}{3111.5 - 962} = 0.13566 \text{ kg}$$



(a)

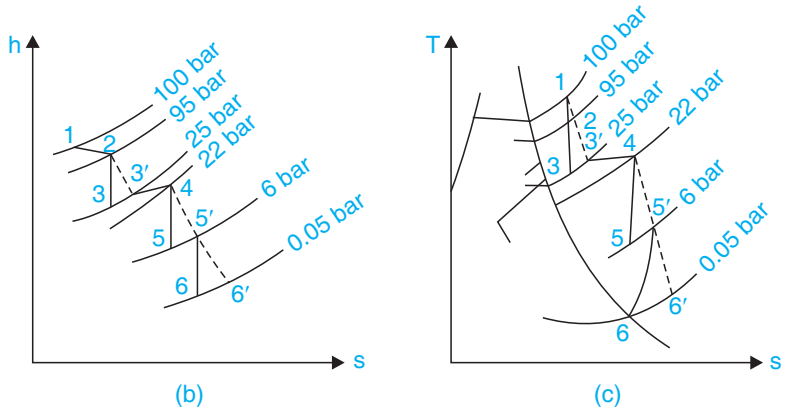


Fig. 3.156

Enthalpy balance for ***contact heater*** **:**

$$m_2 h_5' + (1 - m_1 - m_2)\, h_7 + m_1 h_8 = h_9,$$

neglecting pump work

or $m_2 \times 3207 + (1 - 0.13566 - m_2) \times 137.8 + 0.13566 \times 962 = 670.4$

or $m_2 = 0.1371$ kg.

Pump Work. The specific volume of water as 0.001 m^3/kg.

$$(W_{pump})_{L.P.} = (1 - m_1 - m_2)(6 - 0.05) \times 0.001 \times 10^2$$
$$= (1 - 0.13566 - 0.1371) \times 5.95 \times 0.1$$
$$= 0.4327 \text{ kJ/kg.}$$
$$(W_{pump})_{H.P.} = 1 \times (100 - 6) \times 0.001 \times 10^2$$
$$= 9.4 \text{ kJ/kg}$$

Total pump work (actual)

$$= \frac{0.4327 + 9.4}{0.9} = 10.925 \text{ kJ/kg}$$

Turbine output (indicated)

$$= (h_2 - h_3') + (1 - m_1)(h_4 - h_5') + (1 - m_1 - m_2)(h_5' - h_6')$$
$$= (3460 - 3111.5) + (1 - 0.13566)(3585 - 3207) + (1 - 0.13566 - 0.1371)(3207 - 2466)$$
$$= 1214.105 \text{ kJ/kg}$$

Net electrical output

$$= (\text{Indicated work} - \text{pump work}) \times \eta_{mech.} \times \eta_{gen.}$$
$$= (1214.105 - 10.925) \times 0.9 \times 0.96$$
$$= 1039.55 \text{ kJ/kg}$$

[**Note.** All the above calculations are for 1 kg of main (boiler) flow.]

$\therefore$ Main steam flow rate

$$= \frac{120 \times 10^3 \times 3600}{1039.55} = 4.155 \times 10^5 \text{ kJ/h.}$$

Amounts of bled off are :

(*a*) Surface (high pressure) heater,

$$= 0.13566 \text{ kg/kg or boiler flow}$$

or $$= 0.13566 \times 4.155 \times 10^5$$

i.e., $$= \mathbf{5.6367 \times 10^4 \text{ kg/h.}}$$ **(Ans.)**

(*b*) Direct contact (low pressure) heater

$$= 0.1371 \text{ kg/kg of boiler flow}$$

or $$= 0.1371 \times 4.155 \times 10^5$$

i.e., $$= \mathbf{5.697 \times 10^4 \text{ kg/h.}}$$ **(Ans.)**

(*iii*) Overall thermal efficiency, $\eta_{overall}$:

(*c*) Heat input in boiler

$$= \frac{h_1 - h_{10}}{\eta_{boiler}} = \frac{3460 - 962}{0.9}$$
$$= 2775.6 \text{ kJ/kg of the boiler flow.}$$

Heat input in reheater

$$= \frac{h_4 - h_3'}{\eta_{boiler}} = \frac{3585 - 3111.5}{0.9}$$
$$= 526.1 \text{ kJ/kg of boiler flow}$$

$$\therefore \quad \eta_{overall} = \frac{1039.55}{2775.6 + 526.1} \times 100$$
$$= \mathbf{31.48\%.} \quad \textbf{(Ans.)}$$

(*iv*) Specific steam consumption.

Specific steam consumption

$$= \frac{4.155 \times 10^5}{120 \times 10^3}$$
$$= \mathbf{3.4625 \text{ kg/kWh.}} \quad \textbf{(Ans.)}$$

Example 3.43. (*a*) *How does erosion of turbine blades occur ? State the methods of preventing erosion of turbine blades.*

(*b*) *What do you mean by TTD of a feed water heater ? Draw temperature-path-line diagram of a closed feed water heater used in regenerative feed heating cycle.*

(*c*) *In a 15 MW steam power plant operating on ideal reheat cycle, steam enters the H.P. turbine at 150 bar and*

600°C. The condenser is maintained at a pressure of 0.1 bar. If the moisture content at the exit of the L.P. turbine is 10.4%, determine :

(i) Reheat pressure; (ii) Thermal efficiency; (iii) Specific steam consumption; and (iv) Rate of pump work in kW. Assume steam to be reheated to the initial temperature. **(AMIE)**

Solution. (*a*) The erosion of the moving blades in *caused by the presence of water particles in (wet) steam in the L.P. stages.* The water particles strike the leading surface of the blades. Such impact, if sufficiently heavy, produces *severe local stresses in the blade material causing the surface metal to fail and flake off.*

The erosion, if any, is more likely to occur in the region where the stem is wettest. *i.e.*, in the last one or two stages of the turbine. Moreover, the water droplets are concentrated in the outer parts of the flow annuals where the velocity of impact is highest.

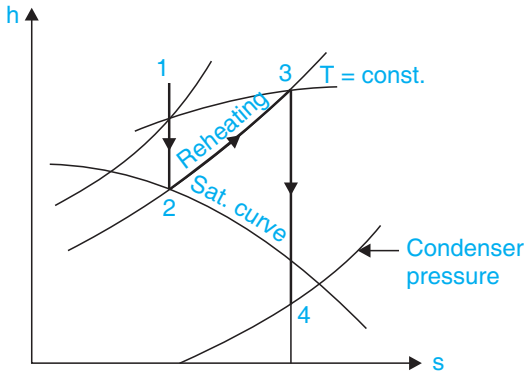


Fig. 3.157

Erosion difficulaties due to moisture in the steam may be avoided by reheating (see Fig. 3.157). The whole of steam is taken from the turbine at a suitable point 2, and a further supply of heat is given to its along 2-3 after which the steam is readmitted to the turbine and expanded along 3-4 to condenser pressure.

Erosion *may also be reduced by using steam traps in between the stages to separate moisture from the steam.*

(*b*) TTD means *terminal temperature difference.* It is the difference between temperatures of bled steam/ condensate and the feed water at the two ends of the feed water heater.

The required temperature-path-line diagram of a closed feed water heater is shown in Fig. 3.158.

(*c*) The cycle is shown on *T-s* (Fig. 3.159) and *h-s* (Fig. 3.160) diagrams. The following values are read from the Mollier diagram.

h_1 = 3580 kJ/kg, h_2 = 3140 kJ/kg,
h_3 = 3675 kJ/kg, and h_4 = 2335 kJ/kg

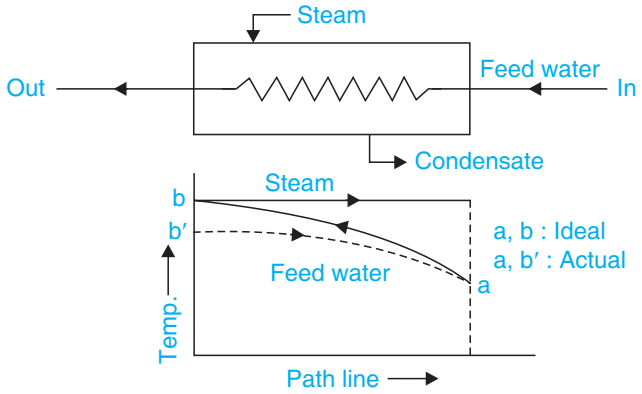


Fig. 3.158

Moisture contents in exit from L.P. turbine = 10.4%

$x_4 = 1 - 0.104 = 0.896$

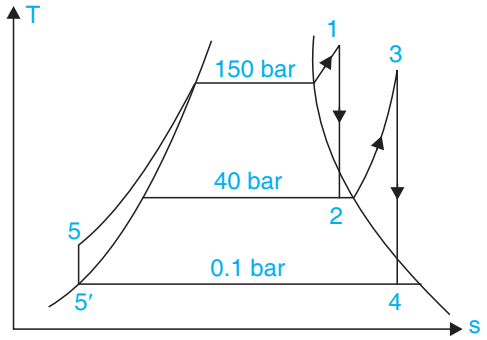


Fig. 3.159

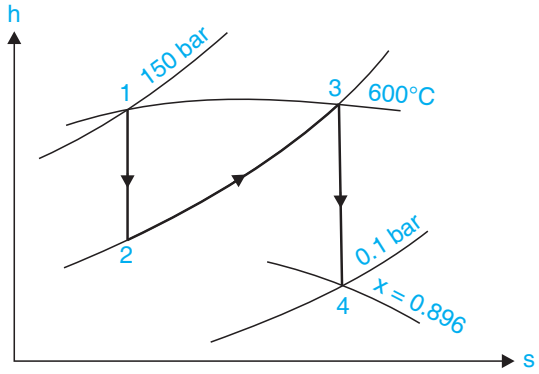


Fig. 3.160

***(i)* Reheat pressure :** From the Mollier diagram, the **reheat pressure is 40 bar.** **(Ans)**

***(ii)* Thermal efficiency, η_{th} :**

Turbine work $= (h_1 - h_2) + (h_3 - h_4)$
$= (3580 - 3140) + (3675 - 2335)$
$= 1780$ kJ/kg.

Assuming specific volume of water
$= 10^{-3}$ m^3/kg, the pump work
$= 10^{-3}\,(150 - 0.1) = 0.15$ kJ/kg,

i.e., may be neglected in computing of η_{th},

$h_5 = h_4 = 191.8$ kJ/kg, (h_f at 0.1 bar) from steam tables

$$Q_{input} = (h_1 - h_5) + (h_3 - h_2)$$
$$= (3580 - 191.8) + (3675 - 3140)$$
$$= 3923.2 \text{ kJ/kg}$$

$$\%\eta_{th} = \frac{1780}{3923.2} \times 100 = \mathbf{45.37\%}. \quad \textbf{(Ans.)}$$

(*iii*) Specific steam consumption :

Steam consumption

$$= \frac{15 \times 10^3}{1780} = 8.427 \text{ kg/s}$$

Specific steam consumption

$$= \frac{8.427 \times 3600}{15 \times 10^3}$$
$$= \mathbf{2.0225 \text{ kg/kWh}}. \quad \textbf{(Ans.)}$$

(*iv*) Rate of pump work :

Rate of pump work

$$= 8.427 \times 0.15 = \mathbf{1.26 \text{ kW}}. \quad \textbf{(Ans.)}$$

Example 3.44. (*a*) *Why is drum type construction preferred to disc type construction in reaction turbine ?*

(*b*) *Why is partial admission of steam adopted for H.P. impulse stages while full admission is essential for any stage of a reaction turbine ?*

(*c*) *In a 50% reaction turbine, the speed of rotation of a blade group is 3000 rpm with mean blade velocity of 120 m/s. The velocity ratio is 0.8 and the exit angle of the blades is 20°. It the mean blade height is 30 mm, calculate the total steam flow rate through the turbine. Neglect the effect of blade edge thickness of the annular area but consider 10% of the total steam flow rate as the tip leakage loss. The mean condition of steam in that blade group is found to be 2.7 bar and 0.95 dry.*

(*d*) *What do you mean by once through boiler ?*

(AMIE)

Solution. (*a*) The rotor of the turbine can be of drum type or disc type. *Disc type construction is difficult (complicated) to make, but lighter in weight.* Hence the centrifugal stresses are lower at a particular speed. On the other hand drum type construction is simple in construction, and it is easy to attach aerofoil shape blades. Further it is easier to design for tip leakage reduction which is a major problem in reaction turbines. Moreover due to small pressure drop per stage (larger number of stages) in reaction turbines, their rotational speeds are lower and so the *centrifugal stresses are not very high* (even the reaction blades are lighter). Therefore *drum type construction is preferred to disc type in reaction turbines.*

To accommodate increase in specific volume at lower pressures the drum diameter is stepped up which allows greater area without unduly increasing blade height. The *increased drum diameter also increases the torque due to steam pressure.*

(*b*) **In impulse turbines** there is no expansion of steam in moving blades, and the pressure of steam remains constant while flowing over the moving blades. The expansion takes place only in the nozzles at the inlet to the turbine in HP stages, or through the fixed blades in the subsequent stages. The nozzles need not occupy the complete circumference. Therefore partial admission of steam is feasible and adopted for HP impulse stages.

In reaction turbines, *pressure drop is required in the moving blades also. This is not possible with partial admission. Hence full admission is essential for all stages of a reaction turbine.*

(*c*) Refer to Fig. 3.96

Given : $N = 3000$ r.p.m. ; $\phi = \alpha = 20°$;

$$C_{bl} = 120 \text{ m/s} ; \frac{C_{bl}}{C_1} = 0.8 ;$$

$$\therefore \quad C_1 = \frac{C_{bl}}{0.8} = \frac{120}{0.8} = 150 \text{ m/s}$$

Also, $C_{bl} = \dfrac{\pi DN}{60}$ or $120 = \dfrac{\pi DN}{60}$

$$\therefore \quad D = \frac{120 \times 60}{\pi \times 3000} = 0.764 \text{ m.}$$

From steam tables, v_g (at 2.7 bar) = 0.668 m^3/kg

$$v = 0.95 \times 0.668 = 0.6346 \text{ m}^3\text{/kg}$$

Flow area $A = \pi Dh = \pi \times 0.764 \times \dfrac{30}{1000} = 0.072$ m^2

Flow velocity,

$$C_f = C_1 \sin \alpha = 150 \sin 20° = 51.3 \text{ m/s}$$
$$(C_{f_1} = C_{f_0} = C_f)$$

Mass flow rate, $m = \dfrac{AC_f}{v} = \dfrac{0.072 \times 51.3}{0.6346}$

$$= 5.82 \text{ kg/s}$$

Accounting for 10 per cent leakage (of total steam flow), the total steam flow rate is

$$\frac{5.82}{0.9} = \mathbf{6.467 \text{ kg/s}}. \quad \textbf{(Ans.)}$$

(*d*) *Once through* boiler is a boiler which *does not require any water or steam drum.* It is a *monotube boiler* using a long tube arranged in the combustion chamber and the furnace. The *economizer, boiler and superheater are in series with no fixed surfaces as separators between the steam and water.*

Benson boiler is an example of once through boiler, operating at supercritical pressure. The tube length to diameter ratio of such a boiler is about 2500. Due to large frictional resistance the feed pressure should be about 1.4 times the boiler pressure.

Example 3.45. (*a*) *List the advantages of steam turbines over gas turbines.*

(*b*) *Determine the isentropic enthalpy drop in the stage of Parson's reaction turbine which has the following particulars :*

Speed = 1500 rpm ; mean diameter of rotor = 1 m ;
stage efficiency = 80% ; speed ratio = 0.7 ;
blade outlet angle = 20°. **(AMIE)**

Solution. (*a*) Advantages of steam turbines over gas turbines :

1. The load control in steam turbines is easy simply by throttle governing or cut-off governing. In gas turbines the air-fuel ratio becomes too high, 100 to 150 at part loads. This causes problems to sustain the flame.

2. The steam turbine works on Rankine cycle. In this cycle most of the heat is supplied at constant temperature in the form of latent heat of evaporation. Also the heat is rejected in the condenser isothermally. Hence the cycle is more efficient, and its efficiency is close to that of Carnot cycle. On the other head, the gas turbine works on Brayton cycle whose efficiency is much less than that of Carnot cycle working between the same maximum and minimum limits of temperatures.

3. The efficiency of steam turbine at part load is not very much reduced. In gas turbines the maximum cycle temperature decreases considerably at part load ; therefore its part load efficiency is considerably low.

4. The blade material for steam turbines is cheap. For gas-turbines the blade material is costly, as it is required to sustain considerably high temperatures.

(*b*) For Parson's reaction turbine, the velocity triangles are symmetrical, as shown in Fig. 3.96.

Given : $N = 1500$ r.p.m., $D = 1$ m,

$\eta_{stage} = 80\%$;

Speed ratio, $\dfrac{C_{bl}}{C_1} = 0.7$, $\phi = \alpha = 20°$

$C_1 = C_{r0}$ and $C_{r1} = C_0$

$$C_{bl} = \frac{\pi DN}{60} = \frac{\pi \times 1 \times 1500}{60}$$

$= 78.54$ m/s

Speed ratio $= 0.7 = \dfrac{C_{bl}}{C_1}$

$$\therefore \quad C_1 = \frac{78.54}{0.7} = 112.2 \text{ m/s}$$

$$C_{r1}^2 = C_1^2 + C_{bl}^2 - 2C_1C_{bl}\cos\alpha$$

$= (112.2)^2 + (78.54)^2 - 2 \times 112.2 \times 78.54 \cos 20°$

$= 2195.84$

or $C_{r1} = 46.86$ m/s

Δh = Actual enthalpy drop for the stage

$$= \tfrac{1}{2}\,[(C_1^2 - C_0^2) + C_{r0}^2 - C_{r1}^2)]$$

$$= \tfrac{1}{2}\,[(C_1^2 - C_{r1}^2) + (C_1^2 - C_{r1}^2)]$$

$$= C_1^2 - C_{r1}^2$$

or $\Delta h = [(112.2)^2 - (46.84)^2] \times 1/1000$ kJ/kg

$= 10.39$ kJ/kg

Isentropic enthalpy drop,

$$(\Delta h') = \frac{(\Delta h)}{\eta_{stage}} = \frac{10.39}{0.8}$$

$= \mathbf{12.99\ kJ/kg.}$ **(Ans.)**

Example 3.46. (*a*) *A 210 MW multistage steam turbine is supplied with steam at 100 bar and 500°C. Vacuum in the condenser is 71 cm of Hg when barometer reads 76 cm of Hg. Assuming stage efficiency of 75% for each stage and reheat factor of 1.04, find the volume rate of cooling water required for the condenser. The rise in cooling water temperature is limited to 10°C and the condensate is undercooled by 2°C.*

(*b*) *A steam turbine discharges 4000 kg of steam per hour at 40°C and 0.85 dry. The estimated air leakage into the condenser is 16 kg per hour. The temperature at the air pump suction is 32°C and the temperature of the condensate is 35°C.*

Find the capacity of the dry air pump if its volumetric efficiency is 80%.

(*c*) *What are the functions of the air cooling section in a surface condenser ?* **(AMIE)**

Solution. (*a*) $\eta_{int} = \eta_{stage} \times$ reheat factor

$= 0.75 \times 1.04 = 0.78$

Condenser pressure

$= (76 - 71) \times 10 = 50$ mm Hg

$$= \frac{50}{1000}\text{ (m)} \times (13.6 \times 1000)\text{ (kg/m}^3) \times 9.8 \times 10^{-5}$$

$= 0.0667$ bar

Corresponding $t_s = 38.1°C$, from Mollier's chart, overall isentropic enthaplpy drop, (Δh) is

$$(\Delta h) = h_1 - h_2 = 3370 - 2040 = 1330 \text{ kJ/kg}$$

Actual enthalpy drop

$= h_1 - h_2' = (\Delta h) \times \eta_{int} = 1330 \times 0.78$

$= 1037.4$ kJ/kg

$h_2' = 3370 - 1037.4 = 2332.6$ kJ/kg

h_f at (38.1 – 2), *i.e.,* 36.1°C = 151 kJ/kg

$$\text{Steam rate} = \frac{210 \times 10^3}{1037.4} = 202.429 \text{ kg/s}$$

Heat rejected in condenser

$= \text{Steam rate} \times (h_2' - h_f)$

Heat gained by cooling

$= m_w \times c_{pw} \times (t_{w_2} - t_{w_1}) = m_w \times 4.187 \times 10$

∴ Cooling water rate, $\dot{m}_w$

$$= \frac{202.429\,(2332.6 - 151)}{4.187 \times 10}$$

$$= 10547.4 \text{ kg/s} = \textbf{10547.4 kl/s.} \quad \textbf{(Ans.)}$$

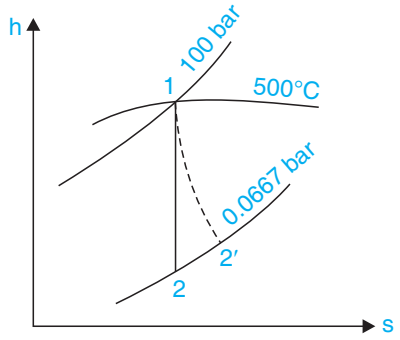


Fig. 3.161

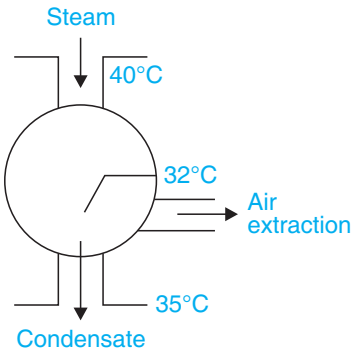


Fig. 3.162

(*b*) Specific volume of steam at inlet = xv_g

($\because$ v_g = 19.52 m³/kg at 40°C)

$$= 0.85 \times 19.52 = 16.59 \text{ m}^3/\text{kg}$$

Volume rate of steam at inlet,

$$V_1 = \frac{4000 \times 16.59}{60} = 1106 \text{ m}^3/\text{min.}$$

This is also the volume rate of air at inlet.

∴ Partial pressure of air at inlet,

$$p_{a1} = \frac{m_a R T_1}{V_1}$$

$$= \frac{16}{60} \times \frac{287 \times (273 + 40)}{1106} \times 10^{-3} \text{ kPa}$$

$$= 0.0216 \text{ kPa}$$

Partial pressure of steam at inlet, at 40°C

= 7.38 kPa.

∴ Total condenser pressure

= 7.38 + 0.0216 = 7.406 kPa

Partial pressure of steam at pump inlet (at 32°C)

= 4.76 kPa

∴ Partial pressure of air at pump suction,

p_{a2} = 7.406 – 4.76 = 2.646 kPa.

∴ *Dry air pump capacity,*

$$V_2 = \frac{m_a R T_2}{p_{a2} \times \eta_{vol}} = \frac{16}{60} \times \frac{287 \times (273 + 32)}{(2.646 \times 10^3) \times 0.8}$$

$$= \textbf{11.03 m}^3. \quad \textbf{(Ans.)}$$

(*c*) The total pressure in the condenser is the sum of partial pressures of water vapour and air. It remains constant at every section of the condenser, whereas the *partial pressure of steam depends upon the temperature at that section.*

In the condenser, air cooling section is provided near the air extraction pump suction. By circulating relatively cold water at this section the temperature is kept low, thereby *lowering the partial pressure of steam.* This serves *two functions :*

(*i*) This amount of steam lost to atmosphere (which is otherwise used as pure condensate for boiler feed) is considerably reduced.

(*ii*) The partial pressure of air in this section becomes considerably high, and so its density. For a given rate of air leakage into the condenser, the volume of air handled by the air-extraction pump is *reduced.* This enables the use of ***a small*** *capacity and power pump.*

Example 3.47. *A surface condenser with separate air pump for removing the air only and providing separate air-cooling section is designed to condense 20 tonnes of steam per hour. The air leakage per hour is 6 kg. The temperature of the condensate is 36°C and temperature near the suction of air pump is 28°C. The steam enters into the condenser at 39°C and dry-saturated condition. Find :*

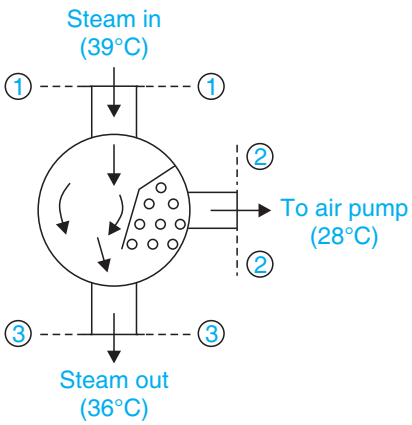
(*i*) *Percentage reduction in air-pump capacity due to separate air-cooling section.*

(*ii*) *Minimum quantity of cooling water if the rise in temperature is limited to 15°C.*

(*iii*) *Saving in the condensate and heat supply in the boiler per hour due to incorporation of air cooling section.*

The loss of condensation is made up with water at 15°C. **(P.U.)**

Solution. Refer to Fig. 3.163



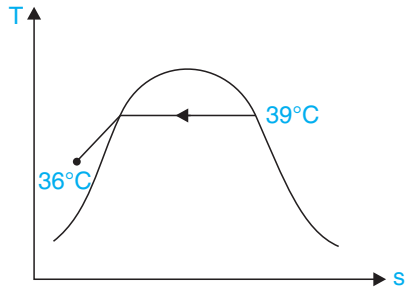


Fig. 3.163

Given : m_s = 20 tonnes/hour ; Air leakage, m_a = 6 kg/h ; t_1 = 39°C ; Condensate temperature, t_3 = 36°C ; Temp. near the suction of air pump, t_2 = 28°C

(*i*) Percentage reduction in air-pump capacity due to separate air-cooling section :

Consider section 1-1.

From steam tables, corresponding to t_1 = 39°C :

p_{s1} = 0.07 bar ;

v_{s1} = 20.53 m³/kg ;

h_{s1} = 2572.5 kJ/kg

Volume of steam entering the condenser,

$$V_{s1} = m_s \times v_{s1} = 20 \times 10^3 \times 20.53$$
$$= 410.6 \times 10^3 \text{ m}^3/\text{h}$$

By Dalton's law,

$$V_{a1} = V_{s1} = 410.6 \times 10^3 \text{ m}^3/\text{h}$$

Applying the equation of state to the air at 1-1, we have :

$$p_{a1} = \frac{m_{a1} R_a T_{a1}}{V_{a1}} = \frac{6 \times 287 (39 + 273)}{410.6 \times 10^3}$$

$$= 1.31 \text{ N/m}^2 \text{ or } 1.31 \times 10^{-5} \text{ bar}$$

$$\therefore \quad p_t = p_{s1} + p_{a1} = 0.07 + 1.31 \times 10^{-5}$$
$$= 0.070013 \text{ bar}$$

Consider section 2-2 :

From steam tables, corresponding to 28°C, we have :

p_{s2} = 0.0378 bar ;

v_{s2} = 36.69 m³/kg ;

h_{s2} = 2552.6 kJ/kg

$$p_{a2} = p_t - p_{s2} = 0.070013 - 0.0378$$
$$= 0.032213 \text{ bar}$$

Applying the equation of state to air at section 2-2, we get:

$$p_{a2} V_{a2} = m_a R_a T_2$$
$$0.032213 \times 10^5 \times V_{a2} = 6 \times 287 (28 + 273)$$
$$\therefore \quad V_{a2} = 160.9 \text{ m}^3/\text{h}$$

As per Daltor's law,

$$V_{s2} = V_{a2} = 160.9 \text{ m}^3/\text{h}$$

Let m_{s2} = Mass of steam carried away with air at section 2-2

$$\therefore \quad V_{s2} = m_{s2} \times v_{s2}$$
$$\text{or,} \quad 160.9 = m_{s2} \times 36.69$$
$$\text{or,} \quad m_{s2} = \frac{160.9}{36.69} = 4.38 \text{ kg/h}$$

Consider section 3-3 and air-pump is not used, then,

From steam tables, corresponding to 36°C, we have :

p_{s3} = 0.0595 bar ; v_{s3} = 23.94 m³/kg

Then, $p_{a3} = p_t - p_{s3} = 0.070013 - 0.0595$
$= 0.010513$ bar

Applying equation of state to air at section 3-3, we get:

$$p_{a3} V_{a3} = m_a R_a T_3$$
$$0.010513 \times 10^5 \times V_{a3}$$
$$= 6 \times 287 (36 + 273)$$
$$\therefore \quad V_{a3} = 506.13 \text{ m}^3/\text{h}$$
$$V_{s3} = V_{a3} = 506.13 \text{ m}^3/\text{h}$$
$$\text{But} \quad V_{s3} = m_{s3} \times v_{s3}$$
$$\text{or,} \quad 506.13 = m_{s3} \times 23.94$$
$$\therefore \quad m_{s3} = 21.14 \text{ kg/h}$$

$\therefore$ Percentage reduction in air pump capacity

$$= \frac{V_{a3} - V_{a2}}{V_{a3}} \times 100 = \frac{506.13 - 160.9}{506.13} \times 100$$
$$= \mathbf{68.21\%}. \quad \textbf{(Ans.)}$$

(*ii*) Minimum quantity of cooling water required ; m_w :

Applying energy balance to condenser, we have :

Heat lost by the steam and air = Heat gained by water + Heat in condensate

$$(m_{s1} h_{s1} - m_{s2} h_{s2}) + (m_{a1} h_{a1} - m_{a2} h_{a2})$$
$$= m_w (h_{w2} - h_{w1}) + m_c h_c$$
$$\text{or,} \quad (m_{s1} h_{s1} - m_{s2} h_{s2}) + (m_{a1} h_{a1} - m_{a2} h_{s2})$$
$$= m_w c_{pw} (\Delta t_w) + m_{s1} h_c$$
$$(m_c = m_{s1} \text{ ... assumed})$$

$\therefore\ m_w\, c_{pw}\, (\Delta t_w) = (m_{s1}h_{s1} - m_{s2}h_{s2})$
$+ (m_{a1}h_{a1} - m_{a2}h_{a2}) - m_{s1}h_c$

$m_w \times 4.18 \times 15 = (20 \times 10^3 \times 2572.5 - 4.38 \times 2552.6)$
$+ [6 \times 1.005 \times (39) - 6 \times 1.005 \times 28]$
$- 20 \times 10^3 \times 4.18 \times (36)$
(where $\Delta t_w = 15°C$ ..... Given)

$62.7\ m_w = [(51450 \times 10^3 - 11180) + 66.33$
$- 3009600]$
$= 48429.3 \times 10^3$

$\therefore\quad m_w \simeq 772.4 \times 10^3$ kg/h (or 772.4 tonnes/h)
$=$ **214.55 kg/s.** **(Ans.)**

(*iii*) Saving in condensate and heat supply in the boiler per hour :

Saving in condensate
$= m_{s3} - m_{s2} = 21.14 - 4.38$
$=$ **16.76 kg/h.** **(Ans.)**

Saving in heat supplied,
$Q = 16.76 \times 4.18\ (36 - 15)$
$=$ **1471.2 kJ/h.** **(Ans.)**

Example 3.48. *At a thermal power station where the boiler pressure is 80 bar and the required flow rate is 130 tonnes / hour, two multistage centrifugal pumps are used in series to pump water from the condenser to the boiler. Each pump is required to produce a head of approximately the total head and run at 1450 r.p.m. If the impellers in stages are identical and the specific speed of each impeller is not less than 15, find :*

(i) The head developed per stage and required number of stages in each pump.

(ii) The required impeller diameters, assuming the speed ratio based on the outer tip diameter to be 0.98 and the shaft power input, if the overall efficiency of each pump is 0.76.

What would you expect if the discharge valve is closed and pump is switched on ? What safety device would you recommend ? **(D.U.)**

Solution. Boiler pressure,
$p = 85$ bar ; flow rate = 130 tonnes/h
Speed of each pump,
$N = 1450$ r.p.m. ;
Specific speed of each impeller,
$N_s = 15$; speed ratio = 0.98
Overall efficiency of each pump,
$\eta_{op} = 0.76$

(*i*) Head developed per stage and no. of stages required in each pump :

$$\text{Total head} = \frac{p}{w} = \frac{80 \times 10^5}{9810} = 815.5 \text{ m}$$
($\because$ For water, $w = 9810$ N/m^3)

$$\text{Head per pump} = \frac{815.5}{2} = 407.75 \text{ m}$$

Let n_s = Number of stages per pump,

Then head per stage, $H = \dfrac{407.75}{n_s}$

Now, specific speed, $N_s = 15 = \dfrac{N\sqrt{Q}}{H^{3/4}}$

where $Q = \dfrac{(130 \times 1000) \times 9.81}{9810 \times 3600}$ m^3/s $= 0.0361$ m^3/s

$$\therefore\quad 15 = \frac{1450 \times \sqrt{0.0361}}{\left(\dfrac{407.75}{n_s}\right)^{3/4}}$$

or $$\left(\frac{407.75}{n_s}\right)^{3/4} = \frac{1450 \times \sqrt{0.0361}}{15} = 18.37$$

or $$\frac{407.75}{n_s} = (18.37)^{4/3} = 48.47$$

or $$n_s = \frac{407.75}{48.47} = 8.41$$

Actual number of stages in each pump = **8.** **(Ans.)**

Head developed per stage
$= \dfrac{407.75}{8} =$ **50.97 m.** **(Ans.)**

(*ii*) Diameter of each impeller (D) and shaft power input, P :

$$\text{Speed ratio} = 0.98 = \frac{u_2}{\sqrt{2gH}}$$

or $$0.98 = \frac{u_2}{\sqrt{2 \times 9.81 \times 50.97}}$$

or $$u_2 = 0.98 \times \sqrt{2 \times 9.81 \times 50.97} = 30.99 \text{ m/s}$$

Also, $$u_2 = \frac{\pi DN}{60} \text{ or } 30.99 = \frac{\pi D \times 1450}{60}$$

or $$D = \frac{30.99 \times 60}{\pi \times 1450}$$
$=$ **0.408 m or 408 mm.** **(Ans.)**

If the discharge valve is closed and pump is switched on, *a pressure wave will be reflected from the valve. A relief valve (safety device) may be used on the delivery side of the pump.*

HIGHLIGHTS

1. A steam power plant converts the chemical energy of the fossil fuels (coal, oil, gas) into mechanical/electrical energy.
2. The layout of a modern steam power plant comprises of the following four circuits :
   (*i*) Coal and ash circuit
   (*ii*) Ash and gas circuit
   (*iii*) Feed water and steam flow circuit
   (*iv*) Cooling water circuit.
3. The choice of steam conditions depends upon the following :
   (*i*) Price of a the coal
   (*ii*) Capital cost of the plant
   (*iii*) Time available for erection
   (*iv*) Thermal efficiency obtainable
   (*v*) The station 'load factor'.
4. Automatic stokers are classified as follows :
   (*i*) Overfeed stokers (*ii*) Underfeed stokers.
5. Pulverised fuel handling systems are classified as :
   (*i*) Unit system (*ii*) Central system.
6. Pulverised fuel burners are classified as follows :
   (*i*) Long flame burners (*ii*) Turbulent burners
   (*iii*) Tangential burners (*iv*) Cyclone burners.
7. Oil burners are classified as follows :
   1. Vapourising oil burners :
      (*a*) Atmospheric pressure atomising burner
      (*b*) Rotating cup burner
      (*c*) Recirculating burner
      (*d*) Wick type burner.
   2. Atomising fuel burners :
      (*a*) Mechanical or oil pressure atomising burner
      (*b*) Steam or high pressure atomising burner
      (*c*) Low pressure air atomising burner.
8. Fluidised bed may be defined as the bed of solid particles behaving as a fluid.
9. Ash handling systems may be classified as follows :
   (*i*) Mechanical handling system
   (*ii*) Hydraulic system
   (*iii*) Pneumatic system
   (*iv*) Steam jet system.
10. The dust collectors may be classified as follows :
    1. Mechanical just collectors
       (*i*) Wet type (scrubbers) : (*a*) Spray type ; (*b*) Packed type ; (*c*) Impingement type.
       (*ii*) Dry type : (*a*) Gravitational separators ; (*b*) Cyclone separators.
    2. Electrical dust collectors
       (*i*) Rod type (*ii*) Plate type.
11. The 'collection efficiency' of a dust collector is the amount of dust removed per unit weight of dust.
12. pH value of water is the logarithm of the reciprocal of hydrogen ion concentration. It is number from 0 to 14 with 7 indicating neutral number.
13. The small pressure difference which causes a flow of gas to take place is termed as a *draught*.
14. *Natural* draught is obtained by the use of a *chimney*. The draught produced by the chimney is due to density difference between the column of hot gases inside the chimney and the cold air outside.

$$h_w = 353\, H\left[\frac{1}{T_a} - \frac{1}{T_g}\left(\frac{m_a + 1}{m_a}\right)\right].$$

The draught pressure produced by the natural draught system in height of hot gases column,

$$H_1 = H\left[\left(\frac{m_a}{m_a + 1}\right) \times \frac{T_g}{T_a} - 1\right].$$

15. Diameter (D) of the chimney is given by,

$$D = 1.128\sqrt{\frac{\dot{m}_g}{\rho g \cdot C}}$$

where $\dot{m}_g$ = mass of gases flowing through any cross-section of the chimney
ρ_g = density of gases
C = velocity of gases passing through the chimney.

16. Condition for maximum discharge through a chimney is :

$$\frac{T_g}{T_a} = 2\left(\frac{m_a + 1}{m_a}\right).$$

17. Efficiency of chimney, $\eta_{\text{chimney}} = \dfrac{\dfrac{H}{J}\left[\left(\dfrac{m_a}{m_a + 1}\right) \times \dfrac{T_g}{T_a} - 1\right]}{c_p\,(T' - T'')}$

where T' = absolute temperature of flue gases leaving the chimney to create the draught of h_w mm of water
T'' = absolute temperature of flue leaving the chimney in case of artificial draught of h_w mm of water.

18. Power required to drive fan :

$$\text{Power of F.D. fan} = 0.998 \times 10^{-8}\left(\frac{hV_a\, m_a MT_a}{\eta_f}\right) \text{kW}$$

$$\text{Power of I.D. fan} = 0.998 \times 10^{-8}\left(\frac{hV_a\, m_a MT_g}{\eta_f}\right) \text{kW}.$$

19. A '*boiler*' is defined as a closed vessel in which steam is produced from water by combination of fuel.
20. Heated feed water enables steam generators to produce more kg of steam and avoids severe thermal stressing by cold water entering a hot drum.
21. 'Equivalent evaporation' may be defined as the amount of water evaporated from water at 100°C to dry and saturated steam at 100°C.
22. A steam nozzle may be defined as a passage of varying cross-section, through which heat energy of steam is converted to kinetic energy.
23. The velocity, $C = 44.72\sqrt{kh_d}$ ..... in SI units
    $C = 91.5\sqrt{kh_d}$ ..... in MKS units

24. Critical pressure ratio,

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

..... condition for maximum discharge.

25. The most important classification of steam turbines is as follows :

(*i*) Impulse turbines (*ii*) Reaction turbines

(*iii*) Combination of impulse and reaction turbines.

26. Force (tangential) on the wheel = $\dot{m}_s(C_{w_1} + C_{w_0})$ Nm

$$\left[= \frac{\dot{m}_s}{g}(C_{w_1} + C_{w_0}) \quad \text{...in MKS units.}\right]$$

Power per wheel $= \dfrac{\dot{m}_s(C_{w_1} + C_{w_0}) \times C_{bl}}{1000}$ kW

$$\left[\text{H.P. per wheel} = \frac{\dot{m}_2\,(C_{w_1} + C_{w_0}) \times C_{bl}}{g \times 75} \quad \text{... is MKS units.}\right]$$

Blade or diagram efficiency, $\eta_{bl} = \dfrac{2C_{bl}(C_{w_1} + C_{w_0})}{C_1^{\,2}}$

Stage efficiency, $\eta_{\text{stage}} = \dfrac{C_{bl}(C_{w_1} + C_{w_0})}{(h_1 - h_2)}$

$$\left[= \frac{C_{bl}\,(C_{w_1} + C_{w_0})}{gJ\,(h_1 - h_2)} \quad \text{... in MKS units.}\right]$$

27. The axial thrust on the wheel due to difference between the velocities of flow at entrance and outlet.

Axial force on the wheel = $\dot{m}_s(C_{f_1} - C_{f_0})$.

$$\left[= \frac{\dot{m}_g}{g}(C_{f_1} - C_{f_0}) \quad \text{..... in MKS units.}\right]$$

28. Energy converted to heat by blade friction = Loss of kinetic energy during flow over blades

$$= \dot{m}_s(C_{r_1}^{\,2} - C_{r_0}^{\,2}).$$

$$\left[= \frac{\dot{m}_s}{g}(C_{r_1}^{\,2} - C_{r_0}^{\,2}) \quad \text{..... in MKS units.}\right]$$

29. Optimum value of ratio of blade speed to steam speed is,

$$\rho_{opt.} = \frac{\cos\alpha}{4}.$$

In general optimum blade speed ratio for maximum blade efficiency or maximum work done is given by

$$\rho_{opt.} = \frac{\cos\alpha}{2n}$$

and the work done in the last row = $\dfrac{1}{2^n}$ of total work,

where n is the number of moving rotating blade rows in series.

30. The degree of reaction of reaction turbine stage is defined as the ratio of heat drop over moving blades to the total heat drop in the stage.

31. The blade efficiency of the reaction turbine is given by

$$\eta_{bl} = 2 - \frac{2}{1 + 2\rho\cos\alpha - \rho^2};$$

η_{bl} becomes maximum when, $\rho = \cos\alpha$

and hence, $(\eta_{bl})_{\max} = \dfrac{2\cos^2\alpha}{1 + \cos^2\alpha}$.

32. The principal methods of steam governing are as follows :

(*i*) Throttle governing

(*ii*) Nozzle governing

(*iii*) By-pass governing

(*iv*) Combination of (*i*), (*ii*) and (*iii*).

33. Condenser efficiency is defined as the ratio of the difference between the outlet and inlet temperatures of cooling water to the difference between the temperature corresponding to the vacuum in the condenser and inlet temperature of cooling water.

34. The quantity of cooling water, m_w is formed by the following expression :

$$m_w = \frac{m_s[xh_{fg} + c_{pw}\,(t_s - t_{w_2})]}{c_{pw}\,(t_{w_2} - t_{w_1})} \text{ kg/h}$$

..... Jet condenser.

$$m_w = \frac{m_s[xh_{fg} + c_{pw}\,(t_s - t_c)]}{c_{pw}\,(t_{w_2} - t_{w_1})} \text{ kg/h}$$

.....Surface condenser.

THEORETICAL QUESTIONS

1. How are steam power plants classified ?
2. Give the layout of a modern steam power plant and explain it briefly.
3. What are the essential requirements of steam power station design ?
4. What factors should be taken into consideration while selecting the site for steam power plant ?
5. How can the capacity of a steam power plant be determined ?
6. On factors does the choice of steam conditions depend ?
7. Enumerate the means by which the coal from coal mines can be transported.
8. What are the requirements of good coal handling plant ?
9. Enumerate and explain the steps involved in handling of the coal.
10. Explain with the help of a neat diagram the arrangement of the Fluidised bed combustion (FBC) system.
11. State the characteristics of a good ash handling plant.
12. Enumerate and explain various modern ash-handling systems.
13. How are dust collectors classified ?
14. Explain with the help of a diagram the working of a 'cyclone separator'.
15. How do you define the 'collection efficiency' of a dust separator ?
16. What are the uses of ash and dust ?

17. Give the general layout of ash handling and dust collection system.
18. What is the function of a boiler chimney ?
19. Why is there no chimney in the case of a locomotive boiler ?
20. What do you understand by the term "Boiler draught" ?
21. What are the limitations of chimney draft ?
22. Define the chimney efficiency and find out expression for the same.
23. What are the various types of draughts used in usual practice ?
24. What are the advantages of artificial draught over natural draught ?
25. What do you understand by steam jet draught ? Where is it general employed ?
26. How are boilers classified ?
27. Explain the unique features of the high pressure boilers.
28. Explain with neat sketches the construction and working of any two of the following high pressure boilers ?
    (*i*) LaMont boiler (*ii*) Loeffler boiler
    (*iii*) Benson boiler (*iv*) Velox boiler.
29. Write short notes on the following :
    (*i*) Supercharged boilers (*ii*) Supercritical boilers.
30. Why are the accessories used in a boiler ?
31. Explain briefly any two of the following boiler accessories :
    (*i*) Economiser
    (*ii*) Air preheater
    (*iii*) Superheater.
32. How are feed water heaters classified ?
33. What is an evaporator ? How are evaporators they classified ?
34. Define the following :
    (*i*) Equivalent evaporation
    (*ii*) Factor of evaporation
    (*iii*) Boiler efficiency.
35. Define the term 'steam nozzle'. Explain various types of nozzles.
36. What is the effect of friction on the flow through a steam nozzle? Explain with the help of a *h-s* diagram.
37. What do you mean by a super-saturated flow ? Explain with the help of *h-s* diagram.
38. Define the following in relation to steam turbines :
    (*i*) Speed ratio
    (*ii*) Blade velocity coefficient
    (*iii*) Diagram efficiency
    (*iv*) Stage efficiency.
39. Discuss various methods of compounding steam turbines.
40. Describe briefly the various methods of 'steam turbine governing'.
41. Define a steam condenser and state its functions.
42. Explain the reasons for inefficiency in surface condensers.
43. Explain the effects of air leakage in a condenser.
44. What is a cooling tower ? How are cooling towers classified ? Explain any one of them with a neat sketch.
45. How are impurities in water classified ?
46. Enumerate various methods of feed water treatment.
47. Explain briefly any two of the following methods of feed water treatment :
    (*i*) Sodium zeolite process
    (*ii*) Deaeration
    (*iii*) Coagulation.
48. What are the requirements of steam piping system ?
49. List the advantages and disadvantages of steam power plants.
50. Give comparison between steam, hydroelectric, diesel and nuclear power plants.

UNSOLVED EXAMPLES

CHIMNEY DRAUGHT

1. Calculate the quantity of air supplied per kg of fuel burnt in the combustion chamber of a boiler when the required draught of 1.85 cm of water is produced by a chimney of 32 m height. The temperatures of the flue gases and ambient air recorded are 370°C and 30°C respectively. [**Ans.** 15.3 kg]
2. Determine the draught produced in cm of water by a chimney of 50 metres height when the temperature of the flue gases passing through the chimney is such that the mass of flue gases discharge is maximum in a given time. The ambient air temperature is 20°C. [**Ans.** 30.2 mm]
3. A boiler is provided with a chimney of 24 m height. The ambient temperature is 25°C. The temperature of flue gases passing through the chimney is 300°C. If the air flow through the combustion chamber is 20 kg/kg of fuel burnt, find (*i*) the theoretical draught in cm of water, (*ii*) velocity of the flue gases passing through the chimney if 50% of the theoretical draught is lost in friction at grate and passage. [**Ans.** 12.9 mm of water, 14 m/s]
4. A forced draught fan discharges 1,200 m^3 of air per minute through the outlet of 2.1 m^2 and maintains a static pressure of 10 cm of water. The temperature of air is 27°C. Calculate the BHP of the motor to drive the forced draught fan if the efficiency of the fan is 80%. Assume that the weight of 1 m^3 of air at N.T.P. is 1.293 kg. [**Ans.** 35.15]
5. Calculate the quantity of air required per kg of coal burnt in a boiler fitted with 32 m high stack. Draught produced is 18.5 mm of water when the temperature of flue gases in the chimney is 370°C and that of boiler house is 30°C. Calculate also the draught produced in terms of height of a column of hot gas in metres. [**Ans.** 15.3 kg, 31.65 m]
6. Forced draught fan delivers air at 10 m/s against a draught of 25 mm of water across the fuel bed on the grate. Determine the H.P. required to drive the fan if 10000 kg of coal is burnt per hour with 13 kg of air required per kg of coal burnt. Barometer reading is 1 kgf/cm^2. Boiler house temperature is 20°C. Assume the efficiency of the fan to be 81.5 per cent. [**Ans.** 16]

7. With a chimney of height 40 metres, the temperature of flue gases with natural draught was 350°C. The same draught was developed by induced draught fan and the temperature of the flue gases was 150°C. Mass of the flue gases formed is 20 kg per kg of coal fired. The boiler house temperature is 38°C. Determine the efficiency of the chimney. Assume c_p = 0.24 kcal/kg K for the flue gases.
[**Ans.** 1.177%]

8. In a steam power plant, the height of the chimney installed is 30 metres. When the plant was working with natural draught, the temperature of the gases was observed to be 327°C. Induced fan was installed and same draught was produced with the temperature of gases falling to 227°C. The gases formed per kg of coal amount to 20 kg. The atmospheric air temperature of surrounding is 27°C. Determine the efficiency of the chimney. Assume c_p = 0.25 kcal/kg °C for gases. [**Ans.** η = 0.254%]

9. A steam plant developing 1500 H.P. has a 55 m high chimney. The coal consumption is 2.27 kg/H.P. hr and air supplied is 19 kg/kg of fuel burnt. Assume an air temperatures of 30°C and the discharge through the chimney is maximum, find the diameter of the chimney.
[**Ans.** 1.12 m]

10. A boiler is to use 1500 kg of coal per hour with the formation of 16 kg of flue gases per kg of fuel burnt. The draught losses are given below :
Loss through the grate = 4.5 mm of water ; loss through the flues = 7.8 mm of water ; loss through bends etc. = 3.4 mm of water ; head equivalent to velocity of gas flow = 0.5 mm of water.
The average temperature of the outside air is 27°C and the chimney gases have a mean temperature of 25°C. The actual draught produced may be assumed to be 80% of the theoretical draught, and the velocity of flow coefficient may be assumed to be 0.35, find the height and diameter of the chimney. [**Ans.** H = 44.25 m, D = 2.8 m]

11. In a boiler plant a draught of 33.25 m column of hot gases is produced with the help of a chimney of 42.5 m height. The mass of flue gases formed per kg of flue burnt is 20 kg. Assuming an ambident air temperature of 33°C, find the following :
(*i*) Temperature of flue gases leaving the chimney.
(*ii*) Extra heat carried away by flue gases if the same draught can be produced by forced draught fan reducing the gas temperature to 120°C which is the limit imposed due to condensation of water vapour. Take c_p (for flue gases) = 0.25 kcal/kg °C.
(*iii*) Efficiency of the chimney.
(*iv*) Percentage of heat of fuel used for creating the draught.
(*v*) Temperature of chimney gases and corresponding draught for the condition of maximum discharge through the chimney. Take calorific vaue of fuel = 7500 kcal/kg.
[**Ans.** (*i*) 302°C, (*ii*) 45.5 kcal/kg of gas, (*iii*) 0.1712%, (*iv*) 12.13%, (*v*) 372°C and 24.5 mm of water column]

PERFORMANCE OF BOILERS

12. 8 kg of steam is produced at 14 bar and 0.95 dryness in a boiler fed with water at 39°C, per kg of coal consumed. Determine the equivalent evaporation from and at 100°C.
[**Ans.** 8.96 kg/kg of coal]

13. A boiler with superheater generates 6000 kg/hour of steam at 15 bar and 0.8 dryness. The boiler exit temperature is 300°C. The feed water temperature is 80°C. The overall efficiency of the plant is 85%. Determine the consumption rate, assuming a calorific value of 30,000 kJ/kg. Also find the equivalent evaporation from and at 100°C. What will be the area of superheater surface if the overall heat transfer coefficient is 450,000 kJ/m^2-h ?
[**Ans.** 646 kg/h, 7200 kg/h, 3.86 m^2]

14. A boiler generates 500 kg/hour of steam at 18 bar the steam temperature being 325°C. The feed water temperature is 49.4°C. The efficiency of the boiler is 80%. When using oil of calorific value 44,500 kJ/kg, the steam generated is supplied to a turbine developing 500 kW, and exhausting at 1.8 bar, the dryness of exhaust steam 0.98. Calculate the oil burnt per hour and turbine efficiency. Also find the energy available in the exhaust steam above 49.4°C.
[**Ans.** 2448.8 kJ/kg]

15. 5400 kg of steam is produced per hour at a pressure of 7.5 bar in a boiler with feed water at 41.5°C. The dryness fraction of steam at exit is 0.98. The amount of coal burnt per hour is 670 kg of calorific value 31000 kJ/kg. Determine :
(*i*) The boiler efficiency (*ii*) Equivalent evaporation.
[**Ans.** (*i*) 66.2%, (*ii*) 9.12 kg/kg of coal]

16. A boiler with superheater generates 600 kg/hour of steam at 15 bar and 0.98 dryness. The boiler exit temperature is 300°C. The feed water temperature is 80°C. The overall efficiency of the plant is 85%.
(*i*) Determine the coal consumption rate if calorific value of coal is 30,000 kJ/kg.
(*ii*) Find the equivalent evaporation from and at 100°C.
(*iii*) What will be the area of superheater surface if the overall heat transfer coefficient is 450000 kJ/m^2-h ?
[**Ans.** (*i*) 646 kg/h, (*ii*) 7200 kg/h-m, (*iii*)3.86 m^2]

17. During a boiler trial the following observations were made :
Duration of trial = 1 hour ; steam generated = 35500 kg ; steam pressure = 12 bar ; steam temperature = 250°C ; temperature of water entering economiser = 17°C, temperature of water leaving economiser = 77°C ; oil burnt = 3460 kg ; calorific value of oil = 39500 kJ/kg.
Calculate :
(*i*) Equivalent evaporation per kg of fuel
(*ii*) Thermal efficiency of plant
(*iii*) Percentage of heat energy of the fuel energy utilised by the economiser.
[**Ans.** (*i*) 13.02 kg, (*ii*) 74.4%, (*iii*) 6.52%]

18. In a boiler trial of one hour duration the following observations were made :
Steam generated = 5250 kg ; coal burnt = 695 kg ; calorific value of coal = 30200 kJ/kg ; dryness fraction of steam = 0.94 ; rated pressure of the boiler = 12 bar ; temperature of steam leaving the superheater = 240°C ; temperature of hot well = 47°C.
Calculate :
(*i*) Equivalent evaporation per kg of fuel without superheater.
(*ii*) Equivalent evaporation per kg of coal with superheater.

(*iii*) Thermal efficiency of the boiler without superheater.
(*iv*) Thermal efficiency of boiler with superheater.
(*v*) Heat supplied by the superheater per hour.
Take c_p of steam 2.184.
[**Ans.** (*i*) 8.26 kg/kg of fuel, (*ii*) 9.04 kg/kg of fuel, (*iii*) 61.7%, (*iv*) 67.53%, (*v*) 1.22×10^5 kJ/h]

19. A boiler is provided with an economiser and a superheater. The steam is generated at 21 bar and 0.97 dry. This steam is passed onto a superheater and it leaves the superheater at 250°C. Feed water is supplied to the economiser at 38°C and leaves the economiser at 77°C. The quantity of feed water supplied is 10 kg/kg of fuel which has a calorific value of 32600 kJ/kg. Determine :
(*i*) Efficiency of the entire boiler plant.
(*ii*) Percentage of heat received in the economiser.
(*iii*) Percentage of heat received in the superheater.
[**Ans.** (*i*) 88.9%, (*ii*) 5.6%, (*iii*) 3.4%]

20. The following observations were made during a boiler trial :
Weight of feed water = 1520 kg/h ; temperature of feed water = 30°C ; steam pressure = 8.5 bar ; steam temperature = 172.9°C ; dryness fraction of steam = 0.95 ; coal burnt = 200 kg/hour ; calorific value of coal = 27200 kJ/kg ; ash and unburnt coal collected = 16 kg/hour ; calorific value of ash and unburnt coal = 2720 kJ/kg ; weight of flue gases = 17.3 kg/kg of coal, temperature of flue gases = 330°C ; boiler room temperature = 18°C ; c_p for gases = 1.006 kJ/kg °C.
Calculate the boiler efficiency. [**Ans.** 70%]

21. Compare the thermal efficiency of two boilers for which the data are given below :

	Boiler 1	*Boiler 2*
Steam pressure	14 bar	14 bar
Steam produced per kg of coal fired	10 kg	14 kg
Quality of steam	0.9 dry	uperheated to 240°C
Feed water temperature	27°C	27°C
Calorific value of fuel	3400 kJ/kg	46000 kJ/kg

Specific heat of feed water is 4.18 kJ/kg K and specific heat of steam is 2.1 kJ/kg K.
Which boiler is more efficient = ?
[**Ans.** $\eta_{\text{boiler 1}} = 7.3\%$, $\eta_{\text{boiler 2}} = 79.5\%$]

STEAM NOZZLES

22. Dry saturated steam enters a steam nozzle at pressure of 12 bar and is discharged to a pressure of 1.5 bar. If the dryness fraction of a discharged steam is 0.95 what will be the final velocity of steam ? Neglect initial velocity of steam. If 12% of the heat drop is lost in friction, find the percentage reduction in the final velocity.
[**Ans.** 633.3 m/s, 6.2%]

23. In a steam nozzle, the steam expands from 3 bar to 1.0 bar. The initial velocity is 90 m/s and initial temperature is 150°C. The nozzle efficiency is 0.95. Determine the exit velocity. [**Ans.** 594 m/s]

24. Steam initially dry and saturated is expanded in a nozzle from 12 bar to 0.95 bar. If the frictional loss in the nozzle is 10% of the total heat drop, calculate the mass of steam discharged when exit diameter of the nozzle is 12 mm.
[**Ans.** 224.3 kg/h]

25. The inlet conditions of steam to a convergent-divergent nozzle is 22 bar and 260°C. The exit pressure is 4 bar. Assuming frictionless flow upto the throat and a nozzle efficiency of 85%, determine :
(*i*) The flow rate for a throat area of 32.2 cm^2.
(*ii*) The exit area. [**Ans.** (*i*) 11 kg/s ; (*ii*) 60.5 cm^2]

26. In a steam nozzle, dry and saturated steam is expanded from 10 bar to 0.1 bar. Using steam tables, calculate :
(*i*) Dryness fraction of steam at exit
(*ii*) Heat drop
(*iii*) The velocity of steam at exit from the nozzle when initial velocity is 135 m/s.
[**Ans.** (*i*) 0.79 ; (*ii*) 694 kJ/kg ; (*iii*) 1185.8 m/s]

27. Determine throat area, exit area and exit velocity for a steam nozzle to pass 0.2 kg/s when the inlet conditions are 12 bar and 250°C and the final pressure is 2 bar. Assume that the expansion is isentropic and that the inlet velocity is negligible. Take $n = 1.3$ for superheated steam.
[**Ans.** 1.674 cm^2; 2.015 cm^2; 831.6 m/s]

28. The inlet conditions to a steam nozzle are 10 bar and 250°C. The exit pressure is 2 bar. Assuming isentropic expansion and negligible velocity, determine :
(*i*) The throat area. (*ii*) The exit velocity.
(*iii*) The exit area of the nozzle.
[**Ans.** (*i*) 1.44 cm^2 ; (*ii*) 795 m/s ; (*iii*) 2.15 cm^2]

29. Dry saturated steam is passed at 7 bar through a convergent-divergent nozzle. The throat cross-sectional area is 4.5 cm^2. Find the mass of steam passing through the nozzle per minute. [**Ans.** 27 kg/min.]

IMPULSE TURBINES

30. A steam jet enters the row of blades with a velocity of 380 m/s at an angle of 22° with the direction of motion of the moving blades. If the blade speed is 180 m/s and there is no thrust on the blades, determine the inlet and outlet blade angles. Velocity of steam while passing over the blades is reduced by 10%. Also determine the power developed by turbine when the rate of flow of steam is 1000 kg per minute. [**Ans.** 879 kW]

31. In a simple impulse turbine, the nozzles are inclined at 20° to the direction of motion of moving blades. The steam leaves the nozzles at 375 m/s. The blade speed is 165 m/s. Find suitable inlet and outlet angles for the blades in order that the axial thrust is zero. The relative velocity of steam as it flows over the blades is reduced by 15% by friction. Determine also the power developed for a flow rate of 10 kg/s. [**Ans.** 34°, 41°, 532 kW]

32. In an impulse turbine the nozzles are inclined at 24° to the plane of rotation of the blades. The steam speed is 1000 m/s and blade speed is 400 m/s. Assuming equiangular blades, determine :
(*i*) Blade angles
(*ii*) Force on the blades in the direction of motion
(*iii*) Axial thrust
(*iv*) Power developed for a flow rate of 1000 kg/h.
[**Ans.** (*i*) 39°, (*ii*) 1.135 kN, (*iii*) 113.5 kW]

33. In a De Laval turbine, the steam issues from the nozzles with a velocity of 850 m/s. The nozzle angle is 20%. Mean blade velocity is 350 m/s. The blades are equiangular. The mass flow rate is 1000 kg/min. Friction factor is 0.8. Determine : (*i*) blade angles, (*ii*) axial thrust on the end bearing, (*iii*) power developed in kW, (*iv*) blade efficiency, (*v*) stage efficiency, if nozzle efficiency is 93%.

[**Ans.** (*i*) 33°, 33°, (*ii*) 500 N, (*iii*) 4666.7 kW, (*iv*) 77.5%, (*v*) 72.1%]

34. In a single stage impulse turbine the nozzles discharge the steam on to the blades at an angle of 25° to the plane of rotation and the fluid leaves the blades with an absolute velocity of 300 m/s at an angle of 120° to the direction of motion of the blades. If the blades have equal inlet and outlet angles and there is no axial thrust, estimate :

(*i*) Blade angle

(*ii*) Power produced per kg/s flow of steam

(*iii*) Diagram efficiency. [**Ans.** (*i*) 36.3°, (*ii*) 144 kW, (*iii*) 0.762]

35. Steam enters the blade row of an impulse turbine with a velocity of 600 m/s at an angle of 25° to the plane of rotation of the blades. The mean blade speed is 255 m/s. The blade angle on the exit side is 30°. The blade friction coefficient is 10%. Determine :

(*i*) Work done per kg of steam

(*ii*) Diagram efficiency

(*iii*) Axial thrust per kg of steam/s.

[**Ans.** (*i*) 150.45 kW, (*ii*) 83.6%, (*iii*) 90 N]

36. The nozzles of an impulse turbine are inclined at 22° to the plane of rotation. The blade angles both at inlet and outlet are 36°. The mean diameter of the blade ring is 1.25 m and the steam velocity is 680 m/s. Assuming shockless entry determine :

(*i*) the speed of the turbine rotor in r.p.m.,

(*ii*) the absolute velocity of steam leaving the blades, and

(*iii*) the torque on the rotor for a flow rate of 2500 kg/h.

[**Ans.** (*i*) 4580 r.p.m., (*ii*) 225 m/s, (*iii*) 290.5 Nm]

37. A single stage steam turbine is provided with nozzles from which steam is released at a velocity of 1000 m/s at an angle of 24° to the direction of motion of blades. The speed of the blades is 400 m/s. The blade angles at inlet and outlet are equal. Find :

(*i*) Inlet blade angle,

(*ii*) Force exerted on the blades in the direction of their motion,

(*iii*) Power developed in kW for steam flow rate of 40,000 kg/h. Assuming that the steam enters and leaves the blades without shock.

[**Ans.** (*i*) 30°, (*ii*) 1135 N, (*iii*) 4540 kW]

38. In a single row impulse turbine the nozzle angle is 30° and the blade speed is 215 m/s. The steam speed is 550 m/s. The blade friction coefficient is 0.85. Assuming axial exit and a flow rate of 700 kg/h, determine :

(*i*) Blade angles

(*ii*) Absolute velocity of steam at exit

(*iii*) The power output of the turbine.

[**Ans.** (*i*) 46°, 49° ; (*ii*) 243 m/s ; (*iii*) 19.8 kW]

39. In a steam turbine, steam expands from an inlet condition of 7 bar and 300°C with an isentropic efficiency of 0.9. The nozzle angle is 20°. The stage operates at optimum blade speed ratio. The blade inlet angle is equal to the outlet angle. Determine :

(*i*) Blade angles

(*ii*) Power developed if the steam flow rate is 0.472 kg/s.

[**Ans.** (*i*) 36°, (*ii*) 75 kW]

40. Steam at 7 bar and 300°C expands to 3 bar in an impulse stage. The nozzle angle is 20°, the rotor blades have equal inlet and outlet angles and the stage operates with the optimum blade speed ratio. Assuming that isentropic efficiency of nozzles is 90% and velocity at entry to the stage is negligible, deduce the blade angles used and the mass flow required for this stage to produce 50 kW.

[**Ans.** 36°, 0.317 kg/s]

41. In a two stage velocity compounded steam turbine, the mean blade speed is 150 m/s while the steam velocity as it is issued from the nozzle is 675 m/s. The nozzle angle is 20°. The exit angle of first row moving blade, fixed blade and the second row moving blades are 25°, 25° and 30° respectively. The blade friction coefficient is 0.9. If the steam flow rate is 4.5 kg/s, determine :

(*i*) Power output (*ii*) Diagram efficiency.

[**Ans.** (*i*) 807 kW; (*ii*) 78.5%]

REACTION TURBINES

42. At a particular stage of reaction turbine, the mean blade speed is 60 m/s and the steam pressure is 3.5 bar with a temperature of 175°C. The identical fixed and moving blades have inlet angles of 30° and outlet angles of 20°. Determine :

(*i*) The blade height if it is $\frac{1}{10}$th of the blade ring diameter, for flow rate of 13.5 kg/s.

(*ii*) The power developed by a pair.

(*iii*) Specific enthalpy drop if the stage efficiency is 85%.

[**Ans.** (*i*) 64 mm, (*ii*) 218 kW, (*iii*) 19.1 kJ/kg]

43. In a stage of impulse reaction turbine operating with 50% degree of reaction, the blades are identical in shape. The outlet angle of the moving blades is 19° and the absolute discharge velocity of steam is 100 m/s in the direction at 100° to the motion of the blades. If the rate of flow of steam through the turbine is 15000 kg/h, calculate the power developed by the turbine in kW. [**Ans.** 327.5 kW]

44. At a stage in a reaction turbine the pressure of steam is 0.34 bar and the dryness 0.95. For a flow rate of 36000 kg/h, the stage develops 950 kW. The turbine runs at 3600 r.p.m. and the velocity of flow is 0.72 times the blade velocity. The outlet angle of both rotator and rotor blades is 20°. Determine at this stage :

(*i*) Mean rotor diameter, (*ii*) Height of blades.

[**Ans.** (*i*) 0.951 m, (*ii*) 115 mm]

45. In a multi-stage reaction turbine at one of the stages the rotor diameter is 1250 mm and speed ratio 0.72. The speed of the rotor is 3000 r.p.m. Determine :

(*i*) The blade inlet angle if the outlet blade angle is 22°,

(*ii*) Diagram efficiency,

(*iii*) The percentage increase in diagram efficiency and rotor speed if turbine is designed to run at the best theoretical speed.

[**Ans.** (*i*) 61.5°, (*ii*) 82.2%, (*iii*) 30.47%]

46. In a 50 per cent reaction turbine stage running at 3000 r.p.m., the exit angles are 30° and the inlet angles are 50°. The mean diameter is 1 m. The steam flow rate is 10000 kg/min and the stage efficiency is 85%. Determine :

(*i*) Power output of the stage.

(*ii*) The specific enthalpy drop in the stage.

(*iii*) The percentage increase in relative velocity of steam when it flows over the moving blades.

[**Ans.** (*i*) 11.6 MW, (*ii*) 82 kJ/kg, (*iii*) 52.2%]

47. Twelve successive stages of a reaction turbine have blades with effective inlet and outlet angles of 80° and 20° respectively. The mean diameter of the blade row is 1.2 m and the speed of rotation is 3000 r.p.m. Assuming constant velocity of flow throughout, estimate the enthalpy drop per stage.

For a steam inlet condition of 10 bar and 250°C and on outlet condition of 0.2 bar, estimate the stage efficiency.

Assume a reheat factor of 1.04, determine the blade height at a stage where the specific volume is 1.02 m^3/kg.

[**Ans.** 40.4 kJ/kg, 70.3%, 57 mm]

STEAM CONDENSERS

48. A prime mover uses 16,000 kg of steam per hour and develops 2600 kW. The steam is supplied at 30 bar and 300°C. The exhaust from the prime mover is condensed at 725 mm Hg (0.984895 bar) when barometer records 755 mm Hg (1.006584 bar). The condensate temperature from the condenser is 30°C and the rise of temperature of circulating water is from 7°C to 17°C. Determine :

(*i*) The quality of steam entering the condenser.

(*ii*) The quantity of circulating cooling water and the ratio of cooling water.

Assume all mechanical drive losses are negligible and no air is present in the condenser.

[**Ans.** (*i*) 0.9496, (*ii*) 873028 kg/h, 54.56 kg/kg]

49. The observations recorded during the trial on a steam condenser are given below :

Condenser vacuum = 685 mm Hg ; Barometer reading = 765 mm Hg ; Mean condensate temperature = 34°C ; Hot well temperature = 28°C ; Condensate formed per hour = 1750 kg ; Circulating cooling water inlet temperature = 18°C, Circulating cooling water outlet temperature = 30°C ; Quantity of cooling water = 1300 kg/min.

Determine :

(*i*) Vacuum efficiency,

(*ii*) Undercooling of condensate,

(*iii*) Condenser efficiency,

(*iv*) Condition of steam as it enters the condenser,

(*v*) Mass of air per kg of uncondensed steam.

Take : R for air = 0.287 kJ/kg K.

Specific heat of water = 4.186 kJ/kg K.

[**Ans.** (*i*) 94.47%, (*ii*) 6°C, (*iii*) 37.5%, (*iv*) 0.898, (*v*) 1.613 kg]

50. A surface condenser is fitted with separate air and condensate outlets. A portion of the cooling surface is screened from the incoming steam and the air passes over these screened tubes to the air extraction and becomes cooled below the condesate temperature. The condenser receives 20000 kg/h of steam dry saturated at 36.2°C. At condensate outlet, the temperature is 34.6°C, and at the air extraction the temperature is 29°C. The volume of air plus vapour leaving the condenser is 3.8 m^3/min. Assuming constant pressure throughout the condenser, calculate :

(*i*) The mass of air removed per 10000 kg of steam.

(*ii*) The mass of steam condensed in the air cooler per minute.

(*iii*) The heat to be removed per minute by the cooling water.

Neglect the partial pressure of the air inlet to the condenser.

[**Ans.** (*i*) 2.63 kg, (*ii*) 0.492 kg, (*iii*) 807050 kJ]

51. Separate air pump and water pump are installed in a condenser. Steam enters the condenser at 40°C and condensate is removed at 37°C. The quantity of air infilrating into the condenser through various zones is 5 kg/hour.

(*i*) What will be the volume of air handled by the air pump?

(*ii*) What will be the quantity of handled by a combined air and condensate pump at 38°C?

Make suitable assumptions and list all such assumptions. [**Ans.** (*i*) 400.8 m^3/h ; (*ii*) 776 m^3/h]

COMPETITIVE EXAMINATIONS QUESTIONS

1. An input-output curve of a 10 MW thermal station is given by an equation :

$$I = 10^6 (18 + 12L + 0.5 L^2) \text{ kcal/hr}$$

where I is in kcal per hour and L is the load on power plant in MW.

Find out (*a*) the load at which the efficiency of the plant will be maximum, and (*b*) the increase in input required to increase the station output from 5 MW to 7 MW by using the input-output equation and by incremental rate curve.

2. (*a*) Explain the different methods used for supplying pulverised fuel to the combustion chambers of the boilers. Discuss the advantages and disadvantages of each.

(*b*) Draw a neat diagram of a cyclone burner and describe its working. What are its outstanding features compared with other burners ? Why are such burners useful for Indian coal ?

3. (*a*) How does dust collection system differ from ash collection ? Explain the working of electrostatic precipitator with neat diagram.

(*b*) It is required to estimate the equivalent evaporation and efficiency of the boiler from the data given below :

Quantity of steam generated = 5500 kg/hour

Condition of steam generated = 8.5 kgf/cm^2 and 0.98 dry

Temperature of feed water = 36.5°C
Coal consumption = 680 kg/hour
Calorific value of coal = 7450 kcal/kg

If by fitting an economiser, the temperature of feed water is raised to 100°C, what will be saving in coal consumption per hour if the other data remains unchanged and there is 5% increase in the efficiency of the boiler ?

4. (*a*) What are the different methods of burning solid coal on a grate ?
(*b*) Explain the over-feed system of combustion.
(*c*) Explain with the help of neat diagram spreader stoker and also explain its advantages over other type of stoker.

5. (*a*) Sketch and describe the elements of a hydraulic ash handling system for slag tap furnace.
(*b*) (*i*) What is the purpose of feed water heating in a steam power plant ?
(*ii*) What are the different types of feed water heaters ?
(*iii*) Explain with the help of a diagram the direct contact feed water heating.

6. (*a*) Explain with the help of neat sketches the working of 'forced draft' and 'induced draft' cooling towers.
(*b*) What is the importance of high purity water in high pressure boilers ? Explain the method used for water purifying when the make up water is required for high pressure boilers.

7. Write notes on *any two* of the following :
(*a*) Scope of tidal power in India ;
(*b*) Super-thermal power stations in India ;
(*c*) Selection of site for a hydro-power station.

8. (*a*) Why is superheating of steam essential in steam power ?
(*b*) A small steam turbine develops 100 H.P. and used 7 kg of steam per horse power hour. The steam is supplied to the turbine pressure of 15 kg/cm^2 at 240°C and the steam is exhausted to condenser at a pressure of 0.1 kg/cm^2. The condensate leaves at 34°C. Calculate the dryness fraction of the exhaust steam entering the condenser. Cooling water is supplied at 10°C and leaves at 22°C. Calculate the amount of cooling water supplied per hour.
Specific heat of superheated steam is 0.6.

9. (*a*) What are the ash handling systems ?
Draw a line diagram of hydraulic ash handling system for modern high capacity plants. Explain its working.
(*b*) Draw a neat line diagram of inplant coal handling system and explain the equipment used at different stages.

10. (*a*) Describe with the help of neat diagram the working of a plate type air heater used in a modern power plant.
(*b*) What are the requirements of the burners used for firing pulverised coal ? Describe with line sketches the various types of burners used and their relative merits and demerits.

11. (*a*) Describe the working of a contact type feed water heater with the help of neat diagram.
(*b*) Draw an outline of ash disposal equipment. State the advantages of hydraulic system of handling ash. What are the problems of has disposal ?

12. (*a*) What are characteristics of turbo-alternators ?
(*b*) During a trial of 20 minutes the following observations were made on a single cyclinder double-acting steam engine when running on light load—barometer 76 cm of Hg ; total steam used 51 kg ; gauge pressure of steam in valve chest 2 kgf/cm^2 ; the engine rejected exhaust steam into a condenser at the pressure of atmosphere which is 1.03 kgf/cm^2. The state of the steam in the valve chest was found to be dry and saturated. Mean engine speed 120 r.p.m. ; mean effective pressure : outstroke 1.06 kgf/cm^2, instroke 0.984 kgf/cm^2 ; piston rod diameter 21.5 cm ; stroke 30.8 cm ; piston rod diameter 3.7 cm. Net brake load (*W-S*) 50.5 kg. Brake wheel radius = 1.2 m condensate at the rate of 2.850 kg/hr with a rise in temperature of 24°C. Temperature of the condensate leaving the condenser 60°C.
Calculate :
(*i*) The steam consumption in kg/1 HP-hr ;
(*ii*) The mechanical efficiency ;
(*iii*) The brake thermal efficiency of the engine.
Draw up a heat balance sheet for the plant on minute basis taking condensate temperature as datum.

13. (*a*) Describe methods of loading steam stations, hydrostations and nuclear stations.
(*b*) State the criteria for optimum loading of power plant.

14. (*a*) Describe with a neat sketch the working of a travelling grate stoker of a steam boiler.
(*b*) Describe pneumatic ash handling system in a modern steam generator.

15. (*a*) Draw *p-v* and *T-s* diagrams for the most commonly used thermodynamic cycle for a thermal station.
(*b*) Steam at pressure 40 kgf/cm^2 and 400°C temperature is supplied to a steam turbine and is exhausted at pressure of 0.07 kgf/cm^2. A single bleed is taken between the H.P. cylinder and L.P. cylinder of the turbine at 2.5 kgf/cm^2 for regenerative feed heating. The isentropic efficiency for both the cylinders of the turbine is 85%. The temperature of the bleed condensate coming out of heat exchanger is 10°C lower than the temperature of the bleed steam. Find out :
(*i*) Amount of bleed steam/kg of steam supplied to the turbine ;
(*ii*) The thermal efficiency of the plant.
(Consider no losses and pump work as negligible. Let the condensate coming out from the heat exchanger and condenser be led to the hot well).

16. Write detailed notes on the following :
(*a*) Switch gears for power stations ;
(*b*) Combined loading of thermal and hydroplants ;
(*c*) Power from tides.

17. (*a*) What are the advantages of high pressure boilers ? Discuss the guide lines for the selection of boilers for steam power plants.
(*b*) A steam power plant working on regenerative cycle utilises steam at 42 kgf/cm^2 and 400°C and the condenser pressure is 0.963 kgf/cm^2 vacuum. After expansion in the turbine to 5 kgf/cm^2, a part of steam is extracted from the turbine for heating feed water from condenser in the open heater. Draw the cycle on *T-s* diagram and find the thermal efficiency of the

plant. Assume the heat drop to be isentropic and the atmospheric pressure may be taken equal to 1.033 kgf/cm^2.

18. (*a*) Make a list of the advantages of pulverised coal firing in a steam power plant.

(*b*) Discuss in brief the ash handling systems in P.F. boilers. What are the difficulties in the handling of ash in a thermal power station ?

19. (*a*) Discuss how coil is handled in a medium capacity thermal power plant.

(*b*) Make a list of advantages and disadvantages of stoker firing and explain the working of chain grate stoker with simple sketch.

20. A steam turbine using regenerative feed heat cycle generates 27000 kW through a directly coupled electric generator. Steam at 60 kgf/cm^2 and 450°C is supplied to the turbine. The condenser pressure is 730 mm Hg vacuum. The steam is bled from steam turbine at 3 kgf/cm^2. The heating of feed water is done in direct contact heater. Find :

(*a*) Steam bled/kg of steam supplied ;

(*b*) Steam generated/hour ;

(*c*) Overall efficiency of the plant.

Assume turbine η of each portion of expansion as 86%, boiler η = 90% alternator η = 95%, mechanical η from turbine to generator 98% and 10% of generator output is used to run the pump. Neglect pump work in calculating input to the boiler.

21. (*a*) Explain the advantages of combined of power plants.

(*b*) Explain the effect of load factor of an electric power station on the cost of energy generated.

(*c*) The steam consumption rates in kg/hr for two steam turbines is given by the following equations ;

$$F_1 = 2{,}000 + 10\,P_1 - 1 \times 10^{-4}\,P_1^2$$

$$F_2 = 4{,}000 + 7\,P_2 - 5 \times 10^{-5}\,P_2^2$$

where P represents the load in kW.

Determine the most economical loading when the total load taken by both units is 30 MW.

22. (*a*) Explain how combustion takes place in overfeed and underfeed stokers. Discuss their relative performance.

(*b*) Explain the working of an electrostatic precipitator and list its outstanding features.

23. (*a*) Show that the thermal efficiency of a regenerative cycle is greater than simple Rankine cycle.

(*b*) Steam at 50 kgf/cm^2 and 400°C is supplied to a two stage turbine. The steam is first expanded in high pressure turbine to 5 kgf/cm^2. The steam is reheated at 5 kgf/cm^2 to 250°C using 0.96 dry steam from the boiler at 50 kgf/cm^2. The reheated steam is passed through low pressure stage and then exhausted to a condenser at 0.03 kgf/cm^2. The isentropic efficiency of high pressure and low pressure stage may be assumed same as 80%. Assuming that the mechanical efficiency is 99% and generator efficiency is 96%, find the weight of steam generated by the boiler per kWh. Assume that the heating steam in the reheater given up heat by condensing only and the pump work and other losses are neglected.

24. (*a*) Explain how the load distribution between two alternators of a generating station can be divided for best economy.

(*b*) The input-output curve of a 10 MW thermal station is given by :

$$I = (10 + 8L + 0.4L^2)\ 10^6 \text{ kcal/h}$$

where L is in MW. Find out the load at which the plant runs at maximum efficiency and also the value of the maximum efficiency.

25. (*a*) Draw an explanatory line diagram of an ash handling system used for a modern high capacity steam power plant. State its merits.

(*b*) Describe, giving a neat diagram the working of a cyclone burner. Why are such burners preferred for Indian coals ?

(*c*) Prove that for the same plant the power required by an inducted draught fan will be more than that required by a forced draught fan assuming that the efficiencies of both the fans are the same.

26. (*a*) List the advantages and disadvantages of a surface condenser.

(*b*) Draw the flow diagram of a steam turbine plant using reheating and regeneration. Represent the various thermodynamic processes on a T-s diagram.

(*c*) A steam turbine develops 2.5 MW when the steam is supplied at 10 kgf/cm^2 abs and 250°C. The pressure in the condenser is 0.14 kgf/m^2 abs. Assuming the expansion efficiency through the turbine stage as 80%, determine :

(*i*) Specific steam consumption of the plant ;

(*ii*) Thermal efficiency of the plant.

27. (*a*) What are the advantages of burning coal in pulverised form ? Name the different types of coal pulverizing mills and discuss the outstanding features of each.

(*b*) Explain, with the help of neat sketch, the working of an electrostatic precipitator and give its outstanding features over other collectors.

28. (*a*) What are the sources of air leakage into a condenser ? Discuss the effect of air leakage on the performance of a condenser.

(*b*) A two-stage regenerative cycle used steam at 70 kgf/cm^2, 400°C with 25 mm of Hg back pressure. Station auxiliary power is 15% of turbine output. The overall electrical and mechanical efficiency of turbine generator is 80% and the boiler efficiency is 85%. The turbine has an engine efficiency of 88%. Compute the overall station heat rate in kcal/kWh.

29. The following data refers to a boiler trial of a steam power plant :

Coal consumption	= 4,0000 kg/hr
Calorific value of coal	= 8,500 kcal/kg
Ultimate analysis of coal	C = 80%, H_1 = 5%, H_2O = 7%, ash = 8%
Orsat analysis of the gases	CO_2 = 10%, O_2 = 8%, CO = 2%, N_2 = 80%
Temperature of the gases	= 300°C
Boiler room temperature	= 20°C
Steam generated	= 40,000 kg/hr

Pressure of steam at stop valve = 14 kg/cm^2 dry
Specific heat of gases = 0.24
Specific heat of superheat steam = 0.50
Feed water temperature = 50°C

Draw the heat balance sheet of boiler based on 1 kg of coal.

Calculate also the amount of air needed in kg/hour if 50% excess air is supplied.

30. (*a*) What difficulties are experienced in ash handling ? Describe with the help of a diagram the working of a pneumatic ash handling system.

(*b*) Explain clearly the difference between overfeed and underfeed systems of coal firing. Which is preferred for high volatile coal and why ?

31. (*a*) Draw a neat schematic diagram and temperature entropy diagram of thermodynamic cycle used in steam power plants and explain it in brief.

(*b*) A steam turbine power plant working on Rankine cycle receives steam at a pressure of 90 kgf/cm^2-ab and temperature of 500°C. Steam is expanded in the first stage of turbine to a pressure of 12 kgf/cm^2-ab. It is then reheated to its initial temperature and then expanded in the second stage to a pressure of 0.07 kgf/cm^2-ab.

Find :

(*i*) The efficiency of the cycle assuming isentropic expansion efficiency of turbine in each stage to be 90% ;

(*ii*) Steam flow rate required to develop 10 MW of power ;

(*iii*) Dryness fraction of steam leaving the turbine.

32. (*a*) What are the advantages of burning fuel in pulverised form ?

(*b*) Name the different types of coal pulverising mills and discuss outstanding features of each. Name one which is commonly used.

(*c*) What are the different methods used for supplying pulverised fuel to combustion chambers ?

33. (*a*) Draw a general layout of a thermal power plant and explain the working of difference circuits.

(*b*) What factors are considered in selecting a site for a big thermal power plant?

34. (*a*) Draw a line diagram of pneumatic ash handling system used for modern capacity power plant. Explain the difficulties encountered in its design and operation. When is this system preferred over other systems ?

(*b*) Draw a neat line diagram of Benson boiler and explain its working. Discuss its relative merits and demerits.

35. (*a*) Draw a neat diagram of multiretort under feed stoker and explain its working. Discuss its merits over other types of stokers.

(*b*) What are the advantages of burning the fuels in pulverised form ?

36. Write brief notes on the following :

(*i*) Heat balance in steam power plant ;

(*ii*) Pumped storage hydroelectric power plant ;

(*iii*) Lubrication system in diesel electric plant ;

(*iv*) Open cycle gas turbine.

37. (*a*) List out the major advantages of high pressure boilers in modern thermal power plants.

(*b*) Draw a neat diagram of a volex boiler and discuss its merits. Explain its working principle.

38. (*a*) Explain the working principle of the following :

(*i*) Economisers ;

(*ii*) Air preheaters ;

(*iii*) Superheaters.

(*b*) The steam at 90 kgf/cm^2 ab. and 480°C is supplied to a steam turbine. The steam is reheated to its original temperature passing the steam through reheater at 12 kgf/cm^2 ab. The expansion after the reheating, takes place to condenser pressure of 0.07 kgf/cm^2 ab. Find the efficiency of reheat cycle and work output if the flow of steam is 1 kg/s. Neglect the pressure loss in the system and assume the expansion through the turbine as isentropic. Do not neglect the pump work.

39. (*a*) Explain with neat diagram the working principle of travelling grate stoker.

(*b*) Why ash should be discharged ? Give reasons. List the difficulties encountered in the ash handling plant layout. Mention the places of disposal of ash.

40. (*a*) Give the classification of coal in the increasing order of their heat value. Discuss each of them.

(*b*) Discuss the following pulverised fuel handling systems :

(*i*) Unit system ;

(*ii*) Central or Bin system. Mention the advantages and disadvantages of them.

41. (*a*) What is the function of cooling tower in a modern steam power plant ? Describe briefly with a neat sketch the working of a hyperbolic cooling tower.

(*b*) The steam at 90 kgf/cm^2-ab and 480°C is supplied to a steam turbine. The steam is reheated to its original temperature passing the steam through reheater at 12 kgf/cm^2-ab. The expansion after reheating takes place to condenser pressure 0.07 kgf/cm^2-ab. Find the efficiency of reheat cycle and work output if the flow of steam is 1 kg/sec. Neglect the pressure loss in the system and assume the expansion through the turbine is isentropic. Do not neglect the pump work.

42. (*a*) What do you understand by the term "Draught" ?

How is the draughts classified ? Explain with neat sketch the balanced draught.

(*b*) What are the advantages of high pressure boiler ? Draw a neat line diagram of LaMont boiler and explain its working.

43. (*a*) What do you understand by proximate and ultimate analysis of coal ? Discuss the role played by each constituent.

(*b*) Explain the coal preparation plant.

(*c*) Explain *any three* equipment used for the transfer of coal from unloading point to the storage site.

44. (*a*) Describe the burning sequence of coal in 'overfeed' and 'underfeed' stokers. Which types of stoker is suitable to burn

(*i*) High ash clinkering coals,

(*ii*) High volatile matter coal and

(*iii*) Low ash content coals ?

(*b*) Why ash and dust handling problem is more difficult than coal handling problems ? Explain them.

45. Write short notes on the following :

(*i*) Electrostatic precipitator ;

(*ii*) Mechanical draft cooling tower ;

(*iii*) Excitor and circuit breaker in a power plant.

46. (*a*) Discuss briefly, with a line sketch, the different types of burners used in firing pulverized coal in steam boilers.

(*b*) The following observations were taken during a test on a steam generator :

Quantity of coal burnt per hour 750 kg

Feed water supplied per hour 7,000 kg

Calorific value of coal fired 8,100 kcal/kg

Feed water temperature entering economizer 25°C

Feed water temperature leaving economizer 80°C

Steam pressure 10 kgf/cm^2

Dryness fraction of steam leaving boiler drum 0.95

Temperature of steam leaving superheater 250°C

Determine the thermal efficiency of the plant and also calculate the heat absorbed by feed water in various components as a percentage of the total heat absorbed.

47. (*a*) Name the different boiler accessories.

(*b*) With a neat line sketch explain the working principle of Schimdt-Hartmann boiler.

(*c*) Why is it important to purify water in high pressure boiler ? How are dissolved oxygen and silica removed from feed water ?

48. (*a*) Why is condenser used in steam power plant ? Discuss the working of different parts of surface condenser.

(*b*) The steam at 100 kgf/cm^2 and 500°C expands in the turbine up to 8.5 kgf/cm^2 with an isentropic efficiency of 80%. The steam is then reheated to original temperature and then it expands in the lower stage of the turbine up to the condenser pressure of 0.05 kgf/cm^2. The isentropic efficiency of the lower stage of the turbine is 85%. Find the thermal efficiency of the cycle assuming the pressure loss in the reheater of 0.5 kgf/cm^2.

If the expansion of the steam is allowed to continue in the lower part of the turbine with an isentropic efficiency of 75% without reheating, then find the thermal efficiency of the cycle. Neglect the pump work in both case.

49. (*a*) How is the efficiency of a steam plant improved through regenerative cycle ? Show the cycle on temperature-enthropy diagram and deduce an expansion for its ideal efficiency.

(*b*) In a single stage regenerative cycle, steam is supplied to the steam turbine at 16 kgf/cm^2 abs and 300°C and exhausts at 0.05 kgf/cm^2 abs. The steam for feed heating is to be extracted at 1.6 kgf/cm^2 abs. The drain from the closed heater, at saturation temperature of bled steam pressure, is returned to the system at a point downstream from the heater and the feed water is heated to saturation temperature of bled steam. Determine the regenerative cycle efficiency and compare it with Rankine cycle working between the same terminal conditions. Neglect pump work. Represent the processes on enthalpy-entropy plane, if used.

50. (*a*) What are the advantages of using high pressure boilers in modern thermal power stations ? Discuss briefly high temperature effects on steam piping in modern boilers.

(*b*) Steam is supplied to a 10 MW turbo-alternator at 40 kgf/cm^2 abs and 400°C. Auxiliaries consume 7 per cent of the output. The condenser pressure is 0.05 kgf/cm^2 abs and the condensate is subcooled to 30°C. Take boiler efficiency as 85 per cent and the relative efficiency of turbine as 0.8 and the mechanical efficiency of the alternator as 95 per cent. Determine :

(*i*) The steam consumption per hour ;

(*ii*) The overall efficiency of the plant ;

(*iii*) The quality of steam at exit from turbine.

Sketch the relevant portion of Mollier diagram, if used for the solution.

51. (*a*) What are meant by 'primary air' and 'secondary air' with regard to combustion for stoker firing and pulverised fuel firing ?

(*b*) Describe briefly with a flow sheet the pulverised coal preparation systems and the method of firing of pulverised fuel. Discuss briefly the advantages and disadvantages of pulverised coal firing.

52. Describe briefly the elements of a hydraulic ash handling system for a boiler furnance in a power station.

53. The following data were obtained during a trial of a coal fired steam boiler with natural draught :

Feed water temperature = 75°C

Feed water supplied per hour to boiler = 4500 kg

Steam pressure = 11 kg/cm^2 abs

Dryness fraction of steam generated in boiler = 0.95

Coal fired per hour = 400 kg

Higher calorific value of coal = 9400 kcal/kg

Moisture in coal 4.25 per cent by mass

Temperature of flue gases discharged = 270°C

Boiler room temperature = 30°C

Analysis of dry coal by mass was : C = 89%, H_2 = 3%, Ash = 4% and other volatile matter = 4%

The analysis of flue gas by volume was : CO_2 = 10.9%, CO = 1.1%, O_2 = 7% and N_2 = 81%.

Draw up the heat balance for the boiler per kg of coal fired, and also determine the thermal efficiency of the

boiler. Assume sp. heat of dry flue gases as 0.23 and sp. heat of superheated steam in products of combustion as 0.48. Also assume partial pressure of water vapour in flue gases as 0.027 kg/cm^2 abs.

54. (*a*) What are the different methods to control superheat temperature in steam generators ?

(*b*) What are the differences between a feed water heater and an economiser ?

(*c*) Discuss briefly the working of an economiser used in modern steam generator. How soot is cleaned from economiser tubes ?

55. (*a*) What are the advantages of using reheat steam cycle ?

(*b*) How in actual practice reheating is done in steam power ?

(*c*) In a reheat cycle, with two stages of reheating, steam at 210 kgf/cm^2 and 550°C, enters the turbine and expands to 41 kgf/cm^2 abs. At this point the whole steam is passed to the first reheater. The steam re-enters the turbine at the same pressure and expands further to 10 kgf/cm^2 abs pressure. After expansion the whole steam is passed to the second reheater. The steam after second stage of reheating further expands to condenser pressure of 0.126 kgf/cm^2 abs. The exist of steam from both the reheaters is at 550°C and there is no pressure drop in the reheaters. For the ideal reheat cycle determine the thermal efficiency.

56. (*a*) Explain how required vacuum is maintained in the condenser of a steam power plant.

(*b*) What are the disadvantages of 'pulverised fuel firing system' ? Discuss how these disadvantages are eliminated in more advanced methods of fuel firing system.

(*c*) What are the harmful effects caused by using impure water in boiler ? State the various methods of purifying feed water.

57. In a 60 MW steam turbine plant steam is supplied to the HP unit at 70 kgf/cm^2 and 450°C. Steam is expanded to 25 kgf/cm^2 in the HP unit and before entering the IP unit steam is reheated at constant pressure to 420°C. Expansion continues upto 10 kgf/cm^2 in the IP unit when a portion of steam held at 10 kgf/cm^2 is taken to a closed feed-water heater with drains pumped ahead. The remaining steam expands to the condenser pressure of 0.07 kgf/cm^2 in the LP unit. The isentropic efficiency of the HP stages 80% while that of IP and LP stages is 83% each. Using the following data only, determine :

(*a*) Quantity of steam bled per kg of flow at the turbine inlet ;

(*b*) Thermal efficiency ; and

(*c*) Steam consumption in tonnes/hour.

Neglect all pump work assume that feed-water is heated to the bled steam temperature in the heater. Draw the schematic diagram of the plant and the corresponding *T-s* diagram.

Diesel Engine Power Plant

4

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4.1. INTRODUCTION

Diesel engine power plants are installed *where supply of coal and water is not available in sufficient quantity* or *where power is to be generated in small quantity* or *where standby sets are required for continuity of supply such as in hospitals, telephone exchanges, radio stations and cinemas.* These plants in the range of 2 to 50 MW capacity are used as *central stations* for supply authorities and works and they are universally adopted to supplement hydro-electric or thermal stations where stand-by generating plants are essential for starting from cold and under emergency conditions.

In several countries, the demand for diesel power plants is increased for electric power generation because of difficulties experienced in construction of new hydraulic plants and enlargement of old hydro-plants. A long term planning is required for the development of thermo and hydro-plants which cannot keep the pace with many times the increased demand by the people and industries.

The diesel units used for electric generation are *more reliable* and *long-lived piece of equipment* compared with other types of plants.

4.2. ADVANTAGES AND DISADVANTAGES OF DIESEL POWER PLANTS

The *advantages* and *disadvantages* of diesel power plants are listed below :

Advantages :

1. Design and installation are very simple.
2. Can respond to varying loads without any difficulty.
3. The standby losses are less.
4. Occupy less space.
5. Can be started and put on load quickly.
6. Require less quantity of water for cooling purposes.
7. Overall capital cost is lesser than that for steam plants.
8. Require less operating and supervising staff as compared to that for steam plants.
9. The efficiency of such plants at part loads does not fall so much as that of a steam plant.
10. The cost of building and civil engineering works is low.
11. Can burn fairly wide range of fuels.
12. These plants can be located very near to the load centres, many times in the heart of the town.
13. No problem of ash handling.
14. The lubrication system is more economical as compared with that of a steam power plant.
15. The diesel power plants are *more efficient than steam power plants* in the range of 150 MW capacity.

Disadvantages :

1. High operating cost.
2. High maintenance and lubrication cost.
3. Diesel units capacity is limited. These cannot be constructed in large size.
4. In a diesel power plant noise is a serious problem.
5. Diesel plants cannot supply overloads continuously whereas steam power plant can work under 25% overload continuously.

6. The diesel power plants are not economical where fuel has to be imported.

7. The life of a diesel power plant is quite small (2 to 5 years or less) as compared to that of a steam power plant (25 to 30 years).

4.3. APPLICATIONS OF DIESEL POWER PLANT

The diesel power plants find wide application in the following fields :

1. Peak load plant
2. Mobile plants
3. Stand-by units
4. Emergency plant
5. Nursery station
6. Starting stations
7. Central stations—where capacity required is small (5 to 10 MW)
8. Industrial concerns where power requirement is small say of the order of 500 kW, diesel power plants become more economical due to their higher overall efficiency.

4.4. SITE SELECTION

The following *factors* should be considered while *selecting the site for a diesel power plant* :

1. Foundation sub-soil condition. The conditions of sub-soil should be such that a foundation at a reasonable depth should be capable of providing a strong support to the engine.

2. Access to the site. The site should be so selected that it is accessible through rail and road.

3. Distance from the load centre. The location of the plant should be near the load centre. This reduces the cost of transmission lines and maintenance cost. The power loss is also minimised.

4. Availability of water. Sufficient quantity of water should be available at the site selected.

5. Fuel transportation. The site selected should be near to the source of fuel supply so that transportation charges are low.

4.5. HEAT ENGINES

Any type of engine or machine which derives heat energy from the combustion of fuel or any other sources and converts this energy into mechanical work is termed as a ***heat engine.***

Heat engines may be classified into two main classes as follows :

1. External Combustion Engines.
2. Internal Combustion Engines.

1. External combustion engine (E.C. engines). In this case, *combustion of fuel takes place outside the cylinder* as in case of *steam engines* where the heat of combustion is employed to generate steam which is used to move a piston in a cylinder. Other examples of external combustion engines are *hot air engines, steam turbine* and *closed cycle gas turbine*. These engines are generally used for driving locomotives, ships, generation of electric power etc.

2. Internal combustion engines (I.C. engines). In this case, *combustion of the fuel with oxygen of the air occurs within the cylinder of the engines*. The internal combustion engines group includes engines employing mixtures of combustible gases and air, known as *gas engines*, those using lighter liquid fuel or spirit known as *petrol engines* and those using heavier liquid fuels, known as *oil compression ignition* or *diesel engines*.

4.6. CLASSIFICATION OF I.C. ENGINES

Internal combustion engines may be *classified* as given below :

1. **According to cycle of operation**
   - (*i*) Two stroke cycle engines
   - (*ii*) Four stroke cycle engines.
2. **According to cycle of combustion**
   - (*i*) Otto cycle engine (combustion at constant volume)
   - (*ii*) Diesel cycle engine (combustion at constant pressure)
   - (*iii*) Dual-combustion or Semi-Diesel cycle engine (combustion partly at constant volume and partly at constant pressure).
3. **According to arrangement of cylinder**
   - (*i*) Horizontal engine
   - (*ii*) Vertical engine
   - (*iii*) V-type engine
   - (*iv*) Radial engine etc.
4. **According to their uses**
   - (*i*) Stationary engine
   - (*ii*) Portable engine
   - (*iii*) Marine engine
   - (*iv*) Automobile engine
   - (*v*) Aero engine etc.
5. **According to the fuel employed and the method of fuel supply to the engine cylinder**
   - (*i*) Oil engine
   - (*ii*) Petrol engine
   - (*iii*) Gas engine
   - (*iv*) Kerosene engine etc.
   - (*v*) Carburettor, hot bulb, solid injection and air injection engine.
6. **According to the speed of the engine**
   - (*i*) Low speed engine
   - (*ii*) Medium speed engine
   - (*iii*) High speed engine.

7. According to method of ignition

(*i*) Spark ignition S.I. engine

(*ii*) Compression ignition C.I. engine.

8. According to method of cooling the cylinder

(*i*) Air-cooled engine

(*ii*) Water-cooled engine.

9. According to method of governing

(*i*) Hit and miss governed engine

(*ii*) Quality governed engine

(*iii*) Quantity governed engine.

10. According to valve arrangement

(*i*) Over head valve engine

(*ii*) L-head type engine

(*iii*) T-head type engine

(*iv*) F-head type engine.

11. According to number of cylinders

(*i*) Single cylinder engine

(*ii*) Multi-cylinder engine.

4.7. DIFFERENT PARTS OF I.C. ENGINES

Fig. 4.1 shows the cross-section of an *air-cooled I.C. engine* with principle parts.

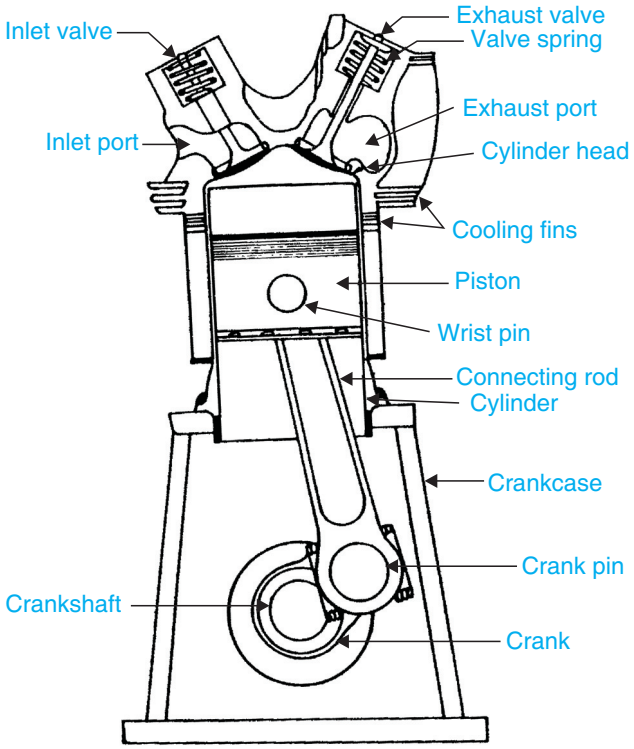


Fig. 4.1. Air-cooled I.C. engine.

A. Parts common to both petrol and diesel engines

1. Cylinder
2. Cylinder head
3. Piston
4. Piston rings
5. Gudgeon pin
6. Connecting rod
7. Crankshaft
8. Crank
9. Engine bearing
10. Crankcase
11. Fly wheel
12. Governor
13. Valves and valve operating mechanisms.

B. Main parts for petrol engines only

1. Spark plugs
2. Carburettor
3. Fuel pump.

C. Main parts of diesel engines only

1. Fuel pump
2. Fuel injector or atomiser.

4.8. TERMS CONNECTED WITH I.C. ENGINES

Refer to Fig. 4.2.

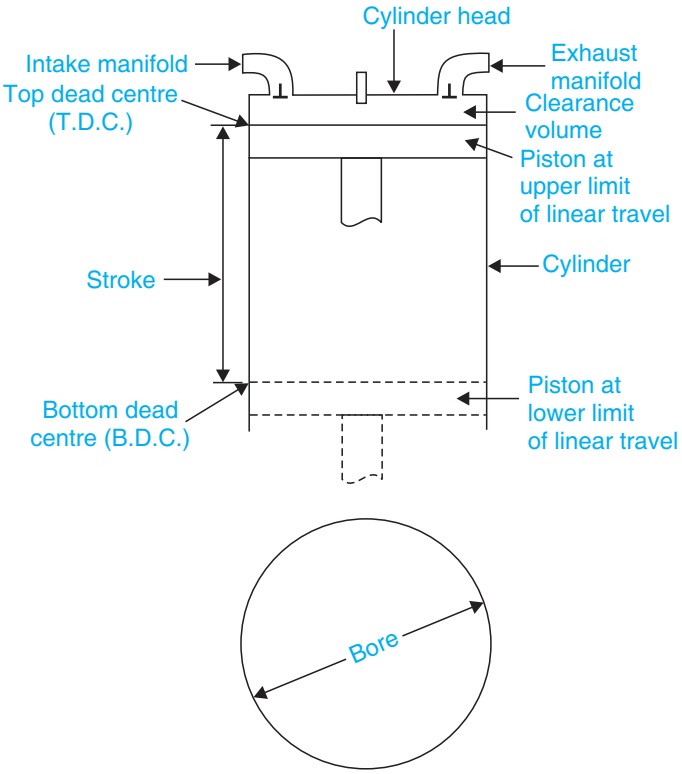


Fig. 4.2. Terms relating to I.C. engines.

Bore. *The inside diameter of the cylinder is called* ***bore.***

Stroke. As the piston reciprocates inside the engine cylinder, it has got limiting upper and lower positions beyond which it cannot move and reversal of motion takes place at these limiting positions.

The linear distance along the cylinder axis between two limiting positions, is called ***stroke.***

Top Dead Centre (T.D.C.). *The top most position of the piston towards cover end side of the cylinder is called* ***top dead centre.*** In case of horizontal engines, this is known as *"inner dead centre."*

Bottom Dead Centre (B.D.C.). *The lowest position of the piston towards the crank end side of the cylinder is called* ***bottom dead centre.*** In case of horizontal engines it is called *"outer dead centre."*

Clearance volume. *The volume contained in the cylinder above the top of the piston, when the piston is at top dead centre, is called the* ***clearance volume.***

Swept volume. *The volume swept through by the piston in moving between top dead centre and bottom dead centre, is called* ***swept volume*** *or* ***piston displacement.*** Thus, when piston is at bottom dead centre, total volume = swept volume + clearance volume.

Compression ratio. *It is the ratio of total cylinder volume to clearance volume.*

Refer to Fig. 4.2. Compression ratio (r) is given by

$$r = \frac{V_s + V_c}{V_c}$$

where V_s = Swept volume, and
V_c = Clearance volume.

The compression ratio varies from 5 : 1 to 9 : 1 in *petrol engines* and from 14 : 1 to 22 : 1 in *diesel engines*.

Piston speed. *The average speed of the piston is called* ***piston speed.***

Piston speed = $2\,LN$

where, L = Length of the stroke, and
N = Speed of the engine in r.p.m.

4.9. FOUR STROKE CYCLE DIESEL ENGINES

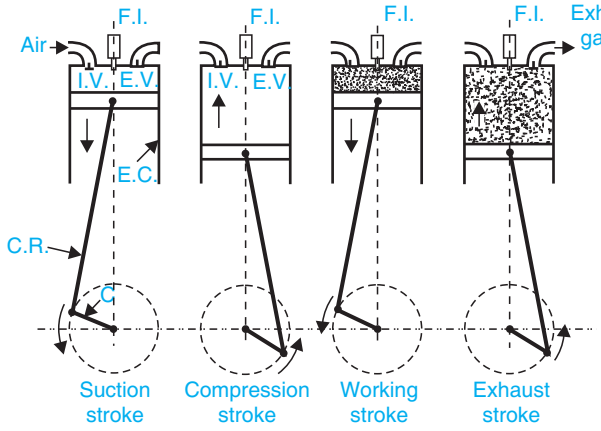
This types of engine comprises of the following *four strokes* :

1. Suction stroke. With the movement of the piston from T.D.C. to B.D.C. during this stroke, the inlet valve opens and the air at atmospheric pressure is drawn inside the engine cylinder ; the exhaust valve however remains closed. This operation is represented by the line 5-1 (Fig. 4.4).

2. Compression stroke. The air drawn at atmospheric pressure during the suction stroke is compressed to high pressure and temperature (to the value of 35 bar and 600°C respectively) as the piston moves from B.D.C. to T.D.C. This operation is represented by 1-2 (Fig. 4.4). Both the inlet and exhaust valves do not open during any part of this stroke.

3. Expansion or working stroke. As the piston starts moving from T.D.C. a metred quantity of fuel is injected into the hot compressed air in fine sprays by the fuel injector and it (fuel) starts burning at constant pressure shown by the line 2-3. At the point 3 *fuel supply is cut-off*. The fuel is injected at the end of compression stroke but in actual practice the ignition of the fuel starts before the end of the compression stroke. The hot gases of the cylinder expand adiabatically to point 4, thus doing work on the piston. The expansion is shown by 3-4 (Fig. 4.4).

4. Exhaust stroke. The piston moves from the B.D.C. to T.D.C. and the exhaust gases escape to the atmosphere through the exhaust valve. When the piston reaches the T.D.C. the exhaust valve closes and the cycle is completed. This stroke is represented by the line 1-5 (Fig. 4.4).



F.I. = Fuel injector I.V. = Inlet valve E.V. = Exhaust valve
E.C. = Engine cylinder C.R. = Connecting rod C = Crank

Fig. 4.3. Four stroke diesel cycle engine.

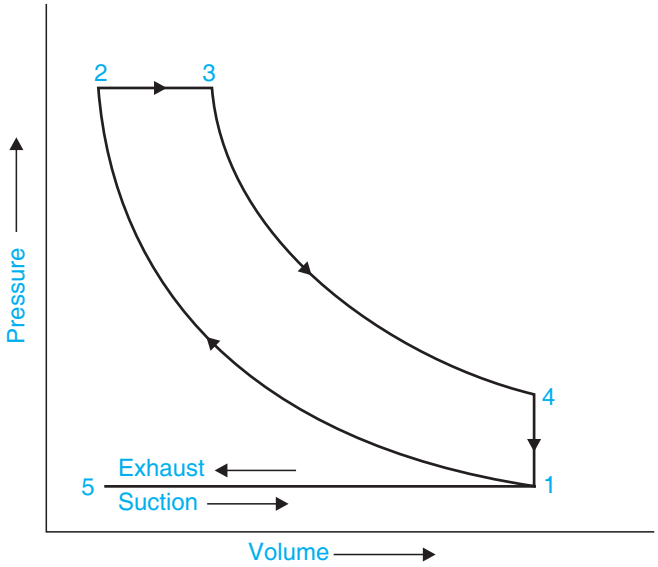


Fig. 4.4. Theoretical p-V diagram of a four stroke diesel cycle.

Fig. 4.5 shows the actual indicator diagram for a four-stroke diesel cycle engine. It may be noted that line 5-1 is below the atmospheric pressure line. This is due to the fact that owing to the restricted area of the inlet

passages the entering air can't cope with the speed of the piston. The exhaust line 4-5 is slightly above the atmospheric line. This is because of the restricted exhaust passages which do not allow the exhaust gases to leave the engine cylinder quickly.

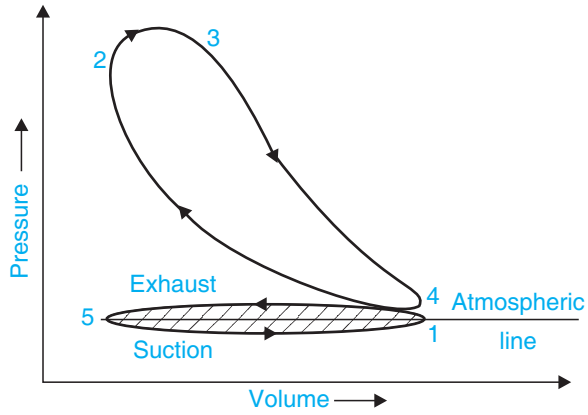
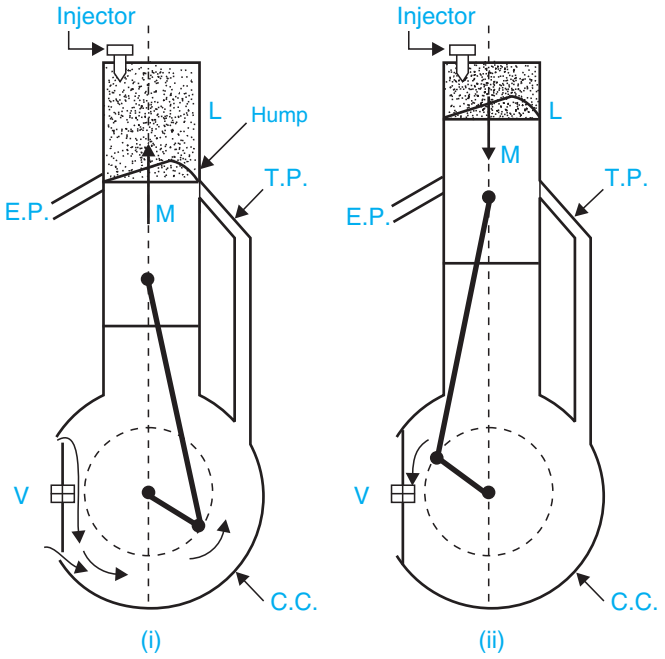


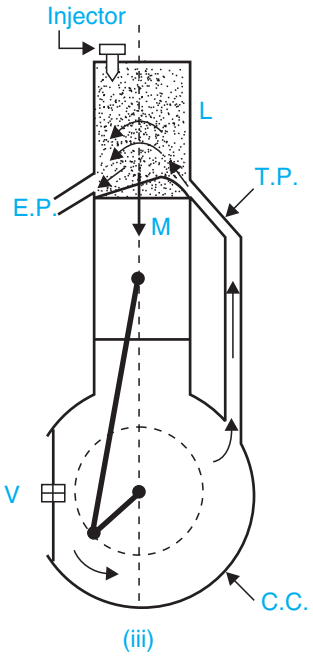
Fig. 4.5. Actual *p-V* diagram of four stroke diesel cycle.

The loop of area 4-5-1 is called *negative loop* ; it gives the *pumping loss* due to admission of air and removal of exhaust gases. The area 1234 is the total or gross work obtained from the piston and net work can be obtained by subtracting area 451 from area 1234.

4.10. TWO STROKE CYCLE DIESEL ENGINES

Fig. 4.6 shows two stroke diesel engine. The cylinder *L* is connected to the closed crank chamber C.C. During the upward stroke of the piston *M*, the gases in *L* are compressed and at the same time *fresh air* enters the crankchamber through the valve *V*. When the piston moves downward, *V* closes and air in the crank chamber is compressed. Refer to Fig. 4.6 *(i)*. The piston is moving upwards and is compressing the air which has previously been supplied to *L* and before it (piston) reaches the T.D.C. (top dead centre) the fuel injector supplies fuel to the engine cylinder. Ignition of fuel takes place due to high temperature of air and gases are produced. These gases expand and the piston then travels downward [Fig. 4.6 (*ii*)] and near the end of this stroke the piston uncovers the exhaust port (E.P.) and the burnt exhaust gases escape through this port [Fig. 4.6 (*iii*)]. The transfer port (T.P.) then is uncovered immediately, and the compressed air from the crank chamber flows into the cylinder and is deflected upwards by the hump provided on the head of the piston. It may be noted that the incoming air helps the removal of gases from the engine-cylinder. The piston then again starts moving from B.D.C. to T.D.C. and the air gets compressed when exhaust port (E.P.) and transfer port (T.P.) are covered by the piston ; thus the cycle is repeated.





L = Cylinder ; M = Piston ;
E.P. = Exhaust port ;
T.P. = Transfer port ;
C.C. = Crank chamber ;
V = Valve

Fig. 4.6. Two stroke cycle engine.

4.11. COMPARISON OF FOUR STROKE AND TWO STROKE CYCLE ENGINES

Four stroke cycle engines	*Two stroke cycle engines*
1. The cycle is completed in four strokes of the piston or in two revolutions of the crankshaft. Thus one power stroke is obtained in every two revolutions of the crankshaft.	1. The cycle is completed in two strokes of the piston or in one revolution of the crankshaft. Thus one power stroke is obtained in each revolution of the crankshaft.
2. Because of the above turning-movement is not so uniform and hence heavier flywheel is needed.	2. More uniform turning movement and hence lighter flywheel is needed.
3. Again because of one power stroke for two revolutions, power produced for same size of engine is small or for the same power the engine is heavy and bulky.	3. Because of one power stroke for one revolution, power produced for same size of engine in more (theoretically twice, actually about 1.8 times) or for the same power the engine is light and compact.
4. Because of one power stroke in two revolutions lesser cooling and lubrication requirements. Lesser rate of wear and tear.	4. Because of one power stroke in one revolution greater cooling and lubrication requirement. Great rate of wear and tear.
5. The four stroke engine contains valve and valve mechanism.	5. Two stroke engines have no valves but only ports (some two stroke engines are fitted with conventional exhaust valves).
6. Because of the heavy weight and complication of valve mechanism, higher is the initial cost.	6. Because of light weight and simplicity due to absence of valve mechanism, cheaper in initial cost.
7. Volumetric efficiency more due to more time of induction.	7. Volumetric efficiency less due to lesser time for induction.
8. Thermal efficiency higher, part load efficiency better than two stroke cycle engine.	8. Thermal efficiency lower, part load efficiency lesser than four stroke cycle engine.
9. Used where efficiency is important ; in *cars, buses, trucks, tractors, industrial engines, aeroplane, power generators* etc.	9. In two stroke petrol engine some fuel is exhausted during scavenging. Used where (*a*) low cost, and (*b*) compactness and light weight important. Two stroke (air cooled) petrol engines used in very small sizes only, *lawn movers, scooters, motor cycles* (lubricating oil mixed with petrol). Two stroke diesel engines used in very large sizes, more than 60 cm bore, for *ship propulsion* because of low weight and compactness.

4.12. COMPARISON BETWEEN A PETROL ENGINE AND A DIESEL ENGINE

Petrol engine	*Diesel engine*
1. Air petrol mixture is sucked in the engine cylinder during suction stroke.	Only air is sucked during suction stroke.
2. Spark plug is used.	Employs an injector.
3. Power is produced by spark ignition.	Power is produced by compression ignition.
4. Thermal efficiency up to 25%.	Thermal efficiency up to 40%.
5. Occupies less space.	Occupies more space.
6. More running cost.	Less running cost.
7. Light in weight.	Heavy in weight.
8. Fuel (Petrol) costlier.	Fuel (Diesel) cheaper.
9. Petrol being volatile is dangerous.	Diesel is not dangerous as it is non-volatile.
10. Pre-ignition possible.	Pre-ignition not possible.
11. Works on Otto cycle.	Works on diesel cycle.
12. Less dependable.	More dependable.
13. Used in *cars* and *motor cycles*.	Used in heavy duty vehicles like *trucks, buses* and *heavy machinery*.

4.13. ESSENTIAL COMPONENTS OF A DIESEL POWER PLANT

Refer to Fig. 4.7. The essential components of a diesel power plant are listed and discussed below :

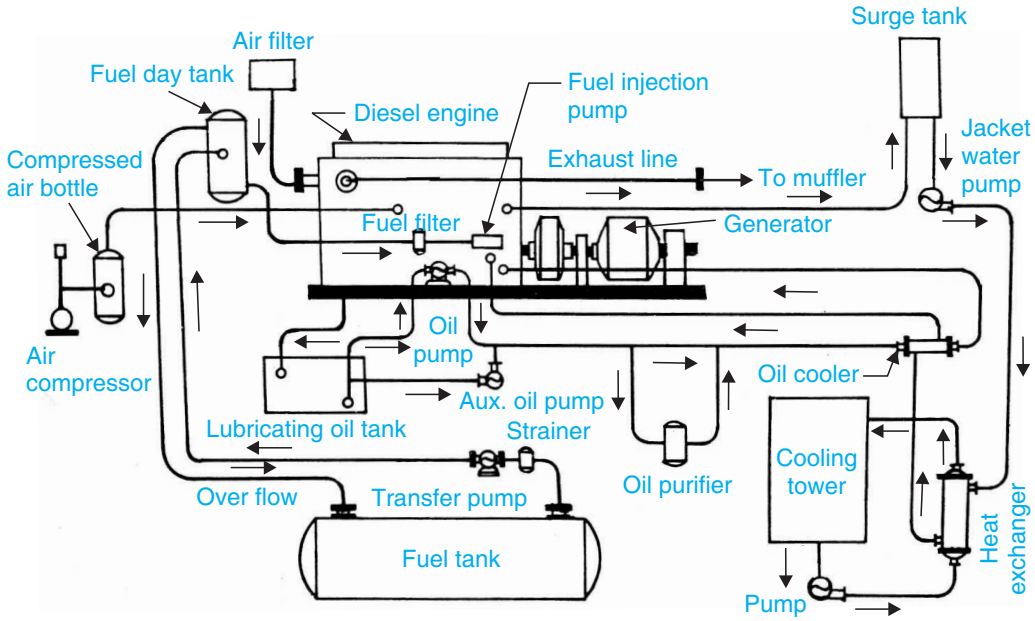


Fig. 4.7. Schematic arrangement of a diesel power plant.

1. Engine
2. Air intake system
3. Exhaust system
4. Fuel system
5. Cooling system
6. Lubrication system
7. Engine starting system
8. Governing system.

4.13.1. Engine

This is the main component of the plant which develops the required power. It is generally directly coupled to the generator as shown in Fig. 4.7.

4.13.2. Air Intake System

The air intake system conveys fresh air through pipes or ducts to : (*i*) Air intake manifold of four stroke engines, *(ii)* The scavenging pump inlet of a two stroke engine, and (*iii*) The supercharger inlet of a supercharged engine.

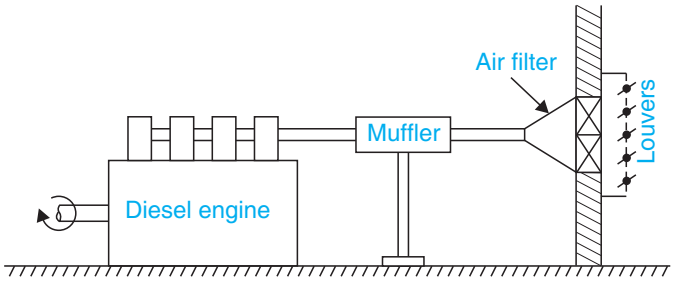


Fig. 4.8. Air intake system.

The air system begins with an intake located outside the building provided with a *filter* to catch dirt which would otherwise cause excessive wear in the engine. The filters may be of *dry or oil bath*. Electrostatic precipitator filters can also be used. *Oil impingement type of filter* consists of a frame filled with metal shavings which are coated with a special oil so that the air in passing through the frame and being broken up into a number of small filaments comes into contact with the oil whose property is to sieze and hold any dust particles being carried by the air. The *dry type* of filter is made of cloth, felt, glass wool etc. In case of *oil bath type of filter* the air is swept over or through a pool of oil so that the particles of dust become coated. Light weight steel pipe is the material for intake ducts. In some cases, the engine noise may be transmitted back through the air intake system to the outside air. In such cases a silencer is provided between the engine and the intake.

Following *precautions* should be taken while constructing a suitable air intake system :

1. Air intakes may not be located inside the engine room.

2. Air should not be taken from a confined space otherwise air pulsations can cause serious vibration problems.
3. The air-intake line used should neither have too small a diameter nor should be too long, otherwise there may crop up engine starvation problem.
4. Air intake filters may not be located close to the roof of the engine room otherwise pulsating air flow through the filters can cause serious vibrations of the roof.
5. Air intake filters should not be located in an inaccessible location.

4.13.3. Exhaust System

Refer to Fig. 4.9. The purpose of the exhaust system is to discharge the engine exhaust to the atmosphere outside the building. The exhaust manifold connects the engine cylinder exhausts outlet to the exhaust pipe which is provided with a muffler to reduce pressure in the exhaust line and eliminate most of the noise which may result if gases are discharged directly into the atmosphere.

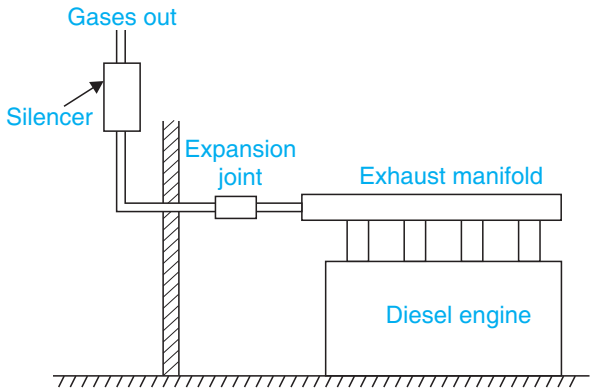


Fig. 4.9. Exhaust system.

The exhaust pipe leading out of the building should be short in length with minimum number of bends and should have one or two flexible tubing sections which take up the effects of expansion, and isolate the system from the engine vibration. Every engine should be provided with its independent exhaust system.

The waste heat utilisation in a *diesel-steam* station may be done by providing waste-heat boilers in which most of the heat of exhaust gases from the engine is utilised to raise low pressure steam. Such application is common on *marine plants*. On the *stationary power plant* the heat of exhaust may be utilised to heat water in gas-to-water heat exchangers consisting of a water coil placed in exhaust muffler and using the water in the plant suitably. If air heating is required, the exhaust pipe from the engine is surrounded by the cold air jacket, and transfers the heat of exhaust gases to the air.

4.13.4. Fuel System

Refer to Fig. 4.10.

The fuel oil may be delivered at the plant site by trucks, railroad tank cars or barge and tankers. From tank car or truck the delivery is through the unloading facility to main storage tanks and then by transfer pumps to small service storage tanks known as *engine day tanks*. Large storage capacity allows purchasing fuel when prices are low. The main flow is made workable and practical by arranging the piping equipment with the necessary heaters, by passes, shut-offs, drain lines, relief valves, strainers and filters, flow meters and temperature indicators. The actual flow plans depend on type of fuel, engine equipment, size of the plant etc. The tanks should contain manholes for internal access and repair, fill lines to receive oil, vent lines to discharge vapours, overflow return lines for controlling oil flow and a suction line to withdraw oil. *Coils heated by hot water or steam reduce oil viscosity to lower pumping power needs*.

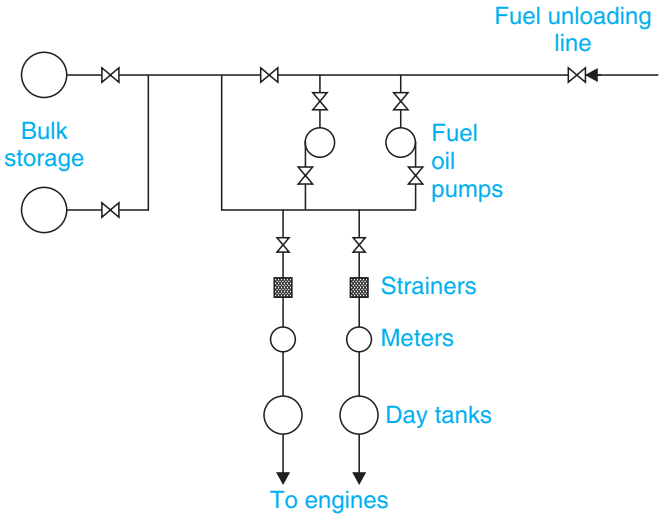


Fig. 4.10. System of fuel storage for a diesel power plant.

The minimum storage capacity of at least a month's requirement of oil should be kept in bulk, but where advantage of seasonal fluctuations in cost of oil is to be availed, it may be necessary to provide storage for a few month's requirements. *Day tanks* supply the daily fuel need of engines and may contain a minimum of about 8 hours of oil requirement of the engines. These tanks are usually placed high so that oil may flow to engines under gravity.

For satisfactory operation of a fuel oil supply system the following points should be taken care of :

1. There should be provisions for cleanliness and for changing over of lines during emergencies.
2. In all suction lines the pipe joints should be made tight.

3. Before being covered, all oil lines should be put under air pressure and the joints tested with soap solution. Small air leaks into the line can be the source of exasperating operating difficulties and are hard to remedy once the plant is in operation.
4. The piping between filter and the engine should be thoroughly oil flushed before being first placed in service.
5. Considerable importance should be given for cleanliness in handling bulk fuel oil. Dirt particles will ruin the fine lap of injection pumps or plug the injection nozzle orifices. So *high-grade filters* are of paramount importance to the diesel oil supply system.

Fuel Injection system

The mechanical heart of the Diesel engine is the *fuel injection system*. The engine can perform no better than its fuel injection system. A very small quantity of fuel must be measured out, injected, atomised, and mixed with combustion air. The mixing problem becomes more difficult—the larger the cylinder and faster the rotative speed. Fortunately the high-speed engines are the small-bore automotive types ; however, special combustion arrangements such as precombustion chambers, air cells, etc. are necessary to secure good mixing. *Engines driving electrical generators have lower speeds and simple combustion chambers.*

Functions of a fuel injection system

1. Filter the fuel.
2. Meter or measure the correct-quantity of fuel to be injected.
3. Time the fuel injection.
4. Control the rate of fuel injection.
5. Automise or break up the fuel to fine particles.
6. Properly distribute the fuel in the combustion chamber.

The injection systems are manufactured with great accuracy, especially the parts that actually meter and inject the fuel. Some of the tolerances between the moving parts are very small of the order of *one micron*. Such closely fitting parts require special attention during manufacture and hence the injection systems are *costly*.

Types of fuel injection systems

The following fuel injection systems are commonly used in diesel power station :

1. Common-rail injection system
2. Individual pump injection system
3. Distributor

Atomisation of fuel oil has been secured by (*i*) *air blast*, and (*ii*) *pressure spray*. Early diesel engines used air fuel injection at about 70 bar. This is sufficient not only to inject the oil, but also to atomise it for a rapid and through combustion. The expense of providing an air compressor and tank led to the development of "*solid*" injection, using a liquid pressure of between 100 and 200 bar which is sufficiently high to atomise the oil it forces through spray nozzles. Great advances have been made in the field of solid injection of the fuel through research and progress in fuel pump, spray nozzles, and combustion chamber design.

1. *Common-rail injection system :*

Two types of common-rail injection systems are shown in Figs. 4.11 and 4.12 respectively.

Refer to Fig. 4.11. A single pump supplies high-pressure fuel to header, a relief valve holds pressure constant. The control wedge adjusts the lift of mechanical operated valve to set amount and time of injection.

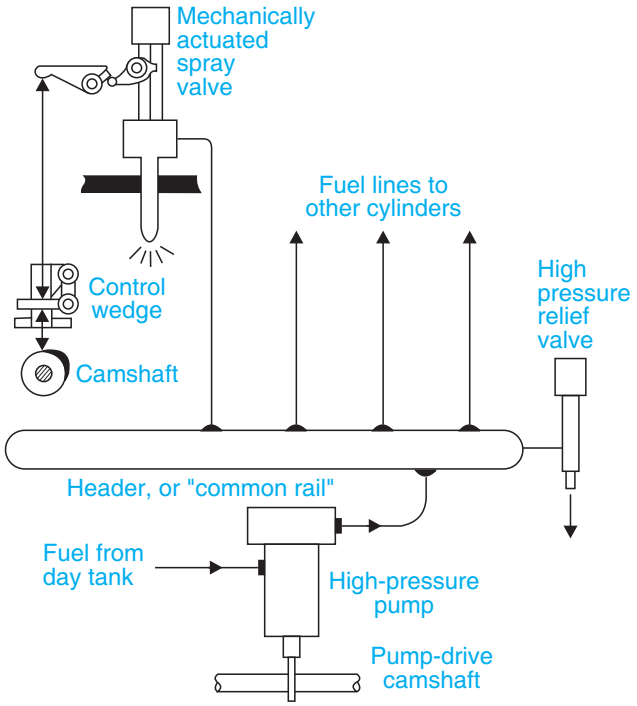


Fig. 4.11

Refer to Fig. 4.12. Controlled-pressure system has pump which maintains set head pressure. Pressure relief and timing valves regulate injection time and amount. Spring loaded spray valve acs merely as a check.

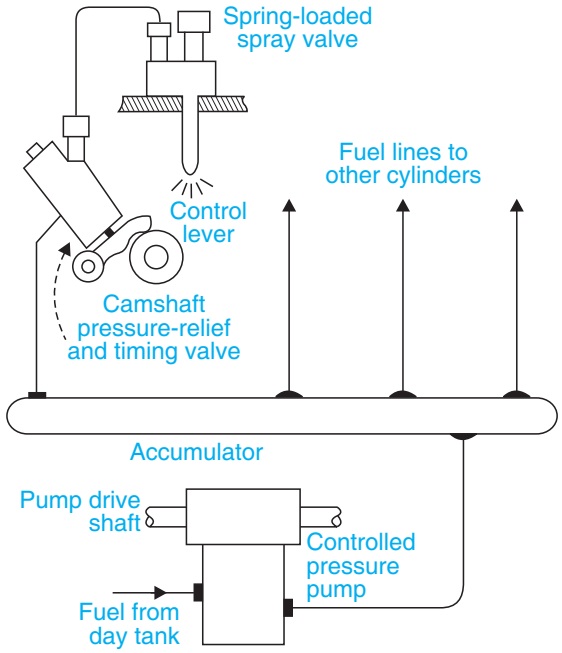


Fig. 4.12

2. *Individual pump injection system :*

Refer to Fig. 4.13. In this system an individual pump or pump cylinder connects directly to each fuel nozzle. Pump meters charge and control injection timing. Nozzles contain a delivery valve actuated by the fuel-oil pressure.

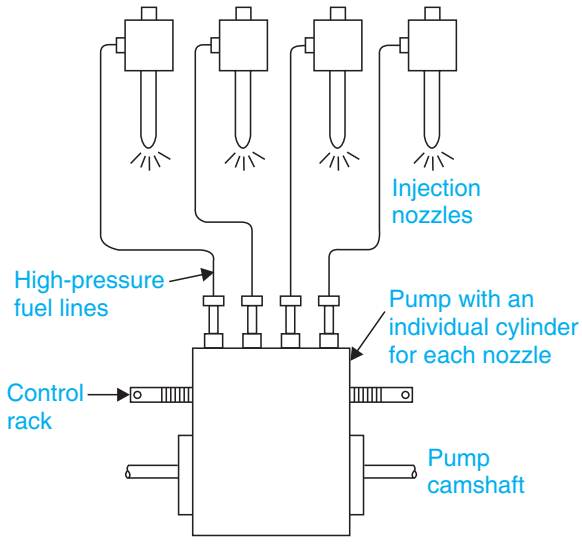


Fig. 4.13. Individual pump injection system.

3. *Distributor system :*

Refer to Fig. 4.14. In this system, the fuel is metered at a central point ; a pump pressurises, meters the fuel and times the injection. From here, the fuel is distributed to cylinders in correct firing order by cam operated poppet valves which open to admit fuel to the nozzles.

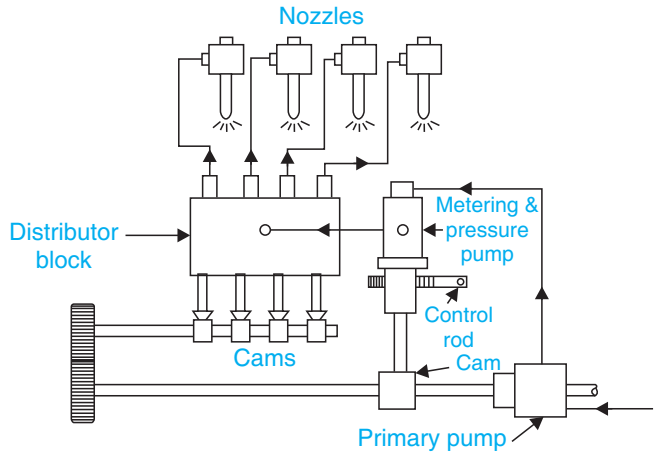


Fig. 4.14. Distributor system.

Fuel Pump

Refer to Fig. 4.15. *L* is the plunger which is driven by a cam and tappet mechanism at the bottom (not shown in Fig. 4.15), *B* is the barrel in which the plunger reciprocates. There is the rectangular vertical groove in the plunger which extends from top to another helical groove. *V* is the delivery valve which lifts off its seat under the liquid fuel pressure and against the spring force (*S*). The fuel pump is connected to fuel atomiser through the passage *P*. *SP* and *Y* are the spill and supply ports respectively. When the plunger is at its bottom stroke the ports *SP* and *Y* are uncovered (as shown in Fig. 4.15) oil from low pressure pump (not shown) after being filtered is forced into the barrel. When the plunger moves up due to cam and tappet mechanism, a stage reaches when both the ports *SP* and *Y* are closed and with the further upward movement of the plunger the fuel gets compressed. The high pressure thus developed lifts the delivery valve off its seats and fuel flows to atomiser through the passage *P*. With further rise of the plunger, at a certain moment, the port *SP* is connected to the fuel in the upper part of the plunger through the rectangular vertical groove by the helical groove, as a result of which a sudden drop in pressure occurs and the delivery valve falls back and occupies its seat against the spring force. The plunger is rotated by the rack *R* which is moved in or out by the governor. By changing the angular position of the helical groove (by rotating the plunger) of the plunger relative to the supply port, the length of stroke during which the oil is delivered can be varied and thereby quantity of fuel delivered to the engine is also varied accordingly.

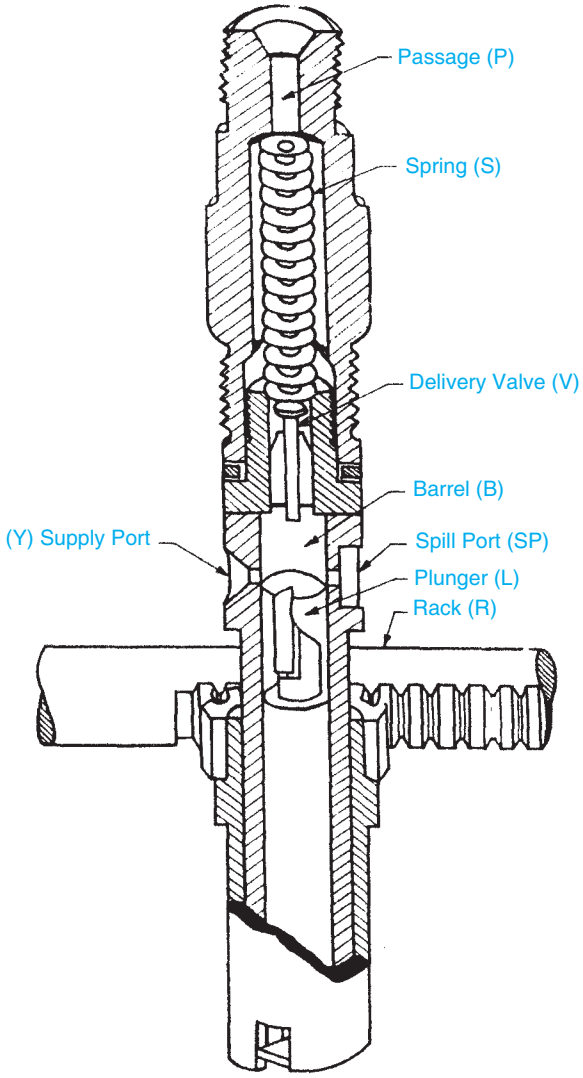


Fig. 4.15. Fuel pump.

Fuel atomiser or injector

Refer to Fig. 4.16. It consists of a nozzle valve (*NV*) fitted in the nozzle body (*NB*). The nozzle valve is held on its seat by a spring '*S*' which exerts pressure through the spindle *E*. '*AS*' is the adjusting screw by which the nozzle valve lift can be adjusted. Usually the nozzle valve is set to lift at 135 to 170 bar pressure. *FP* is the feeling pin which indicates whether valve is working properly or not. The fuel under pressure from the fuel pump enters the injector through the passages *B* and *C* and lifts the nozzle valve. The fuel travels down nozzle *N* and injected into the engine cylinder in the form of fine spray. Then the pressure of the oil falls, the nozzle valve occupies its seat under the spring force and fuel supply is cut-off. Any leakage of fuel accumulated above the valve is led to the fuel tank through the passage *A*. The leakage occurs when the nozzle valve is *worn out*.

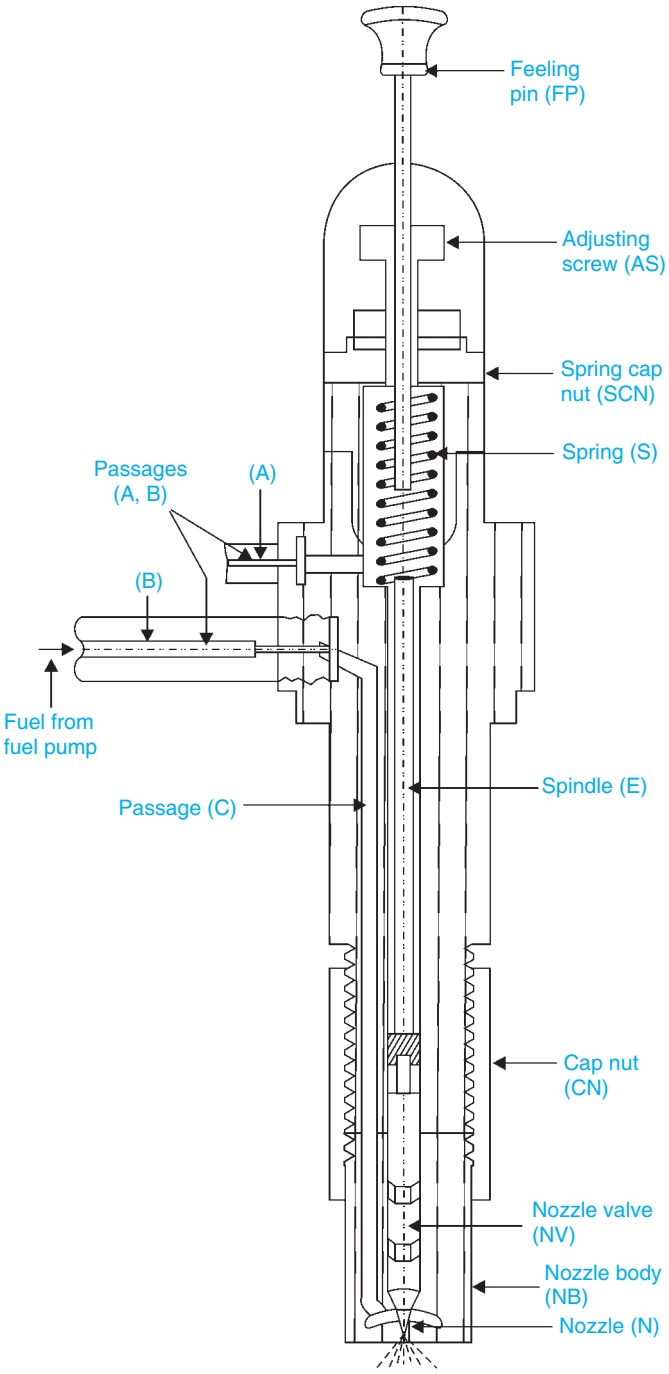


Fig. 4.16. Fuel atomizer or injector.

4.13.5. Cooling Systems

In an I.C. engine, the temperature of the gases inside the engine cylinder may very from 35°C or less to as high as 2750°C during the cycle. If an engine is allowed to run without external cooling, the cylinder walls, cylinder and piston will tend to assume the average temperature of the gases to which they are exposed, which may be of the order of 1000 to 1500°C. Obviously at such high temperature,

the metals will loose their characteristics and piston will expand considerably and sieze the liner. Of course theoretically thermal efficiency of the engine will improve without cooling but actually the engine will sieze to run. If the cylinder wall temperature is allowed to rise above a certain limit, about 65°C, the lubricating oil will begin to evaporate rapidly and both cylinder and piston may be damaged. Also high temperature may cause excessive stress in some parts rendering them useless for further operation. In view of this, part of the heat generated inside the engine cylinder is allowed to be carried away by the cooling system. *Thus cooling system is provided on an engine for the following reasons* :

1. The even expansion of piston in the cylinder may result in seizure of the piston.
2. High temperatures reduce strength of piston and cylinder liner.
3. Overheated cylinder may lead to pre-ignition of the charge, in case of spark ignition engine.
4. Physical and chemical changes may occur in lubricating oil which may cause sticking of piston rings and excessive wear of cylinder.

Almost 25 to 35 per cent of total heat supplied in the fuel is removed by the cooling medium. Heat carried away by lubricating oil and heat lost by radiation amounts 3 to 5 per cent of total heat supplied.

There are mainly two methods of cooling I.C. engine:

1. Air cooling 2. Liquid cooling.

1. Air cooling

In this method, heat is carried away by the air flowing over and around the engine cylinder. It is used in scooters, motorcycles etc. Here fins are cast on the cylinder head and cylinder barrel which provide additional conductive and radiating surface (Fig. 4.17). The fins are arranged in such a way that they are at right angles to the cylinder axis.

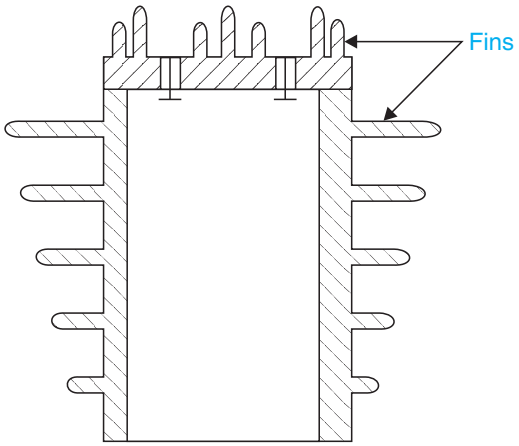


Fig. 4.17. Air cooling.

Advantages :

1. The design of the engine becomes simpler as no water jackets are required. The cylinder can be of identical dimensions and individually detachable and therefore cheaper to renew in case of accident etc.
2. Absence of cooling pipes, radiator etc. makes the cooling system simpler.
3. No danger of coolant leakage etc.
4. The engine is not subjected to freezing troubles etc. usually encountered in case of water cooled engine.
5. The weight per B.P. of the air-cooled engine is less than that of water-cooled engine.
6. In this case engine is rather a self contained unit as it requires no external components *e.g.* radiator, headers, tank etc.
7. Installation of air-cooled engines is easier.

Disadvantages :

1. Their movement is noisy.
2. Non-uniform cooling.
3. The output of air-cooled engine is less than that of a liquid-cooled engine.
4. Maintenance is not easy.
5. Smaller useful compression ratio.

2. Liquid cooling

In this method of cooling engines, the cylinder walls and heads are provided with jackets through which the cooling liquid can circulate. The heat is transferred from cylinder walls to the liquid by convection and conduction. The liquid becomes heated in its passage through the jackets and is itself cooled by means of an air-cooled radiator system. The heat from liquid in turn is transferred to air.

Various methods are used for circulating the water around the cylinder and cylinder head. These are :

1. Thermo-syphon cooling
2. Forced or pump cooling
3. Cooling with thermostatic regulator
4. Pressurised water cooling
5. Evaporative cooling.

1. *Thermo-syphon cooling :*

The basis of this type of cooling is the fact that water becomes light on heating. Fig. 4.18 shows the thermo-syphon cooling arrangement. The top of radiator is connected to the top of water jacket by a pipe and bottom of the radiator to the bottom of the water jacket. Water travels down the radiator across which air is passed to cool it. The air flow can take place due to vehicle motion or a fan can be provided for the purpose.

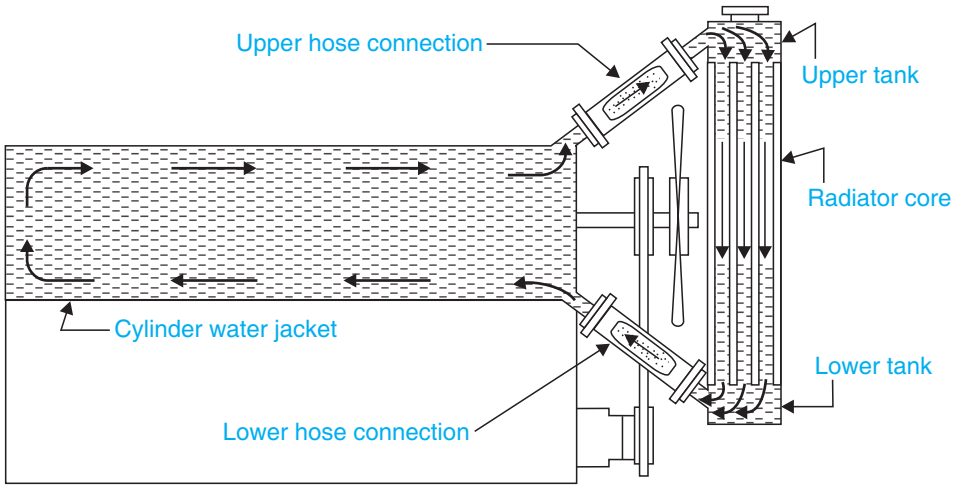


Fig. 4.18. Thermo-syphon cooling.

This system has the advantage that it is quite *simple and automatic* and is without any water pump unless there is leak, there is nothing to get out of order.

The major short coming of this system is that cooling depends only on the temperature and is independent of the engine speed. The rate of circulation is *slow and insufficient*. The circulation of water starts only after the engine has become hot enough to cause thermo-syphon action. This system requires that the radiator be above the engine for gravity flow of water to engine.

Thermo-syphon system is *not widely used at present.*

2. *Forced or pump system :*

Refer to Fig. 4.19. In this system, a pump is used to cause positive circulation of water in the water jacket. Usually the pump is belt driven from the engine.

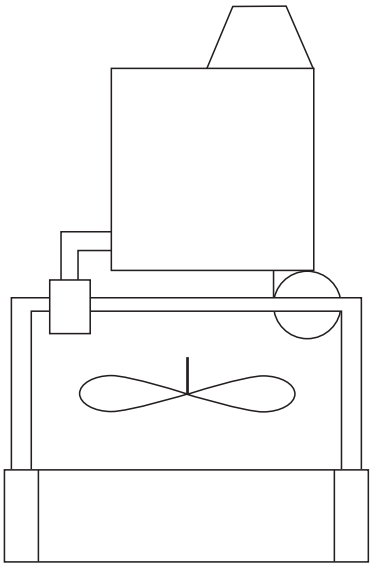


Fig. 4.19. Forced or pump system.

The advantage of forced system is that *cooling is ensured* under all conditions of operation.

This system entails the following *demerits* :

(*i*) The cooling is independent of temperature. This may, under certain circumstances, result in overcooling the engine. (*ii*) While moving uphill the cooling requirement is increased because more fuel is burned. However, the coolant circulation is reduced which may result in over-heating the engine. (*iii*) As soon as the engine is stopped the cooling also ceases. This is undesirable because cooling must continue till the temperatures are reduced to normal values.

3. *Thermostat cooling :*

Too lower cylinder barrel temperature, may result in severe corrosion damage due to condensation of acids on the barrel wall. To avoid such a situation it is customary to use a thermostat (a temperature controlling device) to stop flow of coolant below a pre-set cylinder barrel temperature. Most modern cooling system employ a thermo-static device which prevents the water in the engine jacket from circulating through the radiator for cooling until its temperature has reached to a value suitable for efficient engine operation.

Fig. 4.20 shows a systematic diagram of a thermostatically controlled cooling system. Also shown is a typical thermostat (Fig. 4.21). It consists of bellows which are made of thin copper tubes, partially filled with a volatile liquid like ether or methyl alcohol. The volatile liquid changes into vapour at the correct working temperature, thus creating enough pressure to expand the bellows. The temperature at which the thermostat operates is set by the manufacturers and cannot be altered. The movement of the bellows opens the main valve in the ratio of temperature rise, increasing or restricting the flow of water from engine to the radiator. Hence when the normal

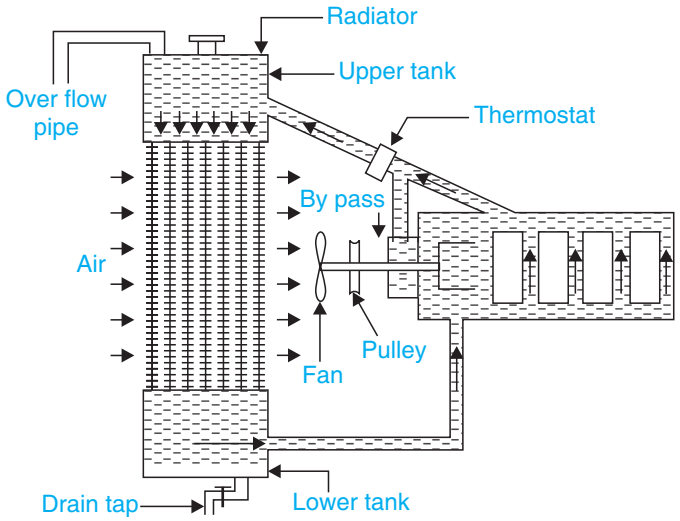


Fig. 4.20. Thermostatically controlled cooling system.

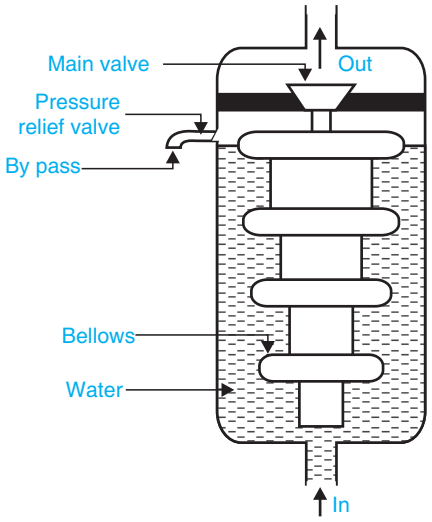


Fig. 4.21. Typical thermostat.

temperature of the engine has been reached the valve opens and circulation of water commences. When the unit is closed the gas condenses and so the pressure falls. The bellows collapse and the thermostat seats on its seat and circulation around thermostat stops. When the thermostat valve is not open and the engine is running the water being pumped rises in pressure and causes the pressure relief valve to open. Thus the water completes its circulation through the by-pass as shown in Figs. 4.20 and 4.21. Now when the temperature of water around the engine-cylinder rises upto a certain limit, it causes the thermostat valve to open. The pressure of water being pumped falls and pressure relief valve closes. So the flow of cooling water in the normal circuit commences through the radiator. This accelerates the rise of temperature of the cylinder walls and water and more power is developed in a few moments of the starting of the engine.

Another method of warming up the radiator water upto the normal temperature is by utilising the shutter in the radiator in order to restrict the incoming air through the radiator till the engine warms up. Thereafter, the shutter is opened gradually so that the desired rate of cooling is achieved.

4. *Pressurised water cooling:*

The boiling point of the coolant can be increased by increasing its pressure. This allows a greater heat transfer to occur in the radiator due to a larger temperature differential. Usually the water pressure is kept between 1.5 bar to 2.0 bar. Use of pressurised water cooling requires an additional valve, called vacuum valve, to avoid formation of vacuum when the water is cooled after engine has stopped. A safety valve in the form of pressure relief valve is provided so that whenever cap is opened the pressure is immediately relieved.

5. *Evaporative cooling:*

In this system, also called steam or vapour cooling, the temperature of the cooling water is allowed to reach a temperature of 100°C. This method of cooling utilises the high latent heat of vapourisation of water to obtain cooling with minimum of water. Fig. 4.22 shows such a system.

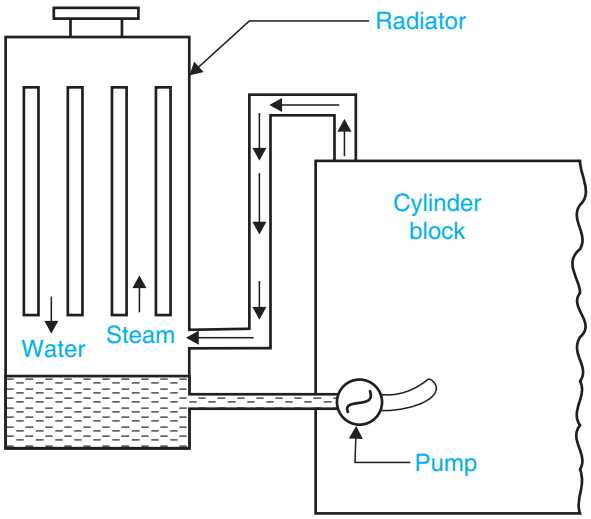


Fig. 4.22. Evaporating cooling.

The cooling circuit is such that coolant is always liquid but the steam formed is flashed off in the separate vessel. The make up water so formed is sent back for cooling. This system is used for cooling of many types of *industrial engines.*

Advantages of liquid cooling :

1. Compact design of engine with appreciable smaller frontal area is possible.
2. The fuel consumption of a high compression liquid-cooled engine is rather lower than for air-cooled one.

3. More even cooling of cylinder barrels and heads due to jacketing makes it easier to reduce the cylinder head and valve seating temperature.
4. In case of water-cooled engine installation is not necessary at the front of mobile vehicles, aircrafts etc. as the cooling system can be conveniently located wherever required. This is not possible in case of air-cooled engines.
5. The size of the engine does not involve serious problem as far as design of cooling system is concerned. In case of air-cooled engines particularly in high horse power range difficulty is encountered in circulation of required quantity of air for cooling purposes.

Disadvantages :

1. This is dependent system in which supply of water/liquid for circulation in the jacket is required.
2. Power absorbed by the pump for water circulation is considerably higher than that for cooling fans.
3. In the event of failure of cooling system serious damage may be caused to the engine.
4. Cost of system is considerably high.
5. System requires considerable attention for the maintenance of various parts of system.

4.13.6. Lubrication Systems

Lubrication is the admittance of oil between two surface having relative motion. The purpose of lubrication may be one or more of the following :

1. To reduce friction and wear between the parts having relative motion.
2. To cool the surfaces by carrying away heat generated due to friction.
3. To seal a space adjoining the surfaces such as piston rings and cylinder liner.
4. To clean the surface by carrying away the carbon and metal particles caused by wear.
5. To absorb shock between bearings and other parts and consequently reduce noise.

The main parts of an engine which need lubrication are as given below :

(*i*) Main crankshaft bearings.
(*ii*) Big-end bearings.
(*iii*) Small end or gudgeon pin bearings.
(*iv*) Piston rings and cylinder walls.
(*v*) Timing gears.
(*vi*) Camshaft and cam shaft bearings.
(*vii*) Valve mechanism.
(*viii*) Valve guides, valve tappets and rocker arms.

Various lubrication systems used for I.C. engines may be classified as :

1. Wet sump lubrication system.
2. Dry sump lubrication system.
3. Mist lubrication system.

1. Wet sump lubrication system

These systems employ a large capacity oil sump at the base of crankchamber, from which the oil is drawn by a low pressure oil pump and delivered to various parts. Oil then gradually returns back to the sump after serving the purpose.

(a) ***Splash system:*** Refer to Fig. 4.23. This system is used on some *small four stroke stationary engines.* In this case the caps on the big end bearings of connecting rods are provided with scoops which, when the connecting rod is in the lowest position, just dip into oil troughs and thus directs the oil through holes in the caps to the big end bearings. Due to splash of oil it reaches the lower portion of the cylinder walls, crankshaft and other parts requiring lubrication. Surplus oil eventually flows back to the oil sump. Oil level in the troughs is maintained by means of a oil pump which takes oil from sump, through a filter.

Splash system is suitable for low and medium speed engines having moderate bearing load pressures. For high performance engines, which normally operate at high bearing pressures and rubbing speeds this system does not serve the purpose.

(b) ***Semi-pressure system:*** This method is a combination of splash and pressure systems. It incorporates the advantages of both. In this case main supply of oil is located in the base of crank-chamber. Oil is drawn from the lower portion of the sump through a filter and is delivered by means of a gear pump at pressure of about 1 bar to the main bearings. The big end bearings are lubricated by means of a spray through nozzles. Thus oil also lubricates the cams, crankshaft bearings, cylinder walls and timing gears. An oil pressure gauge is provided to indicate satisfactory oil supply.

The system is less costly to install as compared to pressure system. It enables higher bearing loads and engine speeds to be employed as compared to splash system.

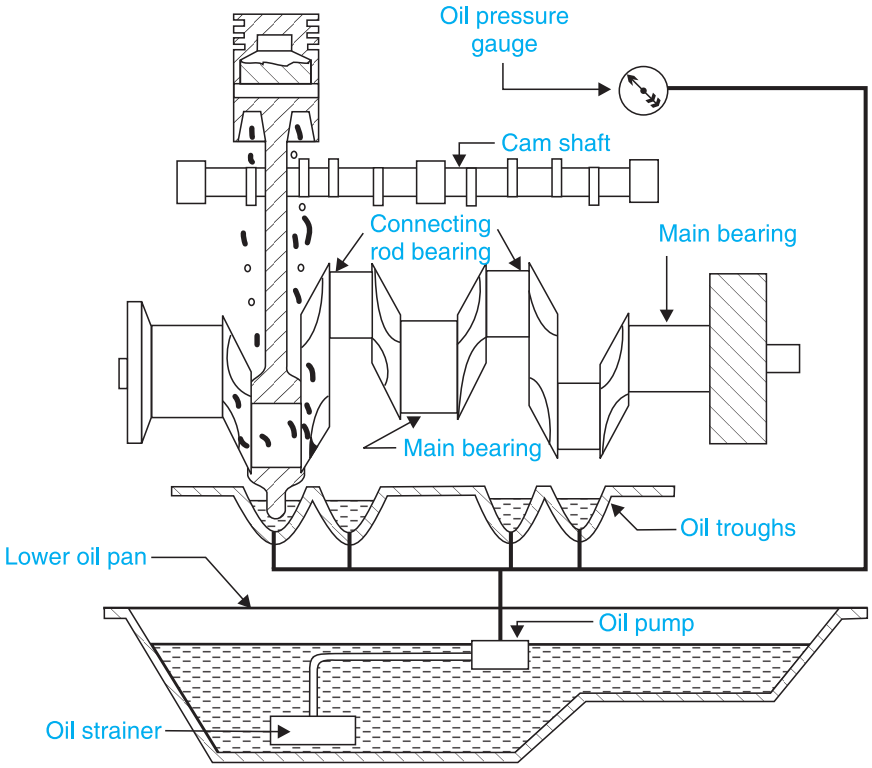


Fig. 4.23. Splash system.

(c) ***Full pressure system:*** In this system, oil from oil sump is pumped under pressure to the various parts requiring lubrication. Refer to Fig. 4.24. The oil is drawn from the sump through filter and pumped by means of a gear pump. Oil is delivered by the pressure pump at pressure ranging from 1.5 to 4 bar. The oil under pressure is supplied to main bearings of crankshaft and camshaft. Holes drilled through the main crankshafts bearing journals, communicate oil to the big end bearings and also small end bearings through holes drilled in connecting rods. A pressure gauge is provided to confirm the circulation of oil to the various parts. A *pressure regulating valve* is also provided on the delivery side of this pump to prevent excessive pressure.

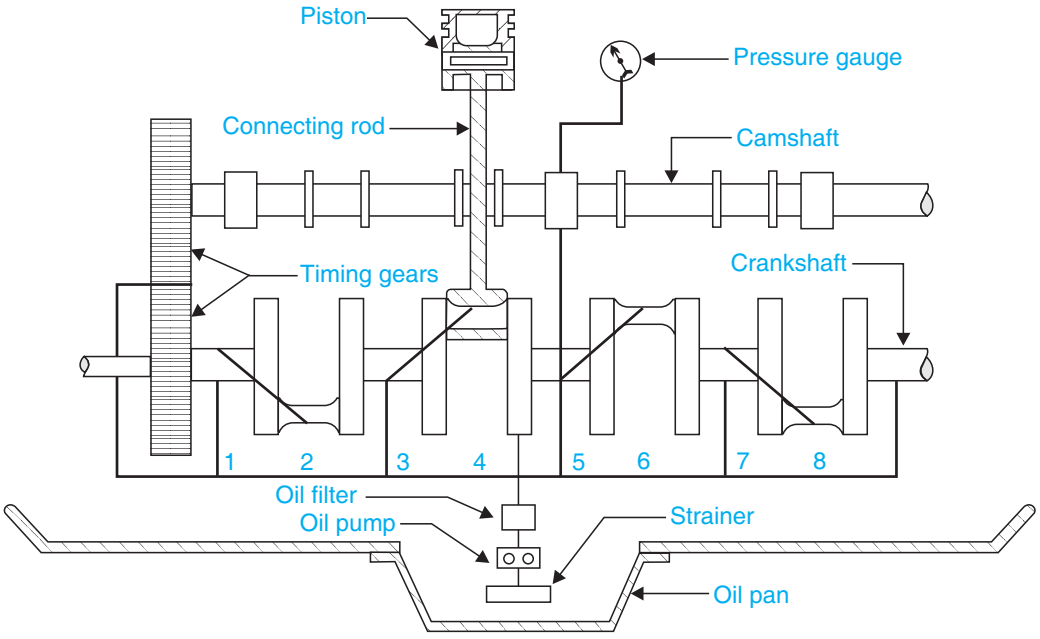


Fig. 4.24. Full pressure system.

This system finds favour from most of the engine manufacturers as it allows high bearing pressure and rubbing speeds.

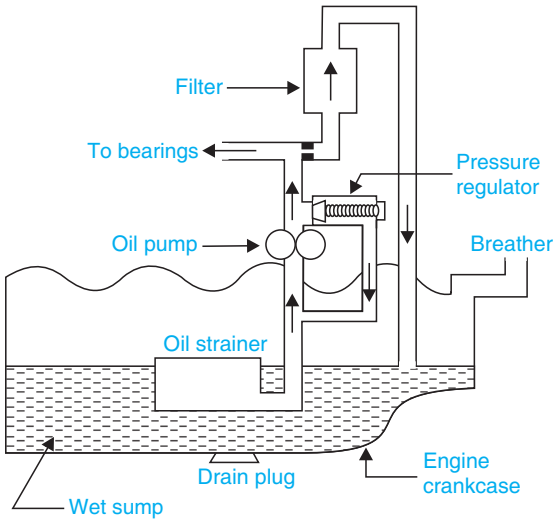


Fig. 4.25. Wet sump lubrication system.

The general arrangement of *wet sump lubrication system* is shown in Fig. 4.25. In this case oil is always contained in the sump which is drawn by the pump through a strainer.

2. Dry sump lubrication system

Refer to Fig. 4.26. In this system, the oil from the sump is carried to a separate storage tank out side the engine cylinder block. The oil from sump is pumped by means of a sump pump through filters to the storage tank. Oil from storage tank is pumped *to the engine cylinder* through oil cooler. Oil pressure may varies from 3 to 8 kgf/cm^2. *Dry sump lubrication system is generally adopted for high capacity engines.*

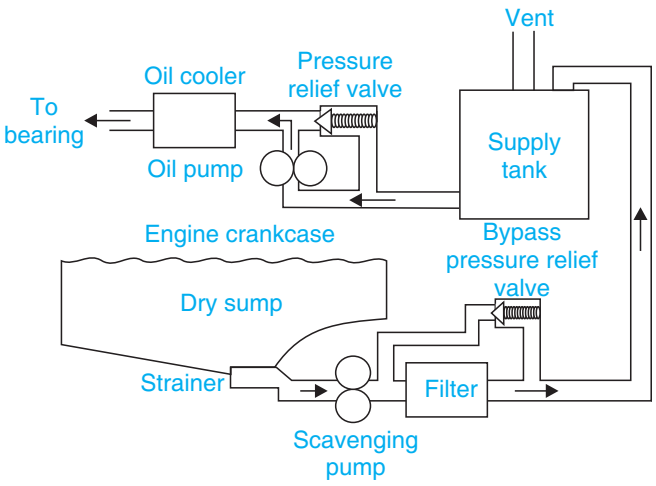


Fig. 4.26. Dry sump libication system.

3. Mist lubrication system

This system is used for two stroke cycle engines. Most of these engines are crankcharged, *i.e.* they employ crankcase compression and thus, are not suitable for cran case lubrication. These engines are lubricated by adding 2 to 3 per cent lubricating oil in the fuel tank. The oil and fuel mixture is induced through the carburettor. The gasoline is vaporised ; and the oil in the form of mist, goes via crankcase into the cylinder. The oil which impinges on the crankcase walls lubricates the main and connecting rod bearings, and rest of the oil which passes on the cylinder during charging and scavanging periods, lubricates the piston, piston rings and the cylinder.

Advantages:

1. System is simple.
2. Low cost (because no oil pump filter etc. are required).

Disadvantages:

1. A portion of the lubricating oil invariably burns in combustion chamber. This bearing oil when burned, and still worse, when partially burned in combustion chamber leads to heavy exhaust emissions and formation of heavy deposit on piston crown, ring grooves and exhaust port which interferes with the efficient engine operation.
2. One of the main functions of lubricating oil is the protection of anti-friction bearings etc. against corrosion. Since the oil comes in close contact with acidic vapours produced during the combustion process, it rapidly loses its anti-corrosion properties resulting in corrosion damage of bearings.
3. For effective lubrication oil and fuel must be thoroughly mixed. This requires either separate mixing prior to use or use of some additive to give the oil good mixing characteristics.
4. Due to higher exhaust temperature and less efficient scavening the crank case oil is diluted. In addition some lubricating oil burns in combustion chamber. This results in 5 to 15 per cent higher lubricant consumption for two stroke engine of similar size.
5. Since there is no control over the lubrication oil, once introduced with fuel, most of the two stroke engines are *over-oiled* most of the time.

4.13.7. Engine Starting System

The following three are the *commonly used starting systems* in large and medium size engines :

1. Starting by an auxiliary engine.
2. Use of electric motors or self starters.
3. Compressed air system.

1. Starting by an auxiliary engine (generally petrol driven) :

In this system an auxiliary engine is mounted close to the main engine and drives the latter through a clutch and gears. The clutch is first disengaged and the auxiliary engine started by hand or by a self starter motor. When it has warmed up and runs normally the drive gear is engaged through the clutch, and the main engine is cranked for starting. To avoid the danger of damage to drive gear it is desirable to have an over-running clutch or starter type drive.

2. Use of electric motors or self starters :

These are employed for small diesel and gasoline engines. A storage battery of 12 to 36 volts is used to supply power to an electric motor which is geared to the flywheel with arrangement for automatic disengagement after the engine has started. The motor draws a heavy current and is designed to be engaged continuously for about 30 seconds only, after which it is required to cool off for a minute or so, and then re-engaged. This is done till the engine starts up. When the engine is running a small D.C. generator on the engine serves to charge the battery.

3. Compressed air system :

The compressed air system is commonly used for starting large diesel engines employed for stationary power plant service. Compressed air at about 17 bar supplied from an air tank or bottle is admitted to a few of the engine cylinders making them work like reciprocating air motors to run the engine shaft. Fuel is admitted to the remaining cylinders and ignites in the normal way causing the engine to start. The air bottle or tank is charged by a motor or gasoline engine driven compressor. The system includes the following :

(*i*) Storage tank/vessel

(*ii*) A safety valve

(*iii*) Interconnecting pipe work.

Methods of Starting and Stopping Engines

Although starting procedure may differ from engine to engine but some common steps are listed below :

Starting of engines :

1. In case of *electric motor* starting check the condition of storage battery. If *compressed air system* is used, then air pressure may be checked first and the air system inspected for possible leakage.

2. As prescribed by the manufactures, all necessary checks for fuel, lubricating oil and cooling water should be made.

3. Crank the engine after ensuring that all load is put off and decompression device is in use, and then let it start.

4. For a few minutes run the engine at slow speed and observe the working of fuel pumps, lubricating systems, fuel and oil pressures etc. The lubrication of generator and excited bearings should also be checked.

5. Increase the engine speed gradually till it synchronizes with the station bus-bar.

6. Connect the generator to the bus-bar when it is in synchronism and increase the engine speed till it begins to share the desired load.

Stopping of engines :

1. Reduce the speed of the engine gradually until practically no power is delivered by the alternator.

2. Disconnect the unit from the bus and allow the engine to idle for a few minute, and then stop it in confirmity with the instructions detailed by the manufacturers.

4.13.8. Governing System

The function of the governing system is to maintain the speed of the engine constant irrespective of load on the plant. This is done generally by varying the fuel supply to the engine according to the load.

4.14. COMBUSTION PHENOMENON IN C.I. ENGINES

The process of combustion in the compression ignition (C.I.) engine is fundamentally different from that in a spark-ignition engine. In C.I. engine combustion occurs by the high temperature produced by the compression of the air, *i.e.* it is an *auto-ignition*. For this a minimum compression ratio of 12 is required. The efficiency of the cycle increases with higher values of compression ratio but the maximum pressure reached in the cylinder also increases. This requires heavier construction. The upper limit of compression ratio in a C.I. engine is due to mechanical factor and is a compromise between high efficiency and low weight and cost. The normal compression ratios are in the range of 14 to 17, but may be upto 23. The air-fuel ratios used in the C.I. engine lie between 18 and 25 as against about 14 in the S.I. engine, and hence C.I. engines are bigger and heavier for the same power than S.I. engines.

In the C.I. engine, the intake is air alone and the fuel is injected at high pressure in the form of fine droplets near the end of compression. This leads to delay period in the C.I. engine, is greater than that in the S.I. engine. The *exact phenomenon of combustion in the C.I. engine* is explained below.

Each minute droplet of fuel as it enters the highly heated air of engine cylinder is quickly surrounded by an envelope of its own vapour and this, in turn, and an appreciable interval is inflamed at the surface of the envelope. To evaporate the liquid, latent heat is abstracted from the surrounding air which reduces the temperature of the thin layer of air surrounding the droplet, and some time must elapse before this temperature can be raised again by abstracting heat from the main bulk of air in this

vicinity. As soon as this vapour and the air in actual contact with it reach a certain temperature, ignition will take place. Once ignition has been started and a flame established the heat required for further evaporation will be supplied from that released by combustion. The vapour would be burning as fast as it can find fresh oxygen, *i.e.*, it will depend upon the rate at which it is moving through the air or the air is moving past it.

In the C.I. engine, the fuel is not fed in at once but is spread over a definite period. The first arrivals meet air whose temperature is only little above their self-ignition temperature and the delay is more or less prolonged. The later arrivals find air already heated to a far higher temperature by the burning of their predecessors and therefore light up much more quickly, almost as they issue from the injector nozzle, but their subsequent progress is handicapped for there is less oxygen to find.

If the air within the cylinder were motionless, only a small proportion of the fuel would find sufficient oxygen, for it is impossible to distribute the droplets uniformly throughout the combustion space. Therefore some air movement is absolutely essential, as in the S.I. engine. But there is a fundamental difference between the air movements in the two types of engines. In the S.I. engine we call it *turbulence* and mean a confusion of whirls and eddies with no general direction of flow, (to break up the surface of the flame front, and to distribute the shreds of flame throughout an externally prepared combustible mixture). In the C.I. engine we call it *air swirl* and mean an orderly movement of the whole body of the air, with or without some eddying or turbulence, so as to bring a continuous supply of fresh air to each burning droplet and sweep away the products of combustion which otherwise tend to suffocate it.

Three phases of C.I. engine combustion

In the C.I. engine, combustion may be considered in three distinct stages as shows in Fig. 4.27.

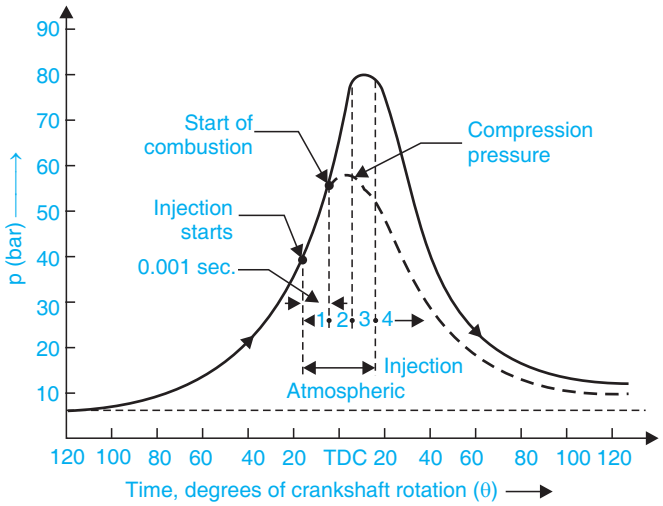


Fig. 4.27. Combustion phenomenon of C.I. engine.

1. Ignition delay period.
2. Period of rapid or uncontrolled combustion.
3. Period of controlled combustion.

The *third phase is followed by 'after burning'* (or burning on the expansion stroke), *which may be called the fourth phase of combustion*.

1. *Ignition delay period:* The delay period is counted from the start of injection to the point where the p-θ combustion curve departs from air compression (or no ignition or motoring) curve. The delay period can be roughly sub-divided into *physical delay* and *chemical delay*. The *period of physical delay* is the time between the beginning of injection and the attainment of chemical reaction conditions. In the *physical delay period,* the fuel is atomized, vaporized, mixed with air, and raised in temperature. In the *chemical delay period* reaction starts slowly and then accelerates until inflammation or ignition takes place (it may be noted that the ignition delay in the S.I. engine is essentially equivalent to the chemical delay in the C.I. engine).

The delay period exerts a great influence in the C.I. engine combustion phenomenon. It is clear that the pressure reached during the second stage will depend upon the duration of the delay period ; the longer the delay, the more rapid and higher the pressure rise, since more fuel will be present in the cylinder before the rate of burning comes under control. This causes rough running and may cause *diesel knock*. Therefore we must *aim to keep the delay period as short as possible, both for the sake of smooth running and in order to maintain control over the pressure changes. But some delay period is necessary otherwise the droplets would not be dispersed in the air for complete combustion*. However, the delay period imposed upon is greater than what is needed and the designer's efforts are to shorten it as much as possible.

2. *Period of rapid or uncontrolled combustion:* The second stage of combustion in C.I. engines, after the delay period, is the period of rapid or uncontrolled combustion. This period is counted from the end of the delay period to the point of maximum pressure on the indicator diagram. In this second stage of combustion, the rise of pressure is rapid because during the delay period the droplets of fuel have had time to spread themselves out over a wide area and they have fresh air all around them. About one-third of heat is evolved during this process.

The rate of pressure rise depends on the amount of fuel present at the end of delay period, degree of turbulence, fineness of atomization and spray pattern.

3. *Period of controlled combustion:* At the end of second stage of combustion, the temperature and pressure, are so high that the fuel droplets injected in the third stage burn almost as they enter and any further pressure rise can be controlled by purely mechanical means, *i.e.* by the injection rate. The period of controlled combustion is assumed to end at maximum cycle temperature. The heat

evolved by the end of controlled combustion is about 70 to 80 per cent.

4. *After burning:* The combustion continues even after the fuel injection is over, because of poor distribution of fuel particles. This burning may continue in the expansion stroke upto 70 to 80° of crank travel from T.D.C. This continued burning, called the *after burning*, may be considered as the *fourth stage of the combustion.* The total heat evolved by the end of entire combustion process is 95 to 97% ; 3 to 5% of heat goes as unburned fuel in exhaust.

In the *p-V* diagram, the stages of combustion are not seen because of little movement of piston with crank angle at the end and reversal of stroke. So for studying the combustion stages, therefore, a pressure-crank angle or time, *p*-θ or *p-t* diagram is invariable used. In the actual diagram, the various stages of combustion look merged, yet the individual stage is distinguishable.

4.15. DELAY PERIOD (OR IGNITION LAG) IN C.I. ENGINES

—In C.I. (compression ignition) engine, the fuel which is in atomised form is considerably colder than the hot compressed air in the cylinder. Although the actual ignition is almost instantaneous, an appreciable time elapses before the combustion is in full progress. This time occupied is called the *delay period* or *ignition lag. It is time immediately following injection of the fuel during which the ignition process is being initiated and the pressure does not rise beyond the value it would have due to compression of air* :

—The delay period extends for about 13°, movement of the crank. The time for which it occurs decreases with increase in engine speed.

The delay period depends upon the following :

(*i*) Temperature and pressure in the cylinder at the time of injection.

(*ii*) Nature of the fuel mixture strength.

(*iii*) Relative velocity between the fuel injection and air turbulence.

(*iv*) Presence of residual gases.

(*v*) Rate of fuel injection.

(*vi*) To small extent the finess of the fuel spray.

The delay period increases with load but is not much affected by injection pressure.

—The delay period should be as short as possible since a long delay period gives a more rapid rise in pressure rise and thus causes knocking.

4.16. DIESEL KNOCK

If the delay period in C.I. engines is long a large amount of fuel will be injected and accumulated in the chamber. The auto-ignition of this large amount of fuel may cause high rate of pressure rise and high maximum pressure which may cause *knocking* in diesel engines. A long delay period not only increases the amount of fuel injected by the moment of ignition but also improves the homogeneity of the fuel-air mixture and its chemical preparedness for explosion type self-ignition similar to detonation is S.I. engines.

The following are the differences in the knocking phenomena of the S.I. and C.I. engines :

1. In the *S.I. engine*, the detonation occurs near the *end of combustion* whereas in the *C.I. engine* detonation occurs near the *beginning of combustion.*
2. The detonation in the S.I. engine is of a *homogeneous charge* causing *very high rate of pressure rise* and very high maximum pressure. In the C.I. engine, the fuel and air are *imperfectly mixed* and hence the *rate of pressure rise is normally lower than that in the detonating part of the charge in the S.I. engine.*
3. In the C.I. engine the fuel is injected into the cylinder only at the end of the compression stroke, there is no question of pre-ignition as in S.I. engine.
4. In the S.I. engine, it is relatively easy to distinguish between knocking and non-knocking operation as the human ear easily finds the distinction.

4.17. CETANE NUMBER

—The cetane rating of a diesel fuel is a *measure of its ability to auto-ignite quickly* when it is injected into the compressed and heated air in the engine. Though ignition delay is affected by several engine design parameters such as compression ratio, injection rate, injection time, inlet air temperature etc., it is also dependent on hydrocarbon composition of the fuel and to some extent on its volatility characteristic. *The cetane number is a numerical measure of the influence the diesel fuel has in determining the ignition delay. Higher the cetane rating of the fuel lesser is the propensity for diesel knock.*

—The procedure for obtaining cetane number is similar to that for obtaining the octane number of petrols. Reference mixtures of *cetane* ($C_{16}H_{34}$) (high ignitability), and α*-methyl-naphthalene* ($C_{11}H_{10}$) (low ignitability), are used. *The mixture is made by volume and the ignitability of the test fuel is quoted as the percentage of cetane in the reference mixture which has the same ignitability.*

—For higher speed engines, the cetane number required is about 50, for medium speed engines about 40, and for slow speed engines about 30.

—Cetane number is the most important single fuel property which affects the exhaust emissions, noise and startability of a diesel engine. In general, *lower the cetane number higher are the hydrocarbon emissions and noise level*. Low centane fuels increase ignition delay so that start of combustion is near to top dead centre. This is similar to retarding of injection timing which is also known to result in higher hydrocarbon levels.

—In general, *a high octane value implies a low cetane value*.

4.18. BASIC DESIGNS OF C.I. ENGINE COMBUSTION CHAMBERS

In C.I. engines several types of combustion chambers are used. Each of these has its own peculiarities, and desirable, as well as undesirable features. Any one of these combustion chambers may produce good results in one field of application, but less desirable, or even poor results in another. No one combustion chamber design has yet been developed which will produce the best result is all types of engines. The particular design chosen, then, must be that which accomplishes the best performance for the application desired.

Four specific design which find wide use in C.I. engines are discussed below :

1. The non-turbulent type
   (*i*) Open combustion chamber.
2. The turbulent type
   (*i*) Turbulent chamber
   (*ii*) Precombustion chamber
   (*iii*) Energy cell.

1. Non-turbulent type

Fig. 4.28 (*a*) illustrates the usual design of *open combustion chamber*, which is representative of non-turbulent type. The fuel is injected directly into the upper portion of the cylinder, which acts as the combustion chamber. This type depends little on turbulence to perform the mixing. Consequently, the heat loss to the chamber walls is relatively low, and easier starting results. In order to obtain proper penetration and dispersal of the fuel necessary for mixing with the air, however, high injection pressures and multi-orifice nozzles are required. This necessitates small nozzle openings and result in more frequent clogging or diversion of the fuel spray by accumulated carbon particles, with consequent higher maintenance costs.

This type of chamber is ordinarily used on *low speed engines,* where injection is spread through a greater period of time and thus ignition delay is a relatively less important factor. Consequently, less costly fuels with longer ignition delay may be used.

2. Turbulent type

The turbulent chamber, precombustion chamber, and energy cell are variation of the turbulent type of chamber, and are illustrated in Fig. 4.28 (*b*), (*c*) and (*d*).

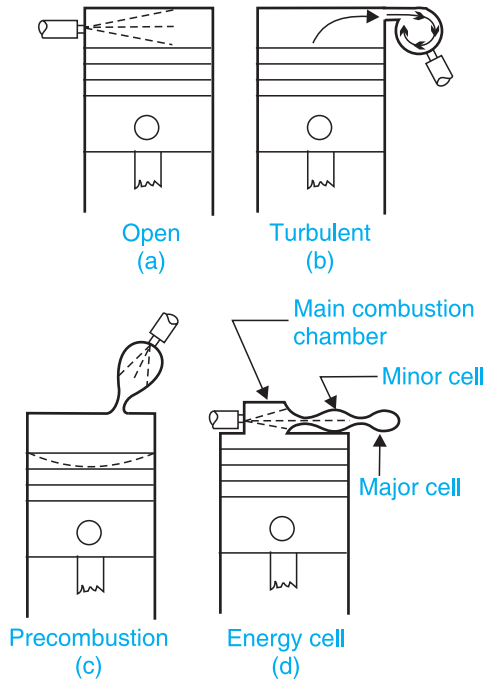


Fig. 4.28. Some commonly used C.I. engine combustion chambers.

—In the '*turbulent chamber*', Fig. 4.28 *(b)*, the upward moving piston forces a flow of air into a small antechamber, thus imparting a rotary motion to the air passing the pintle type nozzle. As the fuel is injected into the rotating air, it is partially mixed with this air, and commences to burn. The pressure built up in the antechamber by the expanding burning gases force the burning and unburned fuel and air mixtures back into the main chamber, again imparting high turbulence and further assisting combustion.

—In the '*precombustion chamber*', Fig. 4.28 *(c)*, the upward moving piston forces part of the air into a side chamber, called the precombustion chamber. Fuel is injected into the air in the precombustion chamber by a pintl type nozzle. The combustion of the fuel and air produces high pressures in the precombustion chamber, thus creating high turbulence and producing good mixing and combustion.

—The '*energy cell*' is more complex than the precombustion chamber. It is illustrated in Fig. 4.28 *(d)*. As the piston moves up on the compression stroke, some of

the air is forced into the major and minor chambers of the energy cell. When the fuel is injected through the pintle type nozzle, part of the fuel passes across the main combustion chamber and enters the minor cell, where it is mixed with the entering air. Combustion first commences in the main combustion chamber where the temperature is higher, but the rate of burning is slower in this location, due to insufficient mixing of the fuel and air. The burning in the minor cell is slower at the start, but due to better mixing, progresses at a more rapid rate. The pressures built up in the minor cell, therefore, force the burning gases out into the main combustion chamber, thereby creating added turbulence and producing better combustion in this chamber. In the mean time, pressure is built up in the major cell, which then prolongs the action of the jet stream entering the main chamber, thus continuing to induce turbulence in the main chamber.

Summarily it may be said that a particular combustion chamber design must be chosen to perform a given job. No one combustion chamber can produce an ultimate of performance in all tasks. The design of the chamber must be based on a compromise, after full considerations of the following factors : (*i*) Heat lost to combustion chamber walls, (*ii*) Injection pressure, (*iii*) Nozzle design, (*iv*) Maintenance, (*v*) Ease of starting, (*vi*) Fuel requirement, (*vii*) Utilisation of air, (*viii*) Weight relation of engine to power output, (*ix*) Capacity for variable speed operation.

4.19. SUPERCHARGING

The purpose of supercharging is to raise the volumetric efficiency above that value which can be obtained by normal aspiration.

The engine is an air pump. Increasing the air consumption permits greater quantities of fuel to be added, and results in a greater potential output. The indicated power produced is almost directly proportional to the engine air consumption. While brake power is not so closely related to air consumption, it is nevertheless, dependent upon the mass of air consumed. It is desirable, then, that the engine takes in greatest possible mass of air.

Three possible methods which might be utilized to increase the air consumption of an engine are :

1. *Increasing the piston displacement*, but this increases the size and weight of the engine, and *introduces additional cooling problems*.
2. *Running the engine at higher speeds*, which results in *increased fluid and mechanical friction losses, and imposes greater inertia stresses on engine parts*.
3. *Increasing the density of the charge*, such that a greater mass of charge is introduced into the same volume or same total piston displacement.

The last method of increasing the air capacity of an engine is widely used, and is termed *supercharging*.

The apparatus used to increase the air density is known as a *supercharger*. It is merely a *compressor* which provides a denser charge to the engine, thereby enabling the consumption of a greater mass of charge with the same total piston displacement. During the process of compressing the charge, the supercharger produces the following effects :

(*i*) *Provides better mixing of the air-fuel mixture*. The turbulent effect created by the supercharger assists in additional mixing of the fuel and air particles. The arrangement of certain types of superchargers, particularly the *centrifugal type*, also encourages more even distribution of the charge to the cylinders.

(*ii*) *The temperature of the charge is raised as it is compressed, resulting in a higher temperature within the cylinders*. This is partially beneficial in that it helps to produce better vapourisation of fuel (in case of S.I. engines) but deterimental in that it tends to lessen the density of the charge. The increase in temperature of the charge also effects the detonation of the fuel.

Supercharging tends to increase the possibility of detonation in a S.I. engine and lessen the possibility in a C.I. engine.

(*iii*) Power is required to drive the supercharger. This is usually taken from the engine and thereby removes, from over-all engine output, some of the gain in power obtained through supercharging.

Compressors used are of the following three types :

(*i*) ***Positive displacement type*** used with many reciprocating engines in stationary plants, vehicles and marine installations.

(*ii*) ***Axial flow type*** seldom used to supercharge reciprocating engines, it is widely used as the compressor unit of the *gas turbines.*

(*iii*) ***Centrifugal type*** *widely used* as the *supercharger for reciprocating engines, as well as compressor for gas turbines.* It is almost exclusively used as the supercharger with reciprocating power plants for *aircraft because it is relatively light and compact, and produces continuous flow rather than pulsating flow as in some positive displacement types.*

Supercharging of S.I. engines

—An ideal *p-V* diagram for a supercharged constant volume cycle is shown in Fig. 4.29.

Apart from increases in pressures over the un-supercharged cycle the main difference is that *pumping loop* (1-5-6-7-1) is now a positive one. The net indicated power (I.P.) is obtained by adding the contribution from pumping loop to that of the *power loop* (1-2-3-4-1). The gas is exhausted from the cylinder at the pressure of point 4 on the diagram. This value is high compared with atmospheric pressure and a considerable amount of energy is lost by allowing the gas to blow down in this way.

The power required to drive a blower mechanically connected to the engine must be subtracted from the engine output to obtain the net brake power (B.P.) of the supercharged engine.

$$\text{Then, } I_{\text{m.e.p.}} = \left(\frac{\text{area } 12341 + \text{area } 15671}{\text{length of diagram}}\right) \times \text{spring number} \quad ...(4.1)$$

and brake power (B.P.) = ($\eta_{\text{mech.}}$ × I.P.) – (power required to drive blower)

(for mechanical driven blowers only) ...(4.2)

(*i*) As far as S.I. engines are concerned, supercharging is employed *only for 'aircraft' and 'racing car engines'*. This is because the *increase in supercharging pressure increases the tendency to detonate*.

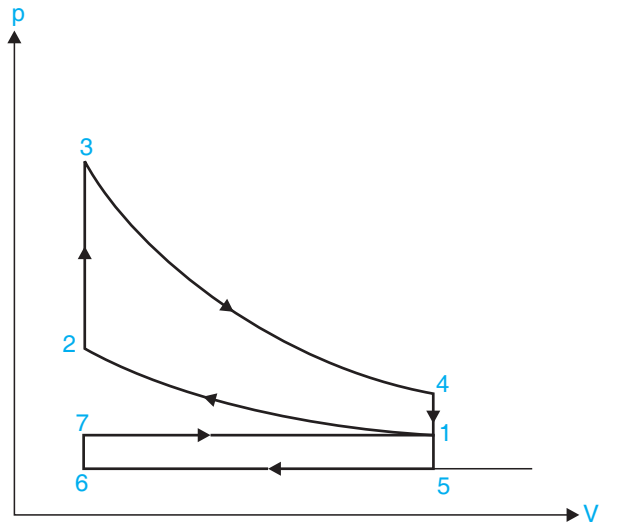


Fig. 4.29. *p-V* diagram for a supercharged constant volume cycle.

(*ii*) Supercharging of petrol engines, because of its poor fuel economy, is not very popular and is used only when a large amount of power is needed or when more power is needed *to compensate altitude loss*.

Supercharging of C.I. engines

Fig. 4.30 shows the *p-V* diagram for a supercharged constant pressure (diesel) cycle.

Unlike S.I. engines supercharging does not result in any combustion problem, *rather it improves combustion in diesel engine*. Increase in pressure and temperature of the intake air reduces significantly delay and hence the rate of pressure rise resulting in a *better, quieter and smoother combustion*. This improvement in combustion allows a poor quality fuel to be used in a diesel engine and it is also not sensitive to the type of fuel used. *The increase in intake temperature reduces volumetric and thermal efficiency but increase in density due to pressure compensates for this and intercooling is not necessary except for highly supercharged engines*.

If an unsupercharged engine is supercharged it will increase the reliability and durability of the engine due to smoother combustion and lower exhaust temperatures. The degree of supercharging is limited by thermal and mechanical load on the engine and strongly depends on the type of supercharger used and design of the engine.

Effects of supercharging on performance of the engine

1. The '*power output*' of a supercharged engine is *higher* than its naturally aspirated counterpart.
2. The '*mechanical efficiencies*' of supercharged engines are *slightly better* than the naturally aspirated engines.
3. Inspite of better mixing and combustion due to reduced delay a mechanically supercharged otto engine almost always have '*specific fuel consumption' higher than a naturally aspirated engine*.

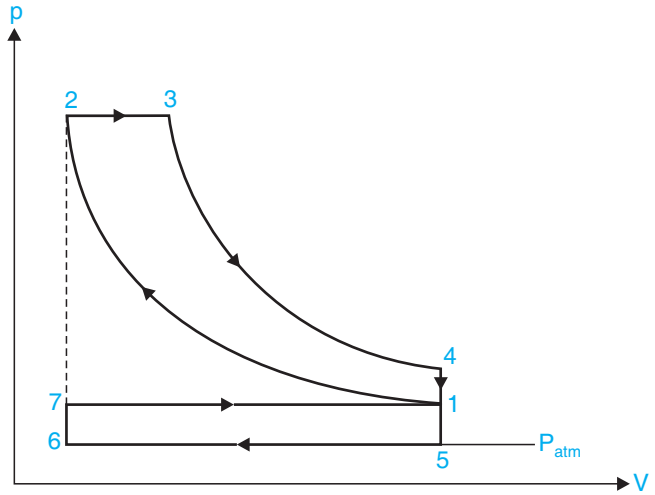


Fig. 4.30. *p-V* diagram for a supercharged constant pressure (diesel) cycle.

Fig. 4.31 shows the effect of supercharging on power and fuel.

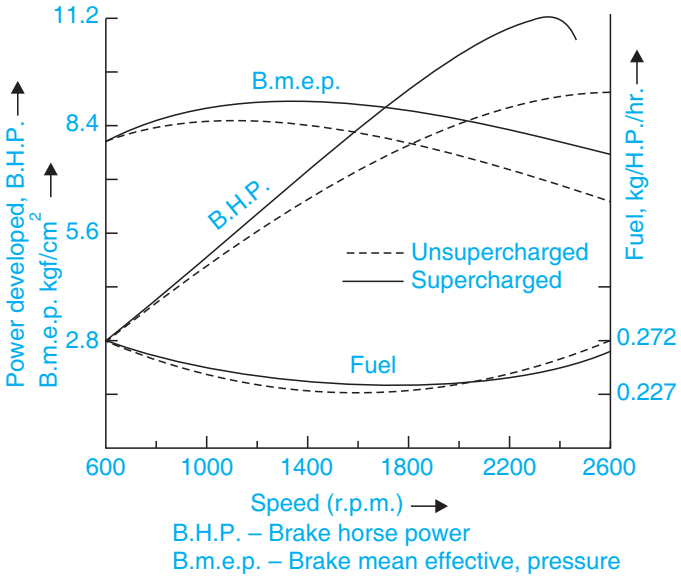


Fig. 4.31. Effect of supercharging on power and fuel.

4.20. OPERATION OF A DIESEL POWER PLANT

When diesel alternator sets are put in parallel, "*hunting*" or "*phase swinging*" may be produced *due to resonance* unless due care is taken in the design and manufacture of the sets. This condition occurs *due to resonance between the periodic disturbing forces of the engine and natural frequency of the system.* The engine forces result from uneven turning moment on the engine crank which are corrected by the flywheel effect. "*Hunting" results from the tendency of each set trying to pull the other into synchronism* and is characterised by flickering of lights.

To ensure *most economical operation of diesel engines* of different sizes when working together and sharing load it is necessary that they should carry the same percentage of their full load capacity at all times as the fuel consumption would be lowest in this condition. For best operation performance the manufacturer's recommendations should be strictly followed.

In order to get good performance of a diesel power plant the following points should be taken care of :

1. It is necessary to maintain the *cooling temperature* within the prescribed range and use of very cold water should be avoided. The cooling water should be free from suspended impurities and suitably treated to be scale and corrosion free. If the ambient temperature approaches freezing point, the cooling water should be drained out of the engine when it is kept idle.

2. During operation the *lubrication system* should work effectively and requisite pressure and temperature maintained. The engine oil should be of the correct specifications and should be in a fit condition to lubricate the different parts. A watch may be kept on the consumption of lubricating oil as this gives an indication of the true internal condition of the engine.

3. *The engine should be periodically run even when not required to be used and should not be allowed to stand idle for more than 7 days.*

4. *Air filter, oil filters and fuel filters* should be periodically serviced or replaced as recommended by the manufacturers or if found in an unsatisfactory condition upon inspection.

5. Periodical checking of engine compression and firing pressures and also exhaust temperatures should be made.

— The engine exhaust usually provides a good indication of satisfactory performance of the engine. *A black smoke in the exhaust is a sign of inadequate combustion or engine over-loading.*

— *The loss of compression resulting from wearing out of moving parts lowers the compression ratio causing inadequate combustion.* These defects can be checked by taking *indicator diagrams* of the engine after reasonable intervals.

4.21. TYPES OF DIESEL ENGINE USED FOR DIESEL POWER PLANTS

The diesel engines may be four-stroke or two stroke cycle engines. *The two-stroke cycle engines are favoured for diesel power plants.*

Efforts are being made to use "*duel fuel engines*" in diesel power plants for better economy and proper use of available gaseous fuels in the country. The gas may be a waste product as in the case of sewage treatment installations or oil fuels where the economic advantage is self evident. With the wider availability of natural gas, the duel fuel engines may become an attractive means of utilising gas as fuel at off-peak tariffs for the electric power generation.

Working of Duel Fuel Engines

The various strokes of a duel fuel engine are as follows :

1. Suction stroke. During this stroke *air and gas are drawn* in the engine cylinder.

2. Compression stroke. During this stroke the pressure of the mixture drawn is increased. Near the end of this stroke the *'pilot oil' is injected into the engine cylinder. The compression heat first ignites the pilot oil* and then gas mixture.

3. Working/power stroke. During this stroke the gases (at high temperature) expand and thus power is obtained.

4. Exhaust stroke. The exhaust gases are released to the atmosphere during the stroke.

4.22. LAYOUT OF A DIESEL ENGINE POWER PLANT

Fig. 4.32 shows the layout of a diesel engine power plant.

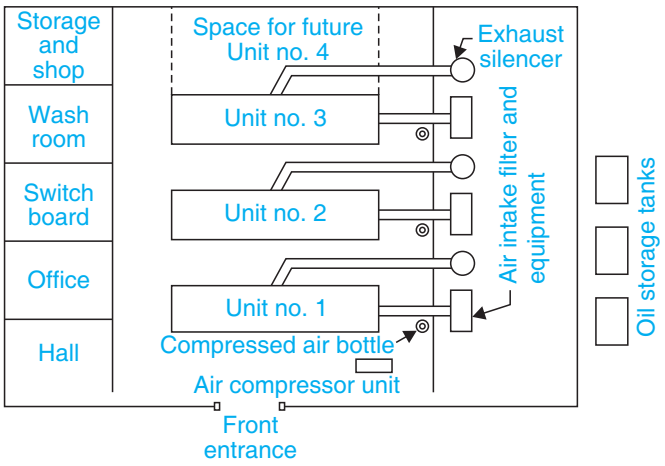


Fig. 4.32. Layout of a diesel engine power plant.

The most common arrangement for diesel engines is with parallel centre lines, with some room left for extension in future. The repairs and usual maintenance works connected with such engines necessitate sufficient space around the units and consideration should be given to the need for dismantling and removal of large components of the engine generator set. The air intakes and filters as well as the exhaust mufflers are located outside the building or may be separated from the main engine room by a partition wall. The latter arrangement is not vibration free. Adequate space for oil storage and repair shop as well as for office should be provided close to the main engine room. Bulk storage of oil may be outdoor. The engine room should be well ventilated.

4.23. PERFORMANCE OF I.C. ENGINES

Engine performance is an indication of the degree of success with which it does its assigned job *i.e.,* conversion of chemical energy contained in the fuel into the useful mechanical work.

In evaluation of engine performance certain basic parameters are chosen and the effect of various operation conditions, design concept and modifications on these parameters are studied. The *basic performance parameters* are enumerated and discussed below :

1. Power and mechanical efficiency
2. Mean effective pressure and torque
3. Specific output
4. Volumetric efficiency
5. Fuel-air ratio
6. Specific fuel consumption
7. Thermal efficiency and heat balance
8. Exhaust smoke and other emissions
9. Specific weight.

1. Power and mechanical efficiency

(*i*) **Indicated power.** *The total power developed by combustion of fuel in the combustion chamber is called* ***indicated power.***

$$\text{I.P.} = \frac{np_{mi}\, LANk \times 10}{6} \text{ kW} \qquad ...(4.1)$$

where, n = Number of cylinders,
p_{mi} = Indicated mean effective pressure, bar,
L = Length of stroke, m,
A = Area of piston, m^2, and
$k = \frac{1}{2}$ for 4-stroke engine
= 1 for 2-stroke engine.

In MKS Units

$$\text{I.H.P.} = \frac{np_{mi}\, LAN\, k}{4500} \qquad ...[4.1\ (a)]$$

where, I.H.P. = Indicated horse power,
n = Number of cylinders,
p_{mi} = Indicated mean effective pressure, kgf/cm^2,
L = Length of stroke, m,
A = Area of piston, cm^2, and
$k = \frac{1}{2}$ for 4-stroke engine
= 1 for 2-stroke engine.

(*ii*) **Brake power (B.P.).** *The power developed by an engine at the output shaft is called the* ***brake power.***

$$\text{B.P.} = \frac{2\pi NT}{60 \times 1000} \text{ kW} \qquad ...(4.2)$$

where, N = Speed in r.p.m., and
T = Torque in Nm.

In MKS Units

$$\text{B.H.P.} = \frac{2\pi NT}{4500} \qquad ...[4.2\ (a)]$$

where B.H.P. = Brake horse power,
N = Speed in r.p.m., and
T = Torque in kgf m.

The difference between I.P. and B.P. is called ***frictional power, F.P.***

i.e., F.P. = I.P. – B.P. ...(4.3)

The ratio of B.P. to I.P. is called *mechanical efficiency*

i.e., *Mechanical efficiency*,

$$\eta_{mech.} = \frac{B.P.}{I.P.} \quad ...(4.4)$$

In MKS Units

F.H.P. = I.H.P. – B.H.P. ...[4.4 (*a*)]

and, $\eta_{mech.} = \frac{B.H.P.}{I.H.P.}$ ...[4.4 (*b*)]

2. Mean effective pressure and torque

Mean effective pressure *is defined as hypothetical pressure which is thought to be acting on the piston throughout the power stroke*. If it is based on I.P. it is called *indicated mean effective pressure* ($I_{m.e.p.}$ or p_{mi}) and if based on B.P. it is called *brake mean effective pressure* ($B_{m.e.p.}$ or p_{mi}). Similarly, frictional mean effective pressure ($F_{m.e.p.}$ or p_{mf}) can be defined as :

$$F_{m.e.p.} = I_{m.e.p.} - B_{m.e.p.} \quad ...(4.5)$$

The torque and mean effective pressure are related by the engine size.

Since the power (P) of an engine is dependent on its size and speed, therefore it is not possible to compare engine on the basis of either power or torque. *Mean effective pressure is the true indication of the relative performance of different engines*.

3. Specific output

It is defined as the *brake output per unit of piston displacement* and is given by :

$$\text{Specific output} = \frac{B.P.}{A \times L}$$

$$= \text{Constant} \times p_{mb} \times \text{r.p.m.} \quad ...(4.6)$$

For the same piston displacement and brake mean effective pressure (p_{mb}) an engine running at higher speed will give more output.

4. Volumetric efficiency

It is defined as the ratio of actual volume (reduced to N.T.P.) of the charge drawn in during the suction stroke to the swept volume of the piston.

The average value of this efficiency is from 70 to 80 per cent but in case of *supercharged engine* it may be *more* than 100 per cent, if air at about atmospheric pressure is forced into the cylinder at a pressure greater than that of air surrounding the engine.

5. Fuel-air ratio

It is the ratio of the mass of fuel to the mass of air in the fuel-air mixture.

"Relative fuel air ratio" is defined as the *ratio of the actual fuel air ratio to that of stoichiometric fuel-air ratio required to burn the fuel supplied.*

6. Specific fuel consumption (s.f.c.)

It is the mass of fuel consumed per kW developed per hour, and is a criterion of economical power production.

i.e., $\text{s.f.c.} = \frac{m_f}{B.P.}$ kg/kWh.

In MKS Units

$\text{s.f.c.} = \frac{m_f}{B.H.P.}$ kg/B.H.P.-hr where m_f is the fuel consumed in kg/hr

7. Thermal efficiency and heat balance

Thermal efficiency. *It is the ratio of indicated work done to energy supplied by the fuel.*

If, $\dot{m}_f$ = Mass of fuel used in kg/sec., and

C = Calorific value of fuel (lower),

Then *indicated thermal efficiency* (based on I.P.),

$$\eta_{th.\,(I)} = \frac{I.P.}{\dot{m}_f \times C} \quad ...(4.7)$$

and *brake thermal efficiency* (based on B.P.)

$$\eta_{th.\,(B)} = \frac{B.P.}{\dot{m}_f \times C} \quad ...(4.8)$$

In MKS Units

$$\eta_{th.\,(I)} = \frac{I.H.P. \times 4500}{J \times m_f \times C} \quad ...[4.7\ (a)]$$

and $$\eta_{th.\,(B)} = \frac{B.H.P. \times 4500}{J \times m_f \times C} \quad ...[4.8\ (a)]$$

Heat balance sheet

The performance of an engine is generally given by heat balance sheet.

To draw a heat balance sheet for I.C. engine, it is run at constant load. Indicator diagram is obtained with the help of an indicator. The quantity of fuel used in a given time and its calorific value, the amount, inlet and outlet temperature of cooling water and the weight of exhaust gases are recorded. After calculating I.P. (or I.H.P.) and B.P. (or B.H.P.), the heat in different items is found as follows :

Heat supplied by fuel :

For *petrol and oil engines*, heat supplied = $m_f \times C$, where m_f and C are mass used per minute (kg) and lower calorific value (kJ or kcal) of the fuel respectively.

For *gas engines*, heat supplied = $V \times C$, where V and C is volume at N.T.P. (m^3/min.) and lower calorific value of gas respectively.

(i) ***Heat absorbed in I.P.:***

Heat equivalent of I.P. (per minute)

$$= \text{I.P.} \times 60 \text{ kJ} \qquad ...(4.9)$$

In MKS units

Heat equivalent of I.H.P. (per minute)

$$= \frac{\text{I.H.P.} \times 4500}{J} \text{ kcal} \qquad ...[4.9\ (a)]$$

(ii) ***Heat taken away by cooling water:***

If, m_w = Mass of cooling water used per minute,

t_1 = Initial temperature of cooling water,

t_2 = Final temperature of cooling water,

Then, heat taken away by water

$$= m_w \times c_{pw} \times (t_2 - t_1) \qquad ...(4.10)$$

where, c_{pw} = Specific heat of water.

(iii) ***Heat taken away by exhaust gases:***

If, m_e = Mass of exhaust gases (kg/min),

c_{pg} = Mean specific heat at constant pressure,

t_e = Temperature of exhaust gases,

t_r = Room (or boiler house) temperature,

Then, heat carried away by exhaust gases

$$= m_e \times c_{pg}(t_e - t_r) \qquad ...(4.11)$$

Note. The mass of exhaust gases can be obtained by adding together mass of fuel supplied and mass of air supplied.

The *heat balance sheet* from the above data can be drawn as follows :

Item	*kJ*	*Per cent*
Heat supplied by fuel	...	...
(*i*) Heat absorbed in I.P. (or I.H.P.)	...	...
(*ii*) Heat taken away by cooling water	...	...
(*iii*) Heat carried away by exhaust gases	...	...
(*iv*) Heat unaccounted for (by difference)	...	...
Total	...	...

8. Exhaust smoke and other emissions

Smoke is an indication of incomplete combustion. It limits the output of an engine if air pollution control is the consideration. *Exhaust emissions* have of late become a matter of grave concern and with the enforcement of legislation on air pollution in many countries, it has become necessary to view them as performance parameters.

9. Specific weight

It is defined as the weight of the engine in kg for each B.H.P. developed. It is an indication of the engine bulk.

10. Basic measurements

To evaluate the performance of an engine following *basic measurements* are usually undertaken :

1. Speed
2. Fuel consumption
3. Air consumption
4. Smoke density
5. Exhaust gas analysis
6. Brake power
7. Indicated power and friction power
8. Heat going to cooling water
9. Heat going to exhaust.

11. Measurement of speed

The speed may be measured by :

(*i*) Revolution counters

(*ii*) Mechanical tachometer

(*iii*) Electrical tachometer.

12. Fuel measurement

The fuel consumed by an engine can be measured by the following methods :

(*i*) Fuel flow method

(*ii*) Gravemetric method

(*iii*) Continuous flow meters.

13. Measurement of air consumption

The air consumption can be measured by the following methods :

(*i*) Air box method

(*ii*) Viscous-flow air meter.

(i) ***Air box method***

Fig. 4.33 shows the arrangement of the system. It consists of air-tight chamber fitted with a sharp edged orifice of known co-efficient of discharge. The orifice is located away from the suction connection to the engine. Due to the suction of engine, there is a pressure depression in the air box or chamber which causes the flow through the orifice. For obtaining a steady flow, the volume of chamber should be sufficiently large compared with the swept volume of the cylinder ; generally 500 to 600 times the swept volume. It is assumed that the intermittent suction of the engine will not effect the air pressure in the air box as volume of the box is sufficiently large, and pressure in the box remains same.

A water manometer is used to measure the pressure difference causing the flow through the orifice. The depression across the orifice should not exceed 100 to 150 mm of water.

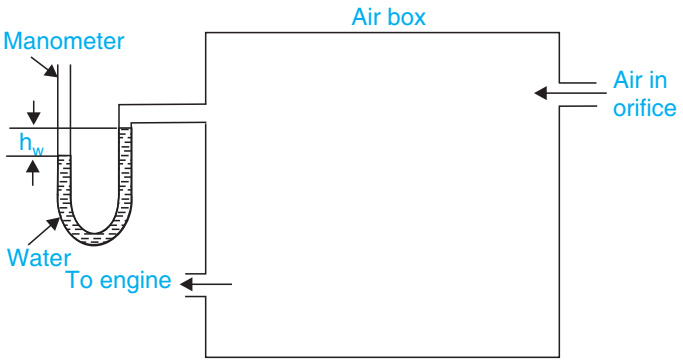


Fig. 4.33. Air-box method for measuring air.

Let, A = Area of orifice, m^2,

d = Diameter of orifice, cm,

h_w = Head of water in cm causing the flow,

C_d = Co-efficient of discharge for orifice,

ρ_a = Density of air in kg/m^3 under atmospheric conditions, and

ρ_w = Density of water in kg/m^3.

Head in metres of air (H) is given by :

$$H.\rho_a = \frac{h_w}{100}\ \rho_w$$

$$\therefore \quad H = \frac{h_w}{100} \times \frac{\rho_w}{\rho_a} = \frac{h_w}{100} \times \frac{1000}{\rho_a} = \frac{10h_w}{\rho_a} \text{ m of air}$$

The velocity of air passing through the orifice is given by,

$$C_a = \sqrt{2gH} \text{ m/s} = \sqrt{2g\,\frac{10h_w}{\rho_a}} \text{ m/s}$$

The volume of air passing through the orifice,

$$V_a = C_d \times A \times C_a = C_d A \sqrt{2g\,\frac{10h_w}{\rho_a}}$$

$$= 14\, AC_d \sqrt{\frac{h_w}{\rho_a}} \text{ m}^3/\text{s}$$

$$= 840\, AC_d \sqrt{\frac{h_w}{\rho_a}} \text{ m}^3/\text{min}.$$

Mass of air passing through the orifice is given by:

$$m_a = V_a\rho_a = 14 \times \frac{\pi d^2}{4 \times 100^2} \times C_d \sqrt{\frac{h_w}{\rho_a}} \times \rho_a$$

$$= 0.0011\, C_d \times d^2 \sqrt{h_w\rho_a} \text{ kg/s}$$

$$= 0.066\, C_a \times d^2 \sqrt{h_w\rho_a} \text{ kg/min.} \qquad ...(4.12)$$

(*ii*) *Viscous-flow air meter*

Alcock viscous-flow air meter is another design of air meter. It is not subjected to the errors of the simple types of flow meters. With the air-box the flow is proportional to the square root of the pressure difference across the orifice. With the Alcock meter the air flows through a form of honey-comb so that flow is viscous. The *resistance of the element is directly proportional to the air velocity* and is measured by means of an inclined manometer. Felt pads are fitted in the manometer connections to damp out fluctuations. The meter is shown in Fig. 4.34.

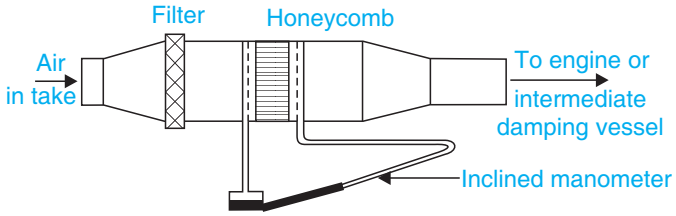


Fig. 4.34. Alcock viscous-flow air meter.

The accuracy is improved by fitting a damping vessel between the meter and the engine to reduce the effect of pulsations.

14. Measurement of exhaust smoke

The following smoke meters are used :

(*i*) Bosch smoke meter

(*ii*) Hatridge smoke meter

(*iii*) PHS smoke meter.

15. Measurement of exhaust emission

Substances which are emitted to the atmosphere from any opening down stream of the exhaust part of the engine are termed as ***exhaust emissions.*** Some of the more commonly used instruments for measuring exhaust components are given below :

(*i*) Flame ionisation detector

(*ii*) Spectroscopic analysers

(*iii*) Gas chromatography.

16. Measurement of B.P. (or B.H.P.)

The B.P. of an engine can be determined by a brake of some kind applied to the brake pulley of the engine. The arrangement for determination of B.P. of the engine is known as *dynamometer*. The dynamometers are classified into following two classes :

(*i*) Absorption dynamometers

(*ii*) Transmission dynamometers.

(*i*) ***Absorption dynamometers.*** *Absorption dynamometers are those that absorb the power to be measured by friction*. The power absorbed in friction is finally dissipated in the form of heat energy.

Common forms of absorption dynamometers are :

- Prony brake
- Rope brake
- Hydraulic brake

- Fan brake
- Electrical brake dynamometers

(a) Eddy current dynamometer

(b) Swinging field D.C. dynamometer.

(ii) ***Transmission dynamometers.*** These are also called *torquemeters*. These are very accurate and are used where continuous transmission of load is necessary. These are used mainly in automatic units.

Here we shall discuss *Rope brake dynamometer* only :

Rope brake dynamometer

Refer to Fig. 4.35. A rope is wound round the circumference of the brake wheel. To prevent the rope from slipping small wooden blocks (not shown in Fig. 4.35) are laced to rope. To one end of the rope is attached a spring balance (S) and the other end carries the load (W). The speed of the engine is noted from the tachometer (revolution counter).

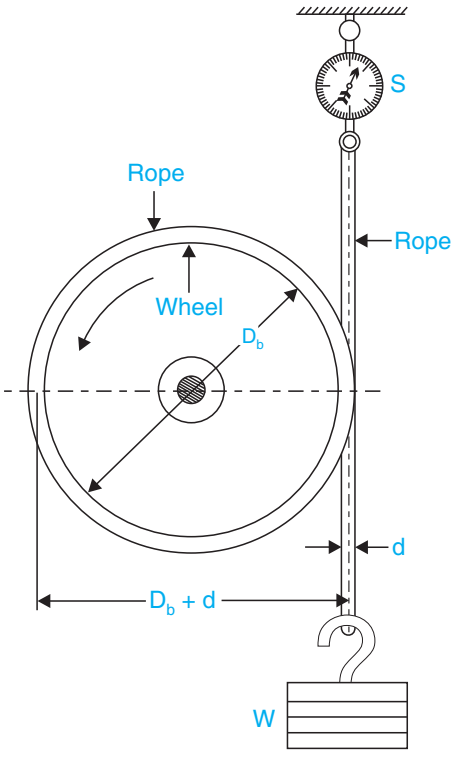


Fig. 4.35. Rope brake dynamometer.

If, W = Weight at the end of the rope N (or kg),

S = Spring balance reading, N (or kg),

N = Engine speed, r.p.m.,

D_b = Diameter of the brake wheel in meters,

d = Diameter of the rope in meters,

$(D_b + d)$ = Effective diameter of the brake wheel,

Then work/revolution

= Torque × angle turned per revolution

$$= (W - S) \times \left(\frac{D_b + d}{2}\right) \times 2\pi$$

$$= (W - S)(D_b + d) \times \pi$$

Work done/min. $= (W - S)\,\pi\,(D_b + d)\,N$

Work done/sec. $= \dfrac{(W - S)\,\pi\,(D_b + d)\,N}{60}$

$$\therefore \quad \text{B.P.} = \frac{(W - S)\,\pi\,(D_b + d)\,N}{60 \times 1000}\ \text{kW} \qquad ...(4.13)$$

$$= \frac{(W - S)\,\pi\,D_b N}{60 \times 1000} \quad \text{..... if } d \text{ is neglected}$$

or $$\left(= \frac{T \times 2\pi N}{60 \times 1000}\ \text{kW}\right) \qquad ...(4.14)$$

In MKS Units

$$\text{B.H.P.} = \frac{(W - S)\,\pi(D_b + d)\,N}{4500} \qquad ...[4.13\ (a)]$$

$$= \frac{(W - S)\,\pi D_b N}{4500} \quad \text{... if } d \text{ is neglected}$$

or $$\left(= \frac{T \times 2\pi N}{4500}\right) \qquad ...[4.14\ (a)]$$

Rope brake is cheap and easily constructed but not very accurate because of changes in friction co-efficient of the rope with temperature.

17. Measurement of Indicated power (I.P.)

The power developed in the engine cylinder or at the piston is necessarily greater than that at the crankshaft due to engine losses. Thus,

I.P. = B.P. + engine losses.

Indicated power is usually determined with the help of a p-V diagram taken with the help of an indicator. In case indicated power cannot be measured directly, it is made possible by measuring the brake power and also the engine losses. If the *indicator diagram* is available, the indicated power may be *computed by measuring the area of* diagram, either with a *planimeter* or by *ordinate method*, and dividing by the stroke measurement in order to obtain the mean effective pressure (m.e.p.).

$$i.e., \quad p_{mi} = \frac{\text{Net area of diagram in mm}^2}{\text{Length of diagram in mm}} \times \text{Spring constant}$$

where, p_{mi} is in bar. ...(4.15)

(The spring constant is given in *bar per mm* of vertical movement of the indicator stylus.)

In MKS Units

$$p_{mi} = \frac{\text{Net area of diagram in cm}^2}{\text{Length of diagram in cm}} \times \text{Spring constant (kgf/cm}^2\text{-cm)} \quad ...[4.15\ (a)]$$

Engine indicators

The main types of engine indicators are :

1. Piston indicator
2. Balanced diaphragm type indicator :
   (*i*) The Farnborough balanced engine indicator
   (*ii*) Dickinson-Newell indicator
   (*iii*) MIT balanced pressure indicator
   (*iv*) Capacitance-type balance pressure indicator.
3. Electrical indicators

In addition to this, *optical indicators* are also used.

Calculation of indicated power (I.P.) :

If, p_{mi} = indicated mean effective pressure, bar,
A = area of piston, m^2,
L = length of stroke, m,
N = speed of the engine, r.p.m.,
$k = \frac{1}{2}$ for 4-stroke engine,
= 1 for 2-stroke engine.

Then, force on the piston = $p_{mi} \times A \times 10^5$ N

Work done per working stroke
= Force × Length of stroke
= $p_{mi} \times A \times 10^5 \times L$ Nm

Work done per second = Work done per stroke × Number of working stroke per second

$$= p_{mi} \times L \times A \times 10^5 \times \frac{N}{60} \times k\text{N m/s or J/s}$$

$$= \frac{p_{mi} \times LANk \times 10^5}{60 \times 1000} \text{ kW}$$

Indicated power, $\text{I.P.} = \frac{p_{mi}\, LANk \times 10}{60 \times 1000}$ kW

If n is the number of cylinders, then

$$\text{I.P.} = \frac{np_{mi}\, LANk \times 10}{6} \text{ kW} \quad ...(4.16)$$

In MKS Units

Calculation of I.H.P.

If p_{mi} = Indicated mean effective pressure, kgf/cm^2,
A = Area of the piston, cm^2,
L = Length of stroke, m,
N = Engine speed, r.p.m.,
$k = \frac{1}{2}$ for 4-stroke engine,
= 1 for 2-stroke engine,

Then, force on the piston = $p_{mi} \times A$ kgf
Work done per working stroke
= $p_{mi} \times A \times L$ kgf m
Work done per minute = Work done per stroke × Number of working stroke per minute
= $p_{mi} \times A \times L \times N \times k$

$$\therefore \quad \text{I.H.P.} = \frac{p_{mi} LANk}{4500}$$

If n is the number of cylinder, then

$$\text{I.H.P.} = \frac{np_{mi} LANk}{4500} \quad ...[4.16\ (a)]$$

Morse test

This test is only applicable to *multi-cylinder engines*.

The engine is run at the required speed and the torque is measured. One cylinder is cut-out, by shorting the plug if an S.I. engine is under test, or by disconnecting an injector if a C.I. engine is under test. *The speed falls because of the loss of power with one cylinder cut-out, but is restored by reducing the load*. The torque is measured again when the speed has reached its original value. If the value of I.P. of the cylinders are denoted by I_1, I_2, I_3 and I_4 (considering a four-cylinder engine), and the power losses in each cylinder are denoted by L_1, L_2, L_3 and L_4, then the value of B.P., B at the test speed with all cylinders firing is given by

$$B = (I_1 - L_1) + (I_2 - L_2) + (I_3 - L_3) + (I_4 - L_4) \quad ...(i)$$

If *number 1 cylinder is cut-out,* then the contribution I_1 is lost ; and if the losses due to that cylinder remain the same as when it is firing, then the B.P., B_1, now obtained at the same speed is

$$B_1 = (0 - L_1) + (I_2 - L_2) + (I_3 - L_3) + (I_4 - L_4) \quad ...(ii)$$

Subtracting equation (*ii*) from (*i*), we get

$$B - B_1 = I_1 \quad ...(4.17)$$

Similarly,

$B - B_2 = I_2$ when cylinder number 2 is cut-out,
and $B - B_3 = I_3$ when cylinder number 3 is cut-out,
and $B - B_4 = I_4$ when cylinder number 4 is cut-out.

Then, for the engine,

$$I = I_1 + I_2 + I_3 + I_4 \quad ...(4.18)$$

Measurement of frictional power (F.P.)

The frictional power of an engine can be determined by the following methods :

1. Willan's line method (used for C.I. engines only)
2. Morse test
3. Motoring test
4. Difference between I.P. and B.P.

1. *Willan's line method*

At a constant engine speed the load is reduced in increments and the corresponding B.P. and gross fuel consumption readings are taken. A graph is then drawn of fuel consumption against B.P. as shown in Fig. 4.36. The graph drawn in called the *Willan's line* (analogous to

Willan's line for a steam engine), and is extrapolated back to cut the B.P. axis at the point *L*. The reading *OL* is taken as the power loss of the engine at that speed. The fuel consumption at zero B.P. is given by *OM* ; and if the relationship between fuel consumption and B.P. is assumed to be linear, then a fuel consumption *OM* is equivalent to a power loss of *OL*.

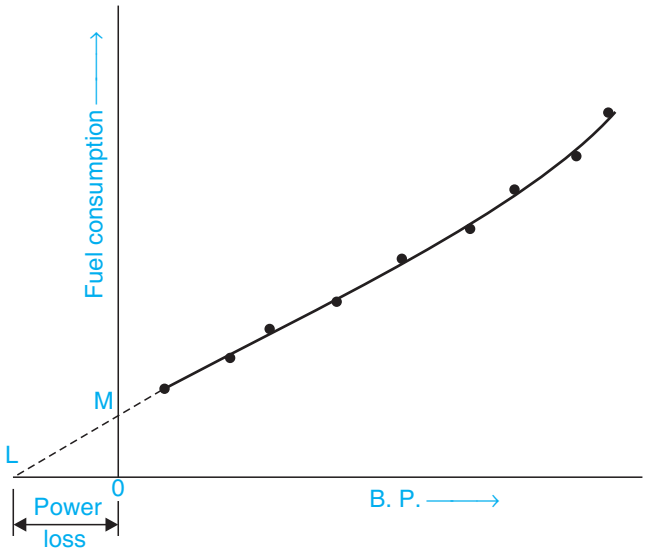


Fig. 4.36. Willian's line method.

2. *Morse test*

In 'Morse test' (already discussed), frictional power can be found by subtracting $(B.P.)_n$ from $(I.P.)_n$

i.e., $F.P. = (I.P.)_n - (B.P.)_n$

where n is the number of cylinders.

3. *Motoring test*

In this test the engine is first run upto the desired speed by its own power and allowed to remain under the given speed and load conditions for sometime so that oil, water and engine component temperatures reach stable conditions. The power of the engine during this period is absorbed by a dynamometer (usually of electrical type). The fuel supply is then cut off and by suitable electric switching devices the dynamometer is converted to run as a motor to drive or 'motor' the engine at the same speed at which it was previously running. The power supply to the motor is measured which is a measure of F.P of the engine.

4. *Difference between I.P. and B.P.*

The method of finding the F.P. by finding the difference between I.P. as obtained from an indicator diagram, and B.P. as obtained by a dynamometer is the *ideal method*. However, due to difficulties in obtaining accurate indicator diagrams, especially at high engine speeds, this method is usually *only used in research laboratories and its use at commercial level is very limited*.

WORKED EXAMPLES

Example 4.1. *Following data refer to a four stroke double acting diesel engine having cylinder diameter 200 mm and piston stroke 350 mm.*

m.e.p. on cover side	*= 6.5 bar*
m.e.p. on crank side	*= 7 bar*
Speed	*= 420 r.p.m.*
Diameter of piston rod	*= 20 mm*
Dead load on the brake	*= 1370 N*
Spring balance reading	*= 145 N*
Brake wheel diameter	*= 1.2 m*
Brake rope diameter	*= 20 mm*

Calculate the mechanical efficiency of the engine.

Solution. *Given :*

$P_{mi(cover)} = 6.5$ bar, $p_{mi(crank)} = 7$ bar,

$D = 0.2$ m, $L = 0.35$ m,

$N = 420$ r.p.m.,

$d_{rod} = 20$ mm $= 0.02$ m,

$W = 1370$ N, $S = 145$ N,

$D_b = 1.2$ m, $d = 0.02$ m,

$k = \frac{1}{2}$ ... 4-stroke cycle engine

Mechanical efficiency ; $\eta_{mech.}$:

Area of cylinder on cover end side,

$$A_{cover} = \pi/4\ D^2 = (\pi/4) \times (0.2)^2 = 0.03141\ m^2$$

Effective area of cylinder on crank end side,

$$A_{crank} = \pi/4\ (D^2 - d_{rod}^2) = \pi/4\ (0.2^2 - 0.02^2)$$
$$= 0.0311\ m^2$$

Indicated power on cover end side,

$$I.P._{(cover)} = \frac{p_{mi\,(cover)} \times LANk \times 10}{6}$$
$$= \frac{6.5 \times 0.35 \times 0.03141 \times 420 \times \frac{1}{2} \times 10}{6}$$
$$= 25\ kW$$

Indicated power on crank end side,

$$I.P._{(crank)} = \frac{p_{mi\,(crank)} \times LANk \times 10}{6}$$
$$= \frac{7 \times 0.35 \times 0.0311 \times 420 \times \frac{1}{2} \times 10}{6}$$
$$= 26.67\ kW$$

Total I.P. = I.P.$_{(cover)}$ + I.P.$_{(crank)}$
= 25 + 26.67 = 51.67 kW

Now, brake power,

$$\text{B.P.} = \frac{(W - S)\,\pi\,(D_b + d)N}{60 \times 1000}$$

$$= \frac{(1370 - 145)\pi(1.2 + 0.02) \times 420}{60 \times 1000}\text{kW}$$

= 32.86 kW

Mechanical efficiency,

$$\eta_{\text{mech.}} = \frac{\text{B.P.}}{\text{I.P.}} = \frac{32.86}{51.67}$$

= 0.6359 = **63.59%.** **(Ans.)**

Example 4.2. *The following data refer to an oil engine working on Otto four stroke cycle :*

Brake power	*= 14.7 kW*
Suction pressure	*= 0.9 bar*
Mechanical efficiency	*= 80%*
Ratio of compression	*= 5*
Index of compression curve	*= 1.35*
Index of expansion curve	*= 1.3*
Maximum explosion pressure	*= 24 bar*
Engine speed	*= 1000 r.p.m.*
Ratio of stroke : bore	*= 1.5*

Find the diameter and stroke of the piston.

Solution. Refer to Fig. 4.37.

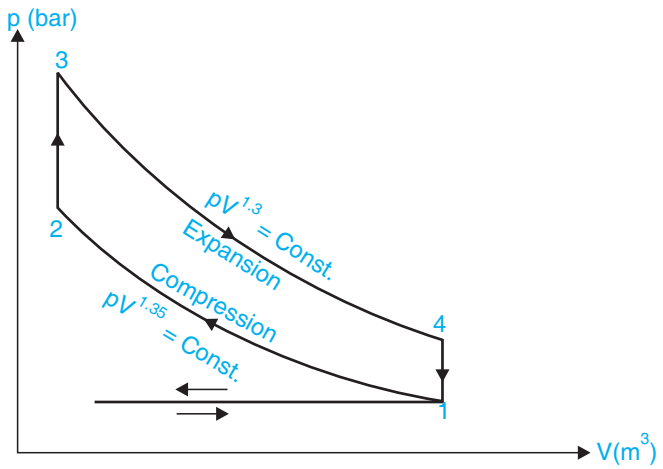


Fig. 4.37

Given : B.P. = 14.7 kW, p_1 = 0.9 bar,
$\eta_{\text{mech.}}$ = 80%, r = 5, p_3 = 24 bar

N = 1000 r.p.m., $\dfrac{L}{D} = 1.5$

$\boldsymbol{D}$ = ?, $\boldsymbol{L}$ = ?

Compression ratio, $r = \dfrac{V_1}{V_2} = \dfrac{V_4}{V_3}$

To find p_2, considering *compression process 1-2,* we have:

$$p_1 V_1^{1.35} = p_2 V_2^{1.35}$$

or, $$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{1.35} = (5)^{1.35} = 8.78$$

$\therefore$ $p_2 = p_1 \times 8.78 = 0.9 \times 8.78$
= 7.9 bar

To find p_4, considering *expansion process 3-4,* we have:

$$p_3 V_3^{1.3} = p_4 V_4^{1.3}$$

or $$\frac{p_3}{p_4} = \left(\frac{V_4}{V_3}\right)^{1.3} = (5)^{1.3} = 8.1$$

$\therefore$ $p_4 = \dfrac{p_3}{8.1} = \dfrac{24}{8.1} = 2.96$ bar

Work done/cycle = Area 1-2-3-4
= Area under the curve 3-4
– Area under the curve 1-2

$$= \frac{p_3V_3 - p_4V_4}{1.3 - 1} - \frac{p_2V_2 - p_1V_1}{1.35 - 1}$$

$$= \frac{p_3V_3 - p_4V_4}{0.3} - \frac{p_2V_3 - p_1V_4}{0.35}$$

$[\because \quad V_1 = V_4 \text{ and } V_2 = V_3]$

$$= \frac{10^5(24V_3 - 2.96V_4)}{0.3} - \frac{10^5(7.9V_3 - 0.9V_4)}{0.35}$$

$$= 10^5\,[(80V_3 - 9.86V_4) - (22.57V_3 - 2.57V_4)]$$

$$= 10^5(80V_3 - 9.86V_4 - 22.57V_3 + 2.57V_4)$$

$$= 10^5(57.43V_3 - 7.29V_4)$$

$$= 10^5(57.43V_3 - 7.29 \times 5V_3) \qquad \left[\because \frac{V_4}{V_3} = 5\right]$$

$= 10^5 \times 20.98\ V_3$ Nm.

Mean effective pressure (theoretical),

$$p_m = \frac{\text{Work done / cycle}}{\text{Stroke volume } (V_s)}$$

$$= \frac{10^5 \times 20.98V_3}{(V_4 - V_3)} = \frac{10^5 \times 20.98V_3}{5V_3 - V_3}$$

$= 10^5 \times 5.245$ N/m^2 or 5.245 bar.

Now, $\eta_{\text{mech.}} = \dfrac{\text{B.P.}}{\text{I.P.}}$

$\therefore$ $\text{I.P.} = \dfrac{\text{B.P.}}{\eta_{\text{mech.}}} = \dfrac{14.7}{0.8} = 18.37$ kW.

To find D and L :

$$\text{I.P.} = \frac{p_{mi} LANk \times 10}{6} \text{ kW}$$

$$14.7 = \frac{5.245 \times 1.5D \times \pi/4 \times D^2 \times 1000 \times \frac{1}{2} \times 10}{6}$$

$$\therefore \quad D^3 = \frac{14.7 \times 6 \times 4 \times 2}{5.245 \times 1.5 \times \pi \times 1000 \times 10} = 0.002855$$

or $D = 0.1418 \simeq$ **0.142 m or 142 mm.** **(Ans.)**

and $L = 1.5D = 1.5 \times 142 =$ **213 mm.** **(Ans.)**

Example 4.3. *The following readings were taken during the test of a single cylinder four stroke oil engine :*

Cylinder diameter	*= 250 mm*
Stroke length	*= 400 mm*
Gross m.e.p.	*= 7 bar*
Pumping m.e.p.	*= 0.5 bar*
Engine speed	*= 250 r.p.m.*
Net load on the brake	*= 1080 N*
Effective diameter of the brake	*= 1.5 metres*
Fuel used per hour	*= 10 kg*
Calorific value of fuel	*= 44300 kJ/kg*

Calculate : (i) Indicated power ;

(ii) Brake power ;

(iii) Mechanical efficiency ;

(iv) Indicated thermal efficiency.

Solution. *Given :* $D = 250$ mm $= 0.25$ m,

$L = 400$ mm $= 0.4$ m, $p_{mg} = 7$ bar,

$p_{mp} = 0.5$ bar, $N = 250$ r.p.m.,

$D_b = 1.5$ m, $\dot{m}_f = \frac{10}{3600} = 0.00277$ kg/s

$C = 44300$ kJ/kg, $n = 1$, $(W - S)$

$= 1080$ N

Net $p_m = p_{mg} - p_{mp} = 7 - 0.5 = 6.5$ bar.

(i) Indicated power I.P. :

$$\text{I.P.} = \frac{np_m LANk \times 10}{6}$$

$$= \frac{1 \times 6.5 \times 0.4 \times \pi/4 \times 0.25^2 \times 250 \times \frac{1}{2} \times 10}{6} \text{ kW}$$

$=$ **26.59 kW.** **(Ans.)**

(ii) Brake power, B.P. :

$$\text{B.P.} = \frac{(W - S)\pi D_b N}{60 \times 1000} \text{ kW}$$

$$= \frac{1080 \times \pi \times 1.5 \times 250}{60 \times 1000}$$

$=$ **21.2 kW.** **(Ans.)**

(iii) Mechanical efficiency, $\eta_{mech.}$:

$$\eta_{mech.} = \frac{\text{B.P.}}{\text{I.P.}} = \frac{21.2}{26.59}$$

$=$ **0.797 or 79.7%.** **(Ans.)**

(iv) Indicated thermal efficiency, $\eta_{th(I)}$:

$$\eta_{th(I)} = \frac{\text{I.P.}}{\dot{m}_f \times C} = \frac{26.59}{0.00277 \times 44300}$$

$=$ **0.216 or 21.6%.** **(Ans.)**

Example 4.4. *The brake thermal efficiency of a diesel engine is 30 per cent. If the air to fuel ratio by weight is 20 and the calorific value of the fuel used is 41800 kJ/kg, what brake mean effective pressure may be expected at S.T.P. conditions ?*

Solution. Brake thermal efficiency,

$\eta_{th\ (B)} = 30\%$

Air-fuel ratio by weight $= 20$

Calorific value of fuel used, $C = 41800$ kJ/kg

Brake mean effective pressure, p_{mb} :

Brake thermal efficiency

$$= \frac{\text{Work produced}}{\text{Heat supplied}}$$

$$0.3 = \frac{\text{Work produced}}{41800}$$

$\therefore$ Work produced per kg of fuel

$= 0.3 \times 41800 = 12540$ kJ

Mass of air used per kg of fuel

$= 20$ kg

S.T.P. conditions refer to 1.0132 bar and 15°C

$$\text{Volume of air used} = \frac{mRT}{p}$$

$$= \frac{20 \times 287 \times (273 + 15)}{1.0132 \times 10^5}$$

$= 16.31$ m^3

Brake mean effective pressure,

$$p_{mb} = \frac{\text{Work done}}{\text{Cylinder volume}}$$

$$= \frac{12540 \times 1000}{16.31 \times 10^5} =$$ **7.69 bar.** **(Ans.)**

☞**Example 4.5.** *A 2-cylinder C.I. engine with a compression ratio 13 : 1 and cylinder dimensions of 200 mm × 250 mm works on two stroke cycle and consumes 14 kg/h of fuel while running at 300 r.p.m. The relative and mechanical efficiencies of engine are 65% and 76% respectively. The fuel injection is effected upto 5% of stroke. If the calorific value of the fuel used is given as 41800 kJ/kg, calculate the mean effective pressure developed.*

Solution. Refer to Fig. 4.38.

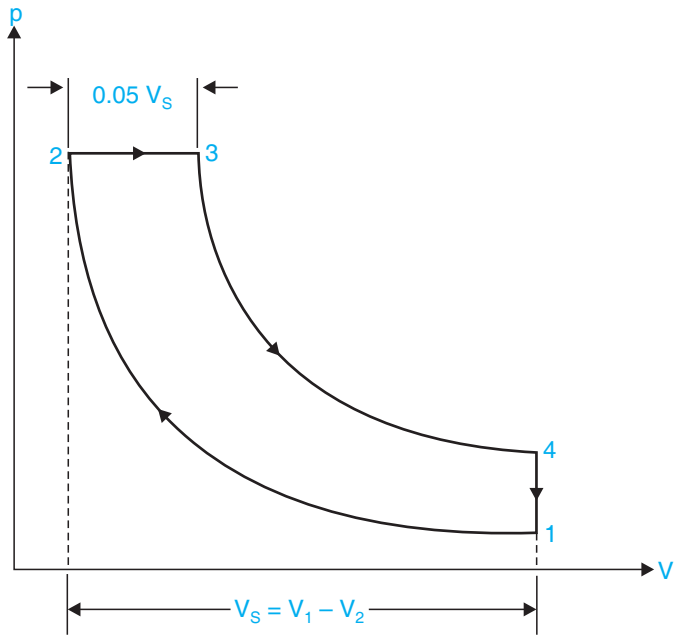


Fig. 4.38

Diameter of cylinder, $D = 200$ mm $= 0.2$ m
Stroke length, $L = 250$ mm $= 0.25$ m
Number of cylinders, $n = 2$
Compression ratio, $r = 14$
Fuel consumption $= 14$ kg/h
Engine speed, $N = 300$ r.p.m.
Relative efficiency, $\eta_{relative} = 65\%$
Mechanical efficiency, $\eta_{mech.} = 76\%$
Cut-off $= 5\%$ of stroke
Calorific value of fuel, $C = 41800$ kJ/kg
$k = 1$ ..... for two-stroke cycle engine

Cut-off ratio, $$\rho = \frac{V_3}{V_2}$$

Also, $$V_3 - V_2 = 0.05V_s$$
$$= 0.05(V_1 - V_2)$$
or, $$V_3 - V_2 = 0.05\,(13V_2 - V_2) \quad \left[\because \frac{V_1}{V_2} = r = 13\right]$$
or, $$V_3 - V_2 = 0.05 \times 12V_2 = 0.6V_2$$
$$\therefore \quad \frac{V_3}{V_2} = 1.6$$

$$\eta_{air\text{-}standard} = 1 - \frac{1}{\gamma(r)^{\gamma-1}}\left[\frac{\rho^{\gamma} - 1}{\rho - 1}\right]$$
$$= 1 - \frac{1}{1.4(14)^{1.4-1}}\left[\frac{1.6^{1.4} - 1}{1.6 - 1}\right]$$
$$= 1 - 0.248 \times 1.55$$
$$= 0.615\% \text{ or } 61.5\%$$

Also, $$\eta_{relative} = \frac{\eta_{thermal}}{\eta_{air\text{-}standard}}$$
$$0.65 = \frac{\eta_{thermal}}{0.615}$$
$$\therefore \quad \eta_{thermal} = 0.65 \times 0.615 = 0.4$$

But $$\eta_{thermal\ (I)} = \frac{\text{I.P.}}{\dot{m}_f \times C}$$
$$0.4 = \frac{\text{I.P.}}{\frac{14}{3600} \times 41800}$$
$$\text{I.P.} = \frac{0.4 \times 14 \times 41800}{3600} = 65 \text{ kW}$$

Now, $$\eta_{mech.} = \frac{\text{B.P.}}{\text{I.P.}}$$
$$0.76 = \frac{\text{B.P.}}{65}$$
$$\therefore \quad \text{B.P.} = 0.76 \times 65 = 49.4 \text{ kW}$$

Mean effective pressure can be calculated based on I.P. or B.P. of the engine.

$$\text{I.P.} = \frac{np_{mi}LANk \times 10}{6}$$

where, p_{mi} = Indicated mean effective pressure

$$65 = \frac{2 \times p_{mi} \times 0.25 \times \pi/4 \times 0.2^2 \times 300 \times 1 \times 10}{6}$$
$$\therefore \quad p_{mi} = \frac{65 \times 6 \times 4}{2 \times 0.25 \times \pi \times 0.2^2 \times 300 \times 10}$$
$$= \mathbf{8.27\ bar.} \quad \textbf{(Ans.)}$$

and brake mean effective pressure,

$$p_{mb} = 0.76 \times 8.27 = \mathbf{6.28\ bar.} \quad \textbf{(Ans.)}$$

Example 4.6. *A single cylinder 4-stroke diesel engine gave the following results while running on full load :*

Area of indicator card $= 300\ mm^2$
Length of diagram $= 40$ mm
Spring constant $= 1$ bar/mm
Speed of the engine $= 400$ r.p.m.
Load on the brake $= 370$ N
Spring balance reading $= 50$ N
Diameter of brake drum $= 1.2$ m
Fuel consumption $= 2.8$ kg/h
Calorific value of fuel $= 41800$ kJ/kg
Diameter of the cylinder $= 160$ mm
Stroke of the piston $= 200$ mm

Calculate : (i) Indicated mean effective pressure.
(ii) Brake power and brake mean effective pressure.
(iii) Brake specific fuel consumption, brake thermal and indicated thermal efficiencies.

Solution. *Given :* $N = 400$ r.p.m., $W = 370$ N,
$S = 50$ N, $D_b = 1.2$ m,
$m_f = 2.8$ kg/h, $C = 41800$ kJ/kg,
$D = 0.16$ m, $L = 0.2$ m,
$k = \frac{1}{2}$ ..... for 4-stroke cycle engine.

(i) Indicated mean effective pressure, p_{mi} :

$$p_{mi} = \frac{\text{Area of indicator diagram or card} \times \text{spring constant}}{\text{Length of diagram}}$$

$$= \frac{300 \times 1}{40} = \mathbf{7.5\ bar.} \quad \textbf{(Ans.)}$$

Indicated power,

$$\text{I.P.} = \frac{np_{mi}LANk \times 10}{6}$$

$$= \frac{1 \times 7.5 \times 0.2 \times \pi/4 \times 0.16^2 \times 400 \times \frac{1}{2} \times 10}{6}$$

$$= 10.05 \text{ kW.}$$

(ii) B.P. : , p_{mb} :

Brake power,

$$\text{B.P.} = \frac{(W - S)\pi D_b N}{60 \times 1000}$$

$$= \frac{(370 - 50)\pi \times 1.2 \times 400}{60 \times 1000}$$

$$= \mathbf{8.04\ kW.} \quad \textbf{(Ans.)}$$

Also, $$\text{B.P.} = \frac{np_{mb} \times LANk \times 10}{6}$$

$$8.04 = \frac{1 \times p_{mb} \times 0.2 \times \pi/4 \times 0.16^2 \times 400 \times \frac{1}{2} \times 10}{6}$$

$$\therefore\ p_{mb} = \frac{8.04 \times 6 \times 4 \times 2}{0.2 \times \pi \times 0.16^2 \times 400 \times 10} = \mathbf{6\ bar.} \quad \textbf{(Ans.)}$$

(iii) b.s.f.c. :, $\eta_{th(B)}$:, $\eta_{th.(I)}$:

Brake specific fuel consumption,

$b.s.f.c$ = Fuel consumption per B.P. hour

$$= \frac{2.8}{8.04} = \mathbf{0.348\ kg/B.P.\ hour.} \quad \textbf{(Ans.)}$$

Brake thermal efficiency,

$$\eta_{th.(B)} = \frac{\text{B.P.}}{\dot{m}_f \times C} = \frac{8.04}{\frac{2.8}{3600} \times 41800}$$

$$= \mathbf{0.2473\ or\ 24.73\%.} \quad \textbf{(Ans.)}$$

Indicated thermal efficiency,

$$\eta_{th.(I)} = \frac{\text{B.P.}}{\dot{m}_f \times C} = \frac{10.05}{\frac{2.8}{3600} \times 41800}$$

$$= \mathbf{0.3091\ or\ 30.91\%.} \quad \textbf{(Ans.)}$$

☞**Example 4.7.** *The following observations were recorded during the test on a 6-cylinder, 4-stroke Diesel engine :*

Bore	*= 125 mm*
Stroke	*= 125 mm*
Engine speed	*= 2400 r.p.m.*
Load on dynamometer	*= 490 N*
Dynamometer constant	*= 16100*
Air orifice diameter	*= 55 mm*
Co-efficient of discharge	*= 0.66*
Head causing flow through orifice	*= 310 mm of water*
Barometer reading	*= 760 mm Hg*
Ambient temperature	*= 25°C*
Fuel consumption	*= 22.1 kg/h*
Calorific value of fuel	*= 45100 kJ/kg*
Per cent carbon in the fuel	*= 85%*
Per cent hydrogen in the fuel	*= 15%*
Pressure of air at the end of suction stroke	*= 1.013 bar*
Temperature at the end of suction stroke	*= 25°C*

Calculate : (i) Brake mean effective pressure,
(ii) Specific fuel consumption,
(iii) Brake thermal efficiency,
(iv) Volumetric efficiency, and
(v) Percentage of excess air supplied.

Solution. *Given :* $n = 6$, $D = 0.125$ m, $L = 0.125$ m,
$N = 2400$ r.p.m.
$W = 490$ N,
C_D = dynamometer constant = 16100
d_0 = Orifice diameter = 0.055 m,
$C_d = 0.66$, $h_w = 310$ mm
$\dot{m}_f = \frac{22.1}{3600} = 0.00614$ kg/s,
$C = 45100$ kJ/kg,
$k = \frac{1}{2}$ ..... for 4-stroke cycle engine.

(i) Brake mean effective pressure, p_{mb} :

Brake power, $$\text{B.P.} = \frac{W \times N}{C_D} = \frac{490 \times 2400}{16100} = 73 \text{ kW}$$

Also, $$\text{B.P.} = \frac{np_{mb}LANk \times 10}{6}$$

$$73 = \frac{6 \times p_{mb} \times 0.125 \times \pi / 4 \times 0.125^2 \times 2400 \times \frac{1}{2} \times 10}{6}$$

$$\therefore \quad p_{mb} = \frac{76 \times 6 \times 4 \times 2}{6 \times 0.125 \times \pi \times 0.125^2 \times 2400 \times 10}$$

$$= \mathbf{3.96\ bar.} \quad \textbf{(Ans.)}$$

(ii) Specific fuel consumption, b.s.f.c. :

$$\text{b.s.f.c.} = \frac{22.1}{73} = \mathbf{0.3027\ kg/kWh.} \quad \textbf{(Ans.)}$$

(iii) Brake thermal efficiency, $\eta_{th.(B)}$:

$$\eta_{th.(B)} = \frac{\text{B.P.}}{\dot{m}_f \times C} = \frac{73}{0.00614 \times 45100}$$

$$= \mathbf{0.2636\ or\ 26.36\%.} \quad \textbf{(Ans.)}$$

(iv) Volumetric efficiency, $\eta_{vol.}$:

Stroke volume of cylinder

$$= \pi/4\ D^2 \times L$$

$$= \pi/4 \times 0.125^2 \times 0.125 = 0.00153\ \text{m}^3$$

The volume of air passing through the orifice of the air box per minute is given by,

$$V_a = 840\ A_0\ C_d \sqrt{\frac{h_w}{\rho_a}}$$

where, C_d = Discharge co-efficient of orifice = 0.66

A_0 = Area of cross-section of orifice

$= \pi/4\ d_0^2 = \pi/4 \times (0.055)^2 = 0.00237\ \text{m}^2$

h_w = Head causing flow through orifice in cm of water

$$= \frac{310}{10} = 31\ \text{cm}$$

ρ_a = Density of air at 1.013 bar and 25°C

$$= \frac{p}{RT} = \frac{1.013 \times 10^5}{287 \times (25 + 273)} = 1.18\ \text{kg/m}^3.$$

$\therefore$ Volume of air,

$$V_a = 840 \times 0.00237 \times 0.66 \sqrt{\frac{31}{1.18}}$$

$$= 6.73\ \text{m}^3/\text{min}$$

$\therefore$ Actual volume of air per cylinder

$$= \frac{6.73}{n} = \frac{6.73}{6} = 1.12\ \text{m}^3/\text{min}$$

$\therefore$ Air supplied per stroke per cylinder

$$= \frac{1.12}{(2400/2)} = 0.000933\ \text{m}^3$$

$$\therefore \quad \eta_{vol.} = \frac{\text{Volume of air actually supplied}}{\text{Volume of air theoretically required}}$$

$$= \frac{0.000933}{0.00153} = \mathbf{0.609\ or\ 60.9\%.} \quad \textbf{(Ans.)}$$

(v) Percentage of excess air supplied :

Quantity of air required per kg of fuel for complete combustion

$$= \frac{100}{23}\left[C \times \frac{8}{3} + H_2 \times \frac{8}{1}\right]$$

where C is the fraction of carbon and H_2 is the fraction of hydrogen present in the fuel respectively.

$$= \frac{100}{23}\left[0.85 \times \frac{8}{3} + 0.15 \times 8\right] = 15.07\ \text{kg/kg of fuel}$$

Actual quantity of air supplied per kg of fuel

$$= \frac{V_a \times \rho_a \times 60}{22.1} = \frac{6.73 \times 1.18 \times 60}{22.1} = 21.56\ \text{kg}$$

$\therefore$ *Percentage excess air*

$$= \frac{21.56 - 15.07}{15.07} \times 100 = \mathbf{43.06\%.} \quad \textbf{(Ans.)}$$

Example 4.8. *In a trial of a single cylinder oil engine working on dual cycle, the following observations were made :*

Compression ratio	= *15*
Oil consumption	= *10.2 kg/h*
Calorific value of fuel	= *43890 kJ/kg*
Air consumption	= *3.8 kg/min*
Speed	= *1900 r.p.m.*
Torque on the brake drum	= *186 Nm*
Quantity of cooling water used	= *15.5 kg/min*
Temperature rise	= *36°C*
Exhaust gas temperature	= *410°C*
Room temperature	= *20°C*
c_p for exhaust gases	= *1.17 kJ/kg K*

Calculate : (i) Brake power,

(ii) Brake specific fuel consumption, and

(iii) Brake thermal efficiency.

Draw heat balance sheet on minute basis.

Solution. *Given :* $n = 1$, $r = 15$, $m_f = 10.2$ kg/h,

$C = 43890$ kJ/kg, $m_a = 3.8$ kg/min.,

$N = 1900$ r.p.m., $T = 186$ Nm,

$m_w = 15.5$ kg/min,

$t_{w_2} - t_{w_1} = 36°\text{C}$, $t_g = 410°\text{C}$,

$t_r = 20°\text{C}$, $c_p = 1.17$.

(i) Brake power, B.P. :

$$\text{B.P.} = \frac{2\pi NT}{60 \times 1000} = \frac{2\pi \times 1900 \times 186}{60 \times 1000}$$

$$= \mathbf{37\ kW.} \quad \textbf{(Ans.)}$$

(ii) Brake specific fuel consumption, b.s.f.c. :

$$\text{b.s.f.c.} = \frac{10.2}{37} = \mathbf{0.2756\ kg/kWh.} \quad \textbf{(Ans.)}$$

(iii) Brake thermal efficiency, $\eta_{th(B)}$:

$$\eta_{th\,(B)} = \frac{\text{B.P.}}{\dot{m}_f \times C} = \frac{37}{\frac{10.2}{3600} \times 43890}$$

$$= \mathbf{0.2975 \text{ or } 29.75\%. \text{ (Ans.)}}$$

—Heat supplied by the fuel per minute

$$= \frac{10.2}{60} \times 43890 = 7461 \text{ kJ/min}$$

(i) Heat equivalent of B.P.

$$= \text{B.P.} \times 60 = 37 \times 60 = 2220 \text{ kJ/min.}$$

(ii) Heat carried away by cooling water

$$= m_w \times c_{pw} (t_{w_2} - t_{w_1}) = 15.5 \times 4.18 \times 36$$

$$= 2332 \text{ kJ/min.}$$

(iii) Heat carried away by exhaust gases

$$= m_g \times c_{pg} \times (t_g - t_r)$$

$$= \left(\frac{10.2}{60} + 3.8\right) \times 1.17 \times (410 - 20)$$

$$= 1811 \text{ kJ/min.}$$

Heat balance sheet (minute basis)

Item	*kJ*	*Per cent*
Heat supplied by fuel	*7461*	*100*
(i) Heat absorbed in B.P.	2220	29.8
(ii) Heat taken away by cooling water	2332	31.2
(iii) Heat carried away exhaust gases	1811	24.3
(iv) Heat unaccounted for (by difference)	1098	14.7
Total	7461	100

☞Example 4.9. *From the data given below, calculate indicated power, brake power and draw a heat balance sheet for a two stroke diesel engine run for 20 minutes at full load :*

r.p.m.	*= 350*
m.e.p.	*= 3.1 bar*
Net brake load	*= 640 N*
Fuel consumption	*= 1.52 kg*
Cooling water	*= 162 kg*
Water inlet temperature	*= 30°C*
Water outlet temperature	*= 55°C*
Air used/kg of fuel	*= 32 kg*
Room temperature	*= 25°C*
Exhaust temperature	*= 305°C*
Cylinder bore	*= 200 mm*
Cylinder stroke	*= 280 mm*
Brake diameter	*= 1 metre*
Calorific value of fuel	*= 43900 kJ/kg*
Steam formed per kg of fuel in the exhaust	*= 1.4 kg*
Specific heat of steam in exhaust	*= 2.09 kJ/kg K*
Specific heat of dry exhaust gases	*= 1.0 kJ/kg K.*

Solution. *Given :* $N = 350$ r.p.m., $p_{mi} = 3.1$ bar, $(W - S) = 640$ N, $m_f = 1.52$ kg, $m_w = 162$ kg, $t_{w_1} = 30°C$, $t_{w_2} = 55°C$, $m_a = 32$ kg/kg of fuel, $t_r = 25°C$, $t_g = 305°C$, $D = 0.2$ m, $L = 0.28$ m, $D_b = 1$ m, $C = 43900$ kJ/kg, $c_{ps} = 2.09$, $c_{pg} = 1.0$, $k = 1$ ..... for two stroke cycle engine.

(i) Indicated power, I.P. :

$$\text{I.P.} = \frac{np_{mi}LANk \times 10}{6}$$

$$= \frac{1 \times 3.1 \times 0.28 \times \pi/4 \times 0.2^2 \times 350 \times 1 \times 10}{6}$$

$$= \mathbf{15.9 \text{ kW.}} \text{ (Ans.)}$$

(ii) Brake power, B.P. :

$$\text{B.P.} = \frac{(W - S)\,\pi\, D_b N}{60 \times 1000} = \frac{640 \times \pi \times 1 \times 350}{60 \times 1000}$$

$$= \mathbf{11.73 \text{ kW.}} \text{ (Ans.)}$$

Heat supplied in 20 minutes

$$= 1.52 \times 43900 = 66728 \text{ kJ}$$

(i) Heat equivalent of I.P. in 20 minutes

$$= \text{I.P.} \times 60 \times 20 = 15.9 \times 60 \times 20$$

$$= 19080 \text{ kJ}$$

(ii) Heat carried away by cooling water

$$= m_w \times c_{pw} \times (t_{w_2} - t_{w_1})$$

$$= 162 \times 4.18 \times (55 - 30) = 16929 \text{ kJ}$$

Total mass of air $= 32 \times 1.52 = 48.64$ kg

Total mass of exhaust gases

$$= \text{Mass of fuel} + \text{Mass of air}$$

$$= 1.52 + 48.64 = 50.16 \text{ kg}$$

Mass of steam formed $= 1.4 \times 1.52 = 2.13$ kg

$\therefore$ Mass of dry exhaust gases

$$= 50.16 - 2.13 = 48.03 \text{ kg}$$

(iii) Heat carried away by dry exhaust gases

$$= m_g \times c_{pg} \times (t_g - t_r)$$

$$= 48.03 \times 1.0 \times (305 - 25) = 13448 \text{ kJ}$$

(iv) Heat carried away by steam

$$= 2.13[h_f + h_{fg} + c_{ps}\,(t_{sup} - t_s)]$$

At 1.013 bar pressure (atmospheric pressure assumed) :

$h_f = 417.5$ kJ/kg, $h_{fg} = 2257.9$ kJ/kg

$$= 2.13\,[417.5 + 2257.9 + 2.09\,(305 - 99.6)]$$

$$= 6613 \text{ kJ/kg} \text{ ..... neglecting sensible heat of water at room temperature}$$

Heat balance sheet (20 minute basis)

Item	*kJ*	*Per cent*
Heat supplied by fuel	*66728*	*100*
(*i*) Heat equivalent of I.P.	19080	28.60
(*ii*) Heat carried away by cooling water	16929	25.40
(*iii*) Heat carried away by dry exhaust gases	13448	20.10
(*iv*) Heat carried away steam in exhaust gases	6613	9.90
(*v*) Heat unaccounted for (by difference)	10658	16.00
Total	66728	100.00

☞**Example 4.10.** *During a test on a two stroke oil engine on full load the following observations were recorded :*

Speed = *350 r.p.m.*
Net brake load = *590 N*
Mean effective pressure = *2.8 bar*
Oil consumption = *4.3 kg/h*
Jacket cooling water = *500 kg/h*
Temperature of jacket water at inlet and outlet = *25°C and 50°C respectively*
Air used per kg of oil = *33 kg*
Temperature of air in test room = *25°C*
Temperature of exhaust gases = *400°C*
Cylinder diameter = *220 mm*
Stroke length = *280 mm*
Effective brake diameter = *1 metre*
Calorific value of oil = *43900 kJ/kg*
Proportion of hydrogen in fuel oil = *15%*
Mean specific heat of dry exhaust gases = *1.0 kJ/kg K*
Specific heat of steam = *2.09 kJ/kg K*
Calculate : (i) Indicated power, and (ii) Brake power.
Also draw up heat balance sheet on minute basis.

Solution. *Given :* $n = 1$, $N = 350$ r.p.m.,
$(W - S) = 590$ *N*, $p_{mi} = 2.8$ bar
$m_f = 4.3$ kg/h, $m_w = 500$ kg/h,
$t_{w_1} = 25°C$, $t_{w_2} = 50°C$
$m_a = 33$ kg/kg of oil, $t_r = 25°C$,
$t_g = 400°C$, $D = 0.22$ m
$L = 0.28$ m, $D_b = 1$ m,
$C = 43900$ kJ/kg, $c_{pg} = 1.0$, $c_{ps} = 2.09$
$k = 1$ ..... for two stroke cycle engine.

(*i*) Indicated power, I.P. :

$$\text{I.P.} = \frac{np_{mi}LANk \times 10}{6}$$

$$= \frac{1 \times 2.8 \times 0.28 \times \pi/4 \times 0.22^2 \times 350 \times 1 \times 10}{6}$$

$$= \mathbf{17.38\ kW.} \quad \textbf{(Ans.)}$$

(*ii*) Brake power, B.P. :

$$\text{B.P.} = \frac{(W - S)\,\pi\, D_b N}{60 \times 1000}$$

$$= \frac{590 \times \pi \times 1 \times 350}{60 \times 1000}$$

$$= \mathbf{10.81\ kW.} \quad \textbf{(Ans.)}$$

Heat supplied per minute

$$= \frac{4.3}{60} \times 43900 = 3146 \text{ kJ/min.}$$

(*i*) Heat equivalent of I.P. = 17.38 × 60
= 1042.8 kJ/min.

(*ii*) Heat lost to cooling water

$$= m_w \times c_{pw} \times (t_{w_2} - t_{w_1})$$

$$= \frac{500}{60} \times 4.18 \times (50 - 25) = 870.8 \text{ kJ/min.}$$

Now,

$$\begin{array}{ccccc} 2H_2 & + & O_2 & = & 2H_2O \\ 4 & & 32 & & 36 \\ 1 & & 8 & & 9 \end{array}$$

i.e., 1 kg of H_2 produces 9 kg of H_2O

∴ Mass of H_2O produced per kg of fuel burnt
$= 9 \times H_2 \times$ mass of fuel used/min.

$$= 9 \times 0.15 \times \frac{4.3}{60} = 0.0967 \text{ kg/min.}$$

Total mass of exhaust gases (wet)/min.
= Mass of air/min. + mass of fuel/min.

$$= \frac{(33 + 1) \times 4.3}{60} = 2.436 \text{ kg/min.}$$

Mass of dry exhaust gases/min.
= Mass of wet exhaust gases/min
– mass of H_2O produced/min.
= 2.436 – 0.0967 = 2.339 kg/min.

(*iii*) Heat lost to dry exhaust gases

$$= m_g \times c_{pg} \times (t_g - t_r)$$

$$= 2.339 \times 1.0 \times (400 - 25) = 887 \text{ kJ/min.}$$

(*iv*) Assuming that steam in exhaust gases exists as superheated steam at atmospheric pressure and exhaust gas temperature, the enthalpy of 1 kg of steam at atmospheric pressure 1.013 ≃ 1 bar and 400°C

$$= h_{sup} - h$$

(where h is the sensible heat of water at room temperature)

$= [h_f + h_{fg} + c_{ps}\,(t_{sup} - t_s)] - 1 \times 4.18 \times (25 - 0)$

$= [417.5 + 2257.9 + 2.09\,(400 - 25)] - 104.5$

$= 3355$ kJ/min.

∴ Heat carried away by steam

$= 0.0967 \times 3355 = 320.6$ kJ/min.

Heat balance sheet (minute basis)

Item	*kJ*	*Per cent*
Heat supplied by fuel	*3146*	*100*
(*i*) Heat equivalent of I.P.	1042.8	33.15
(*ii*) Heat carried away by cooling water	870.8	27.70
(*iii*) Heat carried away by dry gases	887	28.15
(*iv*) Heat carried away by steam	320.6	10.20
(*v*) Heat unaccounted for (by difference)	24.8	0.80
Total	314.6	100

Example 4.11. *During a test on a Diesel engine the following observations were made :*

The power developed by the engine is used for driving a D.C. generator. The output of the generator was 210 A at 200 V ; the efficiency of generator being 82%. The quantity of fuel supplied to the engine was 11.2 kg/h ; Calorific value of fuel being 42600 kJ/kg. The air-fuel ratio was 18 : 1.

The exhaust gases were passed through a exhaust gas calorimeter for which the observations were as follows : Water circulated through exhaust gas calorimeter = 580 litres/h. Temperature rise of water through calorimeter = 36°C. Temperature of exhaust gases at exit from calorimeter = 98°C. Ambient temperature = 20°C.

Heat lost to jacket cooling water is 32% of the total heat supplied.

If the specific heat of exhaust gases be 1.05 kJ/kg K draw up the heat balance sheet on minute basis.

Solution. Output of generator

= 210 A at 200 V

Generator efficiency = 82%

Fuel used = 11.2 kg/h

Calorific value of fuel = 42600 kJ/kg

Air-fuel ratio = 18 : 1

Mass of water circulated through calorimeter,

m_c = 580 litres or 580 kg/h

Temperature rise of water,

$t_{w_2} - t_{w_1} = 36°C$

Temperature of exhaust gases at exit from calorimeter = 98°C

Ambient temperature = 20°C

Heat lost to jacket cooling water

= 32% of the total heat supplied

Specific heat of exhaust gases

= 1.05 kJ/kg K

Total power generated

$= VI = 200 \times 210 = 42000$ W $= 42$ kW

Power available at the brakes of the engine,

$$\text{B.P.} = \frac{42}{0.82} = 51.22 \text{ kW}$$

Total heat supplied to the engine

= Fuel supplied per min. × calorific value of fuel

$$= \frac{11.2}{60} \times 42600 = 7952 \text{ kJ/min.}$$

(*i*) Heat equivalent of B.P.

$= 51.22 \times 60 = 3073$ kJ/min

Mass of exhaust gases formed per minute

$$= \text{Fuel supplied/min.} \left(\frac{A}{F} \text{ ratio} + 1\right)$$

$\left[\frac{A}{F}\text{ ratio means air-fuel ratio}\right]$

$$= \frac{11.2}{60}\,(18 + 1) = 3.55 \text{ kg/min.}$$

(*ii*) Heat carried away by exhaust gases/min.

= Heat gained by water in exhaust gas calorimeter from exhaust gases + heat in exhaust gases at exit from exhaust gas calorimeter above room temperature

$$= m_w \times c_{pw} \times (t_{w_2} - t_{w_1}) + m_g \times c_{pg}(t_g - t_r)$$

$$= \frac{580}{60} \times 4.18 \times 36 + 3.55 \times 1.05\,(98 - 20)$$

$= 1454.6 + 290.7 = 1745.3$ kg/min.

(*iii*) Heat lost to jacket cooling water

$= 0.32 \times 7952 = 2544.6$ kJ/min.

Heat balance sheet (minute basis)

Item	*kJ*	*Per cent*
Heat supplied	*7952*	*100*
(*i*) Heat equivalent of B.P.	3073	38.7
(*ii*) Heat carried away by exhaust gases	1745.3	21.9
(*iii*) Heat lost to jacket cooling water	2544.6	32.0
(*iv*) Heat unaccounted for (by difference)	589.1	7.4
Total	7952	100

☞**Example 4.12.** *During a trial of a single cylinder, 4-stroke diesel engine the following observations were recorded :*

Bore = *340 mm*
Stroke = *440 mm*
r.p.m. = *400*
Area of indicator diagram = *465 mm²*
Length of diagram = *60 mm*
Spring constant = *0.6 bar/mm*
Load on hydraulic dynamometer = *950 N*
Dynamometer constant = *7460*
Fuel used = *10.6 kg/h*
Calorific value of fuel = *49500 kJ/kg*
Cooling water circulated = *25 kg/min*
Rise in temperature of cooling water = *25°C*
The mass analysis of fuel is :
Carbon = *84%*
Hydrogen = *15%*
Incombustible = *1%*
The volume analysis of exhaust gases is :
Carbon dioxide = *9%*
Oxygen = *10%*
Nitrogen = *81%*
Temperature of exhaust gases = *400°C*
Specific heat of exhaust gases = *1.05 kJ/kg°C*
Ambient temperature = *25°C*
Partial pressure of steam in exhaust gases = *0.030 bar*
Specific heat of superheated steam = *2.1 kJ/kg°C.*
Draw up heat balance sheet on minute basis.

Solution. *Given :* $n = 1$, $D = 0.34$ m, $L = 0.44$ m, $N = 400$ r.p.m., $W = 950$ N, C_d (dynamometer constant) $= 7460$, $m_f = 10.6$ kg/h, $C = 49500$ kJ/kg, $m_w = 25$ kg/min., $(t_{w_2} - t_{w_1}) = 25°C$, $t_g = 400°C$, $c_{pg} = 1.05$ kJ/kg°C, $p_{ps} = 2.1$ kJ/kg°C.

Mean effective pressure,

$$p_{mi} = \frac{\text{Area of indicator diagram} \times \text{Spring constant}}{\text{Length of indicator diagram}}$$

$$= \frac{465 \times 0.6}{60} = 4.65 \text{ bar}$$

Indicated power,

$$\text{I.P.} = \frac{np_{mi}LANk \times 10}{6}$$

$$= \frac{1 \times 4.65 \times 0.44 \times \pi/4 \times 0.34^2 \times 400 \times \frac{1}{2} \times 10}{6}$$

$$= 61.9 \text{ kW}$$

Brake power,

$$\text{B.P.} = \frac{W \times N}{C_d} = \frac{950 \times 400}{7460} = 50.9 \text{ kW}$$

Friction power,

F.P. = I.P. – B.P. = 61.9 – 50.9 = 11 kW

Heat supplied per minute

= Fuel used per min. × Calorific value

$$= \frac{10.6}{60} \times 49500 = 8745 \text{ kJ/min.}$$

(*i*) Heat equivalent of B.P.

= B.P. × 60 = 50.9 × 60

= 3054 kJ/min.

(*ii*) Heat lost in friction

= F.P. × 60 = 11 × 60 = 660 kJ/min.

(*iii*) Heat carried away by cooling water

$$= m_w \times c_{pw} \times (t_{w_2} - t_{w_1})$$

= 25 × 4.18 × 25 = 2612.5 kJ/min.

Mass of air supplied per kg of fuel

$$= \frac{N \times C}{33(CO + CO_2)} = \frac{81 \times 84}{33(0 + 9)}$$

= 22.9 kg

Mass of exhaust gases formed per kg of fuel

= 22.9 + 1 = 23.9 kg

Mass of exhaust gases formed/min.

$$= 23.9 \times \frac{10.6}{60} \text{ 4.22 kg}$$

Mass of steam formed per kg of fuel

= 9 × 0.15 = 1.35 kg

∴ Mass of steam formed per min.

$$= 1.35 \times \frac{10.6}{60} = 0.238 \text{ kg/min.}$$

Mass of dry exhaust gases formed per min.

= 4.22 – 0.238 = 3.982 kg.

(*iv*) Heat carried away by dry exhaust gases/min.

$= m_g \times c_{pg} \times (t_g - t_r)$

$= 3.982 \times 1.05 \times (400 - 25) = 1568$ kJ/min.

Steam is carried away by exhaust gases. The temperature of steam is also the same as that of exhaust gases *e.g.* 400°C.

At partial pressure of steam 0.03 bar, the saturation temperature is 24.1°C. Therefore, steam is superheated.

Enthalpy of steam

$= h_g + c_{ps} (t_{sup} - t_s)$

$= 2545.5 + 2.1 (400 - 24.1)$

$= 3334.89$ kJ/kg.

(*v*) ∴ Heat carried by steam in exhaust gases

$= 3334.89 \times 0.238 = 793.7$ kJ/min.

(*vi*) Heat unaccounted for

= Total heat supplied—heat equivalent of B.P.

– heat lost in friction

—heat carried away by cooling water

– heat carried away by dry exhaust gases

– heat carried away by steam in exhaust gases

$= 8745 - (3054 + 660 + 2612.5 + 1568 + 793.7)$

$= 56.8$ kJ/min.

Heat balance sheet on minute basis

Item	*kJ*	*Per cent*
Heat supplied	*8745*	*100*
(*i*) Heat equivalent of B.P.	3054	34.92
(*ii*) Heat lost in friction	660	7.55
(*iii*) Heat carried away by cooling water	2612.5	29.87
(*iv*) Heat carried away by dry exhaust gases	1568	17.93
(*v*) Heat carried away by steam in exhaust gases	793.7	9.07
(*vi*) Heat unaccounted for	56.8	0.66
Total	8745	100

SUPERCHARGING

☞**Example 4.13.** *The average indicated power developed in a C.I. engine is 13 kW/m³ of free air induced per minute. The engine is a three-litre four-stroke engine running at 3500 r.p.m., and has a volumetric efficiency of 81%, referred to free air conditions of 1.013 bar and 15°C. It is proposed to fit a blower, driven mechanically from the engine. The blower has an isentropic efficiency of 72% and works through a pressure ratio of 1.72. Assume that at the end of induction the cylinders contain a volume of charge equal to the swept volume, at the pressure and temperature of the delivery from the blower. Calculate the increase in brake power to be expected from the engine.*

Take all mechanical efficiencies as 78%.

Solution. Capacity of the engine = 3 litres = 0.003 m³

Swept volume $= \frac{3500}{2} \times 0.003$

$= 5.25$ m³/min.

Unsupercharged induced volume

$= 5.25 \times \eta_{vol.}$

$= 5.25 \times 0.81 = 4.25$ m³

Blower delivery pressure $= 1.72 \times 1.013 = 1.74$ bar

Temperature after isentropic compression

$= 288 \times (1.72)^{(1.4 - 1)/1.4}$

$= 336.3$ K $\quad \left[\because \frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma - 1}{\gamma}} \right]$

∴ Blower delivery temperature

$= 288 + \left(\frac{336.3 - 288}{0.72} \right) = 355$ K

$\left[\because \eta_{isen.} = \frac{T_2 - T_1}{T_2' - T_1} \text{ or } T' = T_1 + \frac{T_2 - T_1}{\eta_{isen.}} \right]$

The blower delivery is 5.25 m³/min at 1.74 bar and 355 K.

Equivalent volume at 1.013 bar and 15°C

$= \frac{5.25 \times 1.74 \times 288}{1.013 \times 355} = 7.31$ m³/min.

∴ Increase in induced volume

$= 7.31 - 4.25 = 3.06$ m³/min.

∴ Increase in indicated power from air induced

$= 13 \times 3.06 = 39.78$ kW

Increase in I.P. due to the increased induction pressure

$= \frac{(1.74 - 1.013) \times 10^5 \times 5.25}{10^3 \times 60} = 6.36$ kW

i.e., Total increase in I.P. $= 39.78 + 6.36 = 46.14$ kW

∴ Increase in engine B.P. $= \eta_{mech.} \times 46.14$

$= 0.78 \times 46.14 = 35.98$ kW

From this must be *deducted the power required to drive the blower*

Mass of air delivered by blower

$= \frac{1.74 \times 10^5 \times 5.25}{60 \times 287 \times 355} = 0.149$ kg/s

Work input to blower

$= mc_p (355 - 288)$

$= 0.149 \times 1.005 \times 67$

∴ Power required

$= \frac{0.149 \times 1.005 \times 67}{0.78} = 12.86$ kW

∴ *Net increase in B.P.*

= 35.98 – 12.86 = **23.12 kW.** **(Ans.)**

Example 4.14. *A six-cylinder, four stroke CI engine is tested against a water brake dynamometer for which B.P. = WN/17 × 10^3 in kW where W is the brake load in newton and N is the speed of the engine in the r.p.m. The air consumption was measured by means of a sharp edged orifice. During the test following observations were taken :*

Bore	*= 10 cm*
Stroke	*= 14 cm*
Speed	*= 2500 r.p.m.*
Brake load	*= 480 N*
Barometer reading	*= 76 cm of Hg*
Orifice diameter	*= 3.3 cm*
Coefficient of discharge of orifice	*= 0.62*
Pressure drop across orifice	*= 14 cm of Hg*
Room temperature	*= 25°C*
Fuel consumption	*= 0.32 kg/min.*

Calculate the following :

(i) The volumetric efficiency ; (ii) The brake mean effective pressure (bmep) ; (iii) The engine torque ; (iv) The brake specific fuel consumption (bsfc). **(DU)**

Solution. *(i)* **Volumetric efficiency, η_{vol} :**

V_s = Swept volume,

$$= \frac{\pi}{4} D^2 L \times \frac{N}{60 \times 2}$$

× No. of cylinders, for 4-stroke.

(where N = r.p.m.)

$$= \frac{\pi}{4} (0.1)^2 \times 0.14 \times \frac{2500}{60 \times 2} \times 6$$

$$= 0.137 \text{ m}^3/\text{s}.$$

Barometer

= 76 cm Hg

$$= \left[\frac{76}{100} \times 13.6 \times 10^3 \times 9.81\right] \times 10^{-3}$$

$$= 101.4 \text{ kN/m}^2$$

$$\rho_a = \frac{p}{R_a T} = \frac{101.3}{0.287\,(273 + 25)}$$

$$= 1.1844 \text{ kg/m}^3$$

Δp = 14 cm of Hg

$$= \frac{14}{100} \times 13.6 \times 10^3 \times 9.81$$

$$= 18.678 \times 10^3 \text{ N/m}^2$$

$\Delta p = \rho_a \times 9.81 \times h_a$,

where, h_a = Head, m of air, causing flow

or, $$h_a = \frac{18.678 \times 10^3}{1.1844 \times 9.81} = 1607.5 \text{ m of air}$$

V_a = Volume flow rate of air, at free air conditions

$$= C_d \frac{\pi}{4} (d_0)^2 \sqrt{2gh_a}$$

$$= 0.62 \times \frac{\pi}{4} \left(\frac{3.3}{100}\right)^2 \sqrt{2 \times 9.81 \times 1607.5}$$

$$= 0.094 \text{ m}^3/\text{s}.$$

$$\%\eta_{vol} = \frac{V_a}{V_s} \times 100$$

$$= \frac{0.094}{0.137} \times 100 = \mathbf{68.6\%}. \quad \textbf{(Ans.)}$$

(ii) **The brake mean effective pressure, $p_{mb.}$:**

$$\text{B.P.} = \frac{WN}{17} \times 10^{-3} \text{ kW} = \frac{480 \times 2500}{17} \times 10^{-3}$$

$$= 70.588 \text{ kW}$$

$$= p_{mb} LA \times \frac{N}{60} \times \frac{1}{2} \times 6,$$

for six cylinder, four stroke

or, $$p_{mb} = \frac{70.588 \times 60 \times 2}{0.14 \times \frac{\pi}{4} (0.1)^2 \times 2500 \times 6}$$

$$= \mathbf{513.57 \text{ kN/m}^2}. \quad \textbf{(Ans.)}$$

(iii) **Engine torque, T :**

B.P. = $2\pi NT$

or, Torque, $(T) = \frac{\text{B.P.}}{2\pi N} = \frac{70.588 \times 10^3}{2\pi \times \frac{2500}{60}}$

$$= \mathbf{269.63 \text{ Nm}}. \quad \textbf{(Ans.)}$$

(iv) **Brake specific fuel consumption, bsfc :**

$$bsfc = \frac{m_f \text{ (kg/h)}}{\text{B.P.}} = \frac{0.32 \times 60}{70.588}$$

$$= \mathbf{0.272 \text{ kg / kWh}}. \quad \textbf{(Ans.)}$$

Example 4.15. *An engine is required to develop 100 kW, the mechanical efficiency of the engine is 86% and the engine uses 55 kg/h of fuel. Due to improvement in the design and operating conditions, there is reduction in engine friction to the extent of 4.8 kW. If the indicated thermal efficiency remains the same, determine the saving in fuel in kg/h.* **(UPTU)**

Solution. Required brake power = 100 kW

$$\text{Indicated power} = \frac{100}{0.86} = 116.28 \text{ kW}$$

$$(sfc)_{\text{indicated}} = \frac{55}{116.28} = 0.473 \text{ kg/kWh}$$

Friction power = 116.28 – 100 = 16.28 kW.

Given that indicated thermal efficiency remains same after improvement, the $(sfc)_{ind.}$ also remains the same.

After improvement :

Brake power = 100 kW

Friction power = 16.28 – 4.8 = 11.48 kW

Indicated power = 100 + 11.48 = 111.48 kW

Fuel consumption = 111.48 × 0.473 = 52.73 kg / h

Saving in fuel = 55 – 52.73 = 2.27 kg / h

or $\frac{2.27}{55} \times 100 = \mathbf{4.127\%}$. **(Ans.)**

HIGHLIGHTS

1. Any type of engine or machine which derives heat energy from the combustion of fuel or any other source and converts this energy into mechanical work is termed as a heat engine.
2. Essential components of a diesel power plant are :
   (*i*) Engine (*ii*) Air intake system
   (*iii*) Exhaust system (*iv*) Fuel system
   (*v*) Cooling system (*vi*) Lubrication system
   (*vii*) Engine starting system
   (*viii*) Governing system.
3. Commonly used fuel injection system in a diesel power station :
   (*i*) Common-rail injection system
   (*ii*) Individual pump injection system
   (*iii*) Distribution system.
4. In liquid cooling following methods are used for circulating the water around the cylinder and cylinder head :
   (*i*) Thermo-system cooling
   (*ii*) Forced or pump cooling
   (*iii*) Cooling with thermostatic regulator
   (*iv*) Pressurised cooling
   (*v*) Evaporative cooling.
5. Various lubrication systems use for I.C. engines are :
   (*i*) Wet sump lubrication system
   (*ii*) Dry sump lubrication system
   (*iii*) Mist lubrication system.
6. The following three are the commonly used starting systems in large and medium size engines :
   (*i*) Starting by an auxiliary engine
   (*ii*) Use of electric motors or self starters
   (*iii*) Compressed air system.
7. The purpose of supercharging is to raise the volumetric efficiency above that value which can be obtained by normal aspiration.
8. **Performance of I.C. engines.** Some important relations :

(*i*) Indicated power (I.P.) $= \frac{np_{mi}\, LANk \times 10}{6}$ kW

In MKS Units

Indicated horse power, I.H.P. $= \frac{np_{mi}\, LANk}{4500}$

(*ii*) Brake (B.P.) $= \frac{(W - S)\pi(D_b + d)N}{60 \times 1000}$ kW

or $\left(= \frac{2\pi NT}{60 \times 1000} \text{ kW}\right)$

In MKS Units

Brake horse power, B.H.P. $= \frac{(W - S)\pi(D_b + d)\, N}{4500}$

or $\left(= \frac{2\pi NT}{4500}\right)$

(*iii*) Mechanical efficiency, $\eta_{mech.} = \frac{\text{B.P. (or B.H.P.)}}{\text{I.P. (or I.H.P.)}}$

(*iv*) Thermal efficiency (indicated),

$$\eta_{th.\,(I)} = \frac{\text{I.P.}}{\dot{m}_f \times C}$$

and thermal efficiency (brake), $\eta_{th.\,(B)} = \frac{\text{B.P.}}{\dot{m}_f \times C}$

where m_f = mass of fuel used in kg/sec.

In MKS Units

$$\eta_{th.\,(I)} = \frac{\text{I.H.P.} \times 4500}{J \times m_f \times C}$$

$$\eta_{th.\,(B)} = \frac{\text{B.H.P.} \times 4500}{J \times m_f \times C}$$

where m_f = Mass of fuel used in kg/min.

(*v*) $\eta_{relative} = \frac{\eta_{thermal}}{\eta_{air\text{-}standard}}$

(*vi*) Measurement of air consumption by air box method :

Volume of air passing through the orifice,

$$V_a = 840\, AC_d \sqrt{\frac{h_w}{\rho_a}}$$

and mass of air passing through the orifice,

$$m_a = 0.066\, C_d \times d^2 \sqrt{h_w\, \rho_a} \text{ kg/min.}$$

where, A = Area of orifice, m^2,

d = Diameter of orifice, cm,

h_w = Head of water in 'cm' causing the flow, and

ρ_a = Density of air in kg/m^3 under atmospheric conditions.

THEORETICAL QUESTIONS

1. What are the advantages and disadvantages of diesel power plants ?
2. State the applications of diesel power plant.
3. What factors should be considered while selecting a site for a diesel power plant ?
4. With the help of neat sketches give the construction and working of a four stroke diesel cycle engine.
5. List the essential components of a diesel power plant and explain them briefly.
6. Name and explain briefly various types of fuel injection systems.
7. Explain with the help of a neat sketch the working of a thermostatically controlled cooling system.
8. Explain briefly the following lubrication systems :
   (*i*) Wet sump lubrication system.
   (*ii*) Dry sump lubrication systems.
9. Describe briefly the commonly used starting systems in large and medium size engines.
10. Discuss briefly the basic designs of C.I. engine combustion.
11. Write a short note on "Supercharging".
12. Give the types of diesel engines used for diesel power plants.
13. Give the layout of a diesel engine power plant.

UNSOLVED EXAMPLES

1. A single cylinder petrol engine working on two stroke cycle develops indicated power of 5 kW. If the mean effective pressure is 7.0 bar and the piston diameter is 100 mm, calculate the average speed of the piston.
   [**Hint.** Average piston speed = $2LN$.] [**Ans.** 109.1 m/s]
2. A 4-cylinder petrol engine works on a mean effective pressure of 5 bar and engine speed of 1250 r.p.m. Find the indicated power developed by the engine if the bore is 100 mm and stroke 150 mm. [**Ans.** 6.11 kW]
3. A 4-cylinder four stroke S.I. engine is designed to develop 44 kW indicated power at a speed of 3000 r.p.m. The compression ratio used is 6. The law of compression and expansion is $pV^{1.3}$ = constant and heat addition and rejection takes place at constant volume. The pressure and temperature at the beginning of compression stroke are 1 bar and 50°C. The maximum pressure of the cycle is limited to 30 bar. Calculate the diameter and stroke of each cylinder assuming all cylinders have equal dimensions.
   Assume diagram factor = 0.8 and ratio of stroke/bore = 1.5. [**Ans.** D = 95 mm, L = 142.5 mm]
4. During the trial of a four stroke diesel engine, the following observations were recorded :
   Area of indicator diagram = 475 mm^2, length of indicator diagram = 62 mm, spring number = 1.1 bar/mm, diameter of piston = 100 mm, length of stroke = 150 mm, engine r.p.m. = 375.
   Determine : (*i*) Indicated mean effective pressure ;
   (*ii*) Indicated power.
   [**Ans.** (*i*) 8.43 bar ; (*ii*) 3.1 kW]
5. A 4-cylinder, four stroke diesel engine runs at 1000 r.p.m. The bore and stroke of each cylinder are 100 mm and 160 mm respectively. The cut off is 6.62% of the stroke. Assuming that the initial conditions of air inside the cylinder are 1 bar and 20°C, mechanical efficiency of 75%, calculate the air-standard efficiency and brake power developed by the engine.
   Also, calculate the brake specific fuel consumption if the air/fuel ratio is 20 : 1. Take R for air as 0.287 kJ/kg K and clearance volume as 0.000084 m^3.
   [**Ans.** 61.4%, 21.75 kW, 0.4396 kg/kWh]
6. During a trial of a two stroke diesel engine the following observations were recorded :
   Engine speed = 1500 r.p.m., load on brakes = 120 kg, length of brake arm = 875 mm.
   Determine : (*i*) Brake torque, (*ii*) Brake power.
   [**Ans.** (*i*) 1030 Nm ; (*ii*) 161.8 kW]
7. A four stroke gas engine develops 4.2 kW at 180 r.p.m. and at full load. Assuming the following data, calculate the relative efficiency based on indicated power and air-fuel ratio used. Volumetric efficiency = 87%, mechanical efficiency = 74%, clearance volume = 2100 cm^3, sweept volume = 9000 cm^3, fuel consumption = 5 m^3/h, calorific value of fuel = 16750 kJ/m^3. [**Ans.** 50.2%, 7.456 : 1]
8. During the trial of a four stroke cycle gas engine the following data were recorded :

Area of indicator diagram	= 565.8 mm^2
Length of indicator diagram	= 74.8 mm
Spring index	= 0.9 bar/mm
Cylinder diameter	= 220 mm
Stroke length	= 430 mm
Number of explosions/min	= 100

   Determine : (*i*) Indicated mean effective pressure;
   (*ii*) Indicated power.
   [**Ans.** (*i*) 6.8 bar ; (*ii*) 18.5 kW]
9. The following observations were recorded during a trial of a four stroke engine with rope brake dynamometer :
   Engine speed = 650 r.p.m., diameter of brake drum = 600 mm, diameter of rope = 50 mm, dead load on the brake drum = 32 kg, spring balance reading = 4.75 kg.
   Calculate the brake power. [**Ans.** 5.9 kW]
10. The following data refer to a four stroke petrol engine :
    Engine speed = 2000 r.p.m., ideal thermal efficiency = 35%, relative efficiency = 80%, mechanical efficiency = 85%, volumetric efficiency = 70%.

If the engine develops 29.42 kW brake power calculate the cylinder swept volume. [**Ans.** 0.00185 m^3]

11. A single cylinder four-stroke gas engine has a bore of 178 mm and a stroke of 330 mm and is governed by hit and miss principle. When running at 400 r.p.m. at full load, indicator cards are taken which give a working loop mean effective pressure of 6.2 bar, and a pumping loop mean effective pressure of 0.35 bar. Diagrams from the dead cycle give a mean effective pressure of 0.62 bar. The engine was run light at the same speed (*i.e.* with no load), and a mechanical counter recorded 47 firing strokes per minute.

Calculate : (*i*) Full load brake power,

(*ii*) Mechanical efficiency of the engine.

[**Ans.** (*i*) 13.54 kW ; (*ii*) 84.7%]

12. During a 60 minutes trial of a single cylinder four stroke engine the following observations were recorded : Bore = 0.3 m, stroke = 0.45 m, fuel consumption = 11.4 kg, calorific value of fuel = 42000 kJ/kg, brake mean effective pressure = 6.0 bar, net load on brakes = 1500 N, r.p.m. = 300, brake drum diameter = 1.8 m, brake rope diameter = 20 mm, quantity of jacket cooling water = 600 kg, temperature rise of jacket water = 55°C, quantity of air as measured = 250 kg, exhaust gas temperature = 420°C, c_p for exhaust gases = 1 kJ/kg K, ambient temperature = 20°C.

Calculate :

(*i*) Indicated power ;

(*ii*) Brake power ;

(*iii*) Mechanical efficiency ;

(*iv*) Indicated thermal efficiency.

Draw up a heat balance sheet on minute basis.

[**Ans.** (*i*) 47.7 kW; (*ii*) 42.9 kW; (*iii*) 89.9%; (*iv*) 35.86%]

13. A quality governed four-stroke, single cylinder gas engine has a bore of 146 mm and a stroke of 280 mm. At 475 r.p.m. and full load the net load on the friction brake is 433 N, and the torque arm is 0.45 m. The indicator diagram gives a net area of 578 mm^2 and a length of 70 mm with a spring rating of 0.815 bar/mm.

Calculate :

(*i*) The indicated power (*ii*) Brake power

(*iii*) Mechanical efficiency.

[**Ans.** (*i*) 12.5 kW; (*ii*) 9.69 kW; (*iii*) 77.5%]

14. A two-cylinder four stroke gas engine has a bore of 380 mm and a stroke of 585 mm. At 240 r.p.m. the torque developed is 5.16 kNm.

Calculate :

(*i*) Brake power

(*ii*) Mean piston speed in m/s

(*iii*) Brake mean effective pressure.

[**Ans.** (*i*) 129.8 kW; (*ii*) 4.68 m/s; (*iii*) 4.89 bar]

15. The engine of Problem 14 is supplied with a mixture of coal gas and air in the proportion of 1 to 7 by volume. The estimated volumetric efficiency is 85% and the calorific value of the coal gas is 16800 kJ/m^3. Calculate the brake thermal efficiency of the engine. [**Ans.** 27.4%]

16. A 4-cylinder, four-stroke diesel engine has a bore of 212 mm and a stroke of 292 mm. At full load at 720 r.p.m., the b.m.e.p. is 5.93 bar and the specific fuel consumption is 0.226 kg/kWh. The air/fuel ratio as determined by exhaust gas analysis is 25 : 1. Calculate the brake thermal efficiency and volumetric efficiency of the engine.

Atmospheric conditions are 1.01 bar and 15°C and calorific value for the fuel may be taken as 44200 kJ/kg.

[**Ans.** 36% ; 76.5%]

17. A 4-cylinder petrol engine has an output of 52 kW at 2000 r.p.m. A Morse test is carried out and the brake torque readings are 177, 170, 168 and 174 Nm respectively. For normal running at this speed the specific fuel consumption is 0.364 kg/kWh. The calorific value of fuel is 44200 kJ/kg.

Calculate : (*i*) Mechanical efficiency ;

(*ii*) Brake thermal efficiency of the engine.

[**Ans.** (*i*) 82% ; (*ii*) 22.4%]

18. A V-8 four stroke petrol engine is required to give 186.5 kW at 440 r.p.m. The brake thermal efficiency can be assumed to be 32% at the compression ratio of 9 : 1. The air/fuel ratio is 12 : 1 and the volumetric efficiency at this speed is 69%. If the stroke to bore ratio is 0.8, determine the engine displacement required and the dimensions of the bore and stroke. The calorific value of the fuel is 44200 kJ/kg, and the free air conditions are 1.013 bar and 15°C.

[**Ans.** 5.12 litres ; 100.6 mm ; 80.5 mm]

19. During the trial (60 minutes) on a single cylinder oil engine having cylinder diameter 300 mm, stroke 450 mm and working on the four stroke cycle, the following observations were made :

Total fuel used = 9.6 litres, calorific value of fuel = 45000 kJ/kg, total number of revolutions = 12624, gross indicated mean effective pressure = 7.24 bar, pumping i.m.e.p. = 0.34 bar, net load on the brake = 3150 N, diameter of brake wheel drum = 1.78 m, diameter of the rope = 40 mm, cooling water circulated = 545 litres, cooling water temperature rise = 25°C, specific gravity of oil = 0.8.

Determine : (*i*) Indicated power,

(*ii*) Brake power,

(*iii*) Mechanical efficiency.

Draw up the heat balance sheet on minute basis.

[**Ans.** (*i*) 77 kW ; (*ii*) 61.77 kW ; (*iii*) 80.22%]

20. The following results were obtained on full load during a trial on a two stroke oil engine :

Engine speed	= 350 r.p.m.
Net brake load	= 600 N
m.e.p.	= 2.75 bar
Oil consumption	= 4.25 kg/h
Temperature rise of jacket cooling water	= 25°C
Air used per kg of oil	= 31.5 kg
Temperature of air in test room	= 20°C
Temperature of exhaust gases	= 390°C

Following data also apply to the above test :

Cylinder diameter	= 220 mm
Stroke	= 280 mm
Effective brake diameter	= 1 metre
Calorific value of oil	= 45000 kJ/kg

Proportion of hydrogen in fuel oil = 15%
Partial pressure of steam in exhaust gases = 0.04 bar
Mean specific heat of exhaust gases = 1.0 kJ/kg K
Specific heat of superheated steam = 2.1 kJ/kg K
Specific heat of water = 4.186 kJ/kg K
Determine : (*i*) Indicated power, (*ii*) Brake power, (*iii*) Mechanical efficiency.
Draw up heat balance sheet for the test.

[**Ans.** (*i*) 17.1 kW ; (*ii*) 11 kW ; (*iii*) 64.33%]

21. A 4-cylinder, four-stroke diesel engine develops 83.5 kW at 1800 r.p.m. with specific fuel consumption of 0.231 kg/kWh, and air/fuel ratio of 23 : 1. The analysis of fuel is 87% carbon and 13% hydrogen, and the calorific value of the fuel is 43500 kJ/kg. The jacket cooling water flows at 0.246 kg/s and its temperature rise is 50 K. The exhaust temperature is 316°C. Draw up an energy balance for the engine. Take R = 0.302 kJ/kg K and c_p = 1.09 kJ/kg K for the dry exhaust gases and c_p = 1.86 kJ/kg K for superheated steam. The temperature in the test house is 17.8°C, and the exhaust gas pressure is 1.013 bar.

[**Ans.** B.P. = 35.8%, cooling water = 22.1%, exhaust = 24%, radiation and unaccounted = 16.7%]

COMPETITIVE EXAMINATIONS QUESTIONS

1. (*a*) State and explain the factors which are required to be considered in the choice of diesel engine for a diesel power plant.
(*b*) With the help of diagrams, show the general shape of (*i*) fuel consumption (kg/kWh) *versus* percentage rated load, and (*ii*) energy produced per unit weight of fuel (kWh/kg) *versus* percentage capacity factor characteristic of diesel engines. How is the rating of a diesel engine effected by the altitude above sea-level ?
(*c*) Define (*i*) the thermal efficiency, in the terms of indicated horse-power, weight of fuel etc., and (*ii*) the brake power in kW of a diesel engine.

2. (*a*) Why is supercharging necessary in diesel power plant ? What methods are used for supercharging the diesel engines ?
(*b*) Draw a neat diagram of a fuel storage and fuel supply system used for diesel power plants. What are the advantages of underground fuel storage ?

3. (*a*) Under what conditions diesel generating plants are preferred ?
(*b*) On what factors is the size of the generating plant selected ?
(*c*) Draw the neat diagram of a cooling system used for diesel power plant showing all the essential components. What are the advantages of double circuit over single circuit system ? What precautions should be taken to ensure that cooling is satisfactory ?

4. For a diesel power station discuss briefly about the following :
(*a*) Cooling system ;
(*b*) Lubricating system ;
(*c*) Supercharging system.

5. (*a*) Under what conditions diesel power plants are selected in preference to steam power plants ? Explain giving suitable examples.
(*b*) Describe the working of a gas turbine plant with the help of T-ϕ chart. How can the efficiency be improved ?

6. (*a*) Draw line diagram to show the layout of diesel power plant and describe it in brief.
(*b*) State the factors to be considered for selection of prime movers in a medium sized power plant.

7. (*a*) Explain the starting and stopping procedure in a diesel power plant.
(*b*) Make a layout of a modern diesel power plant showing the following systems :
(*i*) Air intake system ;
(*ii*) Cooling system ;
(*iii*) Fuel supply system ;
(*iv*) Lubrication system ;
(*v*) Exhaust system.

8. (*a*) What are the advantages of supercharging ? Explain the methods used for supercharging diesel engines.
(*b*) Calculate the cooling water required in litres per minute from the following performance data available for a particular diesel engine :

Brake horse-power	= 4500
Jacket loss	= 23%
Water temperature rise	= 35°C
Mechanical efficiency	= 83%
Indicated thermal efficiency	= 34%

9. (*a*) Give a general layout of a diesel engine power plant showing clearly all the essential circuits.
(*b*) A four cylinder 40 cm diameter and 60 cm stroke, four stroke diesel engine has a fuel consumption of 0.20 kg per I.H.P. hour based on 10,000 kcal/kg oil. Engine speed is 275 r.p.m. with an indicated mean effective pressure of 8.5 kgf/cm^2. Jacket water carries away 24% of the heat supplied. Calculate the quantity of water in kg/hr needed to maintain an outlet temperature of jacket water at 50°C. Temperature of atmosphere is 20°C.
Calculate also the indicated thermal efficiency of this engine.

10. The following data is obtained during a test on a 4-stroke, 4-cylinder diesel engine :

Cylinder diameter	= 35 cm
Stroke	= 40 cm
Speed of the engine	= 315 r.p.m.
Indicated m.e.p.	= 7 kgf/cm^2
B.H.P. of the engine	= 330
Fuel consumption	= 80 kg/hour
Calorific value of fuel	= 10500 kcal/kg

Hydrogen content in hydrocarbon fuel = 13%

Air consumption	= 30 kg/min
Cooling water circulated	= 90 kg/min
Rise in temperature of cooling water	= 38°C
Exhaust gas temperature	= 324°C
Specific heat of air	= 0.24
Specific heat of exhaust gases	= 0.26
Ambient temperature	= 24°C
Specific heat for superheated steam	= 0.5
Partial pressure of steam in exhaust gases	= 0.030 kgf/cm^2

Find :

(*i*) Mechanical efficiency, indicated thermal efficiency and specific fuel consumption on I.H.P. basis.

(*ii*) Cost of energy per kWh assuming cost of fuel as ₹ 2.50 per litre and specific gravity of fuel as 0.93.

(*iii*) Draw up the heat balance on minute and percentage basis.

Find : (*i*) The fixed cost of power generation per kW per annum ; (*ii*) The total cost of power generation per kWh. Cost of primary distribution is chargeable to generation.

11. Write brief notes on the following :

(*a*) Lubrication system in diesel power plant ;

(*b*) Intercooling in gas turbine plant ;

(*c*) Earthing of a power system ;

(*d*) Flat plate solar collectors.

12. What are the advantages and disadvantages of diesel power plant over steam power plant ? What is the status of diesel power plants in our country ?

13. (*a*) Make a neat layout line diagram of a diesel power plant showing in particular the fuel system and the water cooling system.

(*b*) What are the primary advantages of a diesel power plant ?

(*c*) Cooling water from a 400 kW diesel power plant enters a cooling tower at 60°C and leaves the tower at 37.8°C in an atmosphere with a dry bulb temperature of 32.2°C and a wet bulb temperature of 27.8°C. If thermal efficiency of the plant is 30% and 32% of the energy input is lost to the cooling water, estimate the kg/min of cooling water handled by the tower and the cooling efficiency of the tower.

Gas Turbine Power Plants

5

5.1. Gas turbines—General aspects. 5.2. Applications of gas turbine plants. 5.3. Advantages and disadvantages of gas turbine power plants over diesel and thermal power plants. 5.4. Site selection. 5.5. The simple gas turbine plant. 5.6. Energy cycle for a simple-cycle gas turbine. 5.7. Performance terms. 5.8. Classification of gas turbine power plants. 5.9. Classification of gas turbines. 5.10. Merits of gas turbines. 5.11. Constant pressure combustion gas turbines—Open cycle gas turbine—Methods for improvement of thermal efficiency of open cycle gas turbine plant—Closed cycle gas turbine—Merits and demerits of closed cycle turbine over open cycle turbine. **5.12. Constant volume combustion turbines. 5.13. Gas turbine fuels. 5.14. Effect of operating variables on thermal efficiency. 5.15. Combination gas turbine cycles**—Combined gas turbine and steam power plants—Combined gas turbine and diesel power plants—Advantages of combined cycle. **5.16. Operation of a gas turbine. 5.17. Gas turbine power plant layout. 5.18. Components of a gas turbine power plant. 5.19. Various arrangements of gas turbine power plants. 5.20. Effect of thermodynamic variables on air rate. 5.21. Free-piston engine plant. 5.22. Relative thermal efficiencies of different cycles**—*Worked Examples—Highlights—Theoretical Questions—Unsolved Examples—Competitive Examinations Questions.*

5.1. GAS TURBINES—GENERAL ASPECTS

Probably a windmill was the first turbine to produce useful work, wherein there is no pre-compression and no combustion. The characteristic features of a gas turbine as we think of the name today include a *compression process* and a *heat-addition* (or combustion) process. The gas turbine represents perhaps the *most satisfactory way of producing very large quantities of power in a self-contained and compact unit*. The gas turbine may have an ample future use in conjunction with the oil engine. For smaller gas turbine units, the inefficiencies in compression and expansion processes become greater and to improve the thermal efficiency it is necessary to use a heat exchanger. In order that a small gas turbine may compete for economy with the small oil engine or petrol engine it is necessary that a compact effective heat exchanger be used in the gas turbine cycle. The thermal efficiency of the gas turbine alone is still quite modest 20 to 30% compared with that of a modern steam plant 38 to 40%. It is possible to construct *combined plants* whose efficiencies are of order of 45% or more. Higher efficiencies might be attained in future.

The following are the major fields of application of gas turbines :

1. Aviation
2. Power generation
3. Oil and gas industry
4. Marine propulsion.

The efficiency of a gas turbine is not the criteria for the choice of this plant. A gas turbine is used in *aviation* and marine fields because *it is self contained, light weight not requiring cooling water and generally fit into the overall shape of the structure.* It is selected for '*power generation*' because of its *simplicity, lack of cooling water, needs quick installation and quick starting*. It is used in *oil and gas industry* because of *cheaper supply* of *fuel and low installation cost*.

The gas turbines have the following ***"limitations"*** :

1. They are not self starting.
2. Low efficiencies at part loads.
3. Non-reversibility.
4. Higher rotor speeds.
5. Low overall plant efficiency.

In the last two decides, rapid progress has been observed in the *development and improvement of the gas turbine plants for electric power production*. The major progress has been observed in the following *directions* :

(*i*) Increase in unit capacities of gas turbine units.

(*ii*) Increase in their efficiency.

(*iii*) Drop in capital cost.

5.2. APPLICATIONS OF GAS TURBINE PLANTS

Gas turbine plants for the purpose of power plant engineering, find the following *applications* :

1. To drive generators and supply peak loads in steam, diesel or hydroplants.

2. To work as combination plants with conventional steam boilers.

3. To supply mechanical drive for auxiliaries.

— These plants are well suited for *peak load service* since the fuel costs are somewhat higher and initial cost low. Moreover, *peak load operation permits use of water injection which increases turbine work by about 40% with an increase in heat rate of about 20%*. The short duration of increase in heat rate does not prove of any much harm.

— The combination arrangement of gas turbines with conventional boilers may be supercharging or for heat recovery from exhaust gases. In the *supercharging system* air is supplied to the boiler under pressure by a compressor mounted on the common shaft with turbine and gases formed as result of combination after coming out of the boiler pass through the gas turbine before passing through the economiser and the chimney.

— The application of the gas turbine to drive the auxiliaries is not strictly included under direct electric power generation by the turbines and would not be discussed.

5.3. ADVANTAGES AND DISADVANTAGES OF GAS TURBINE POWER PLANTS OVER DIESEL AND THERMAL POWER PLANTS

A. Advantages over Diesel Plants :

1. The work developed per kg of air is large compared with diesel plant.
2. Less vibrations due to perfect balancing.
3. Less space requirements.
4. Capital cost considerably less.
5. Higher mechanical efficiency.
6. The running speed of the turbine (40,000 to 100,000 r.p.m.) is considerably large compared to diesel engine (1000 to 2000 r.p.m.).
7. Lower installation and maintenance costs.
8. The torque characteristics of turbine plants are far better than diesel plants.
9. The ignition and lubrication systems are simpler.
10. The specific fuel consumption does not increase with time in gas turbine plant as rapidly as in diesel plants.
11. Poor quality fuels can be used.

Disadvantages :

1. Poor part load efficiency.
2. Special metals and alloys are required for different components of the plants.
3. Special cooling methods are required for cooling the turbine blades.
4. Short life.

B. Advantages Over Steam Power Plant:

1. No ash handling problem.
2. Low capital cost.
3. The gas turbine plants can be installed at selected load centre as space requirement is considerably less where steam plant cannot be accommodated.
4. Fewer auxiliaries required/used.
5. Gas turbines can be built relatively quicker. They require much less space and civil engineering works and water supply.
6. The gas turbine plant as peak load plant is more preferable as it can be brought on load quickly and surely.
7. The components and circuits of a gas turbine plant can be arranged to give the most economic results in any given circumstances which is not possible in case of steam power plants.
8. For the same pressure and initial temperature conditions the ratio of exhaust to inlet volume would be only 3.95 in case of gas turbine plant as against 250 for steam plant.
9. Above 550°C, the thermal efficiency of the gas turbine plant increases three times as fast the steam cycle efficiency for a given top temperature increase.
10. The site of the steam power plant is dictated by the availability of large cooling water whereas an open cycle gas turbine plant can be located near the load centre as no cooling water is required. The cooling water required for closed cycle gas turbine is hardly 10% of the steam power plant.
11. The gas turbine plants can work quite economically for short running hours.
12. Storage of fuel is much smaller and handling is easy.

5.4. SITE SELECTION

While selectinig the site for a gas turbine plant. The following *points* should be given due consideration :

1. The plant should be located near the load centre to avoid transmission costs and losses.

2. The site should be away from business centres due to noisy operations.

3. Cheap and good quality fuel should be easily available.

4. Availability of labour.

5. Availability of means of transportation.
6. The land should be available at a cheap price.
7. The bearing capacity of the land should be high.

5.5. THE SIMPLE GAS TURBINE PLANT

A gas turbine plant may be defined as one "*in which the principal prime mover is of the turbine type and the working medium is a permanent gas*".

Refer to Fig. 5.1. A simple gas turbine plant consists of the following :

1. *Turbine*.
2. *A compressor* mounted on the same shaft or coupled to the turbine.
3. *The combustor.*
4. *Auxiliaries* such as starting device, auxiliary lubrication pump, fuel system, oil system and the duct system etc.

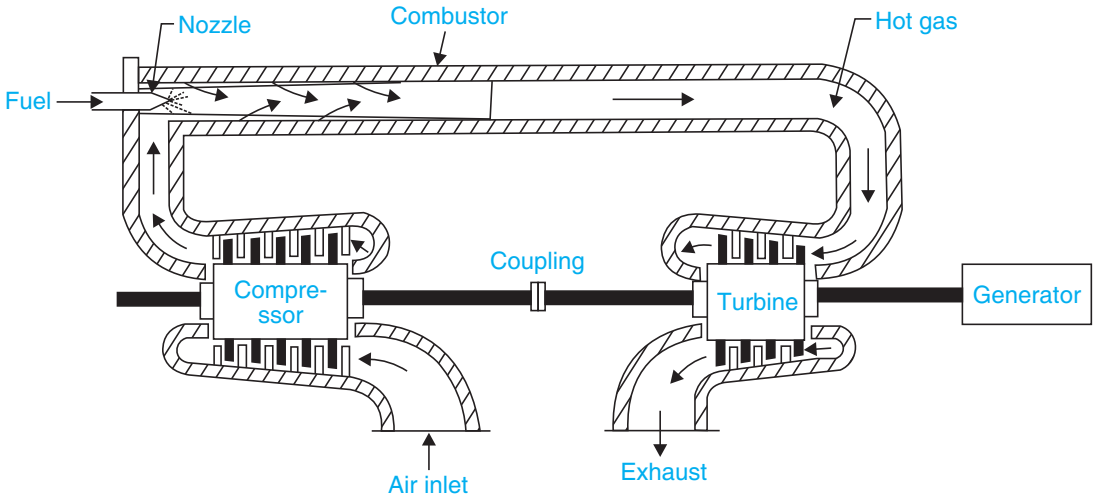


Fig. 5.1. Arrangement of a simple gas turbine plant.

A modified plant may have in addition to above an *intercooler, a regenerator, a reheater* etc.

The working fluid is compressed in a compressor which is generally rotary, multistage type. Heat energy is added to the compressed fluid in the chamber. This high energy fluid, at high temperature and presssure, then expands in the turbine unit thereby generating power. Part of the power generated is consumed in driving the generating compressor and accessories and the rest is utilised in electrical energy. The gas turbines work on open cycle, semi-closed cycle or closed cycle. In order to improve efficiency, compression and expansion of working fluid is carried out in multistages.

5.6. ENERGY CYCLE FOR A SIMPLE-CYCLE GAS TURBINE

Fig. 5.2 shows an energy-flow diagram for a simple-cycle gas turbine, the description of which is as follows :

— The air brings in minute amount of energy (measured above 0°C).
— Compressor adds considerable amount of energy.
— Fuel carries major input to cycle.
— Sum of fuel and compressed-air energy leaves combustor to enter turbine.
— In turbine smallest part of entering energy goes to useful output, largest part leaves in exhaust.

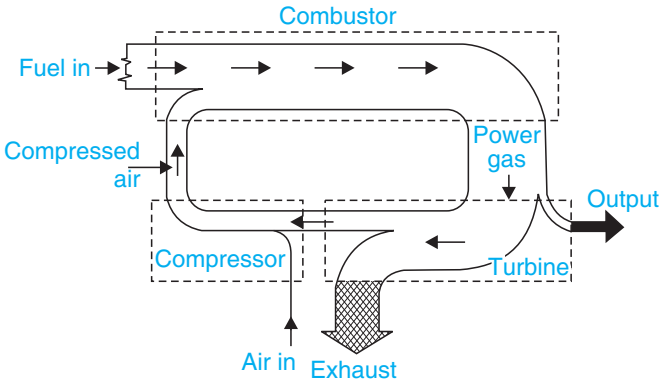


Fig. 5.2. Energy flow diagram for gas-turbine unit.

Shaft energy to drive compressor is about twice as much as the useful shaft output.

Actually the shaft energy keeps circulating in the cycle as long as the turbine runs. The important comparison is *the size of the output with the fuel input*. For the simple-cycle gas turbine the output may run about 20 per cent of the fuel input for pressure and temperature conditions at turbine inlet. This means 80% of the fuel energy is wasted. While the 20% thermal efficiency is not too bad, it can be improved by including *additional heat recovery apparatus.*

5.7. PERFORMANCE TERMS

Some of the important terms used to measure performance of a gas turbine are defined as follows :

1. Pressure ratio. It is the *ratio of cycle's highest to its lowest pressure*, usually highest-pressure-compressor discharges to the lowest-pressure-compressor inlet pressures.

2. Work ratio. It is the *ratio of network output to the total work developed in the turbine or turbines.*

3. Air ratio. *kg of air entering the compressor inlet per unit of cycle net output*, for example, kg/kWh.

4. Compression efficiency. It is the *ratio of work needed for ideal air compression through a given pressure range to work actually used by the compressor.*

5. Engine efficiency. It is the *ratio of the work actually developed by the turbine expanding hot power gas through a given pressure range to that would be yielded for ideal expansion conditions.*

6. Machine efficiency. It is the collective term *meaning both engine efficiency and compressor efficiency of turbine and compressor, respectively.*

7. Combustion efficiency. It is the *ratio of heat actually released by 1 kg of fuel to heat that would be released by complete perfect combustion.*

8. Thermal efficiency. It is the *percentage of total energy input appearing as net work output of the cycle.*

5.8. CLASSIFICATION OF GAS TURBINE POWER PLANTS

The gas turbine power plants may be classified according to the following criteria :

1. By application :

(*i*) *In aircraft*
(*a*) Jet propulsion (*b*) Prop-jets
(*ii*) *Stationary*
(*a*) Peak load unit (*b*) Standby unit
(*c*) End of transmission line unit
(*d*) Base load unit
(*e*) Industrial unit.
(*iii*) Locomotive
(*iv*) Marine
(*v*) Transport.

2. By cycle :

(*i*) Open cycle (*ii*) Closed cycle
(*iii*) Semi-closed cycle.

3. According to arrangement :

(*i*) Simple (*ii*) Single shaft
(*iii*) Multi-shaft (*iv*) Intercooled
(*v*) Reheat (*vi*) Regenerative
(*vii*) Combination.

4. According to combustion :

(*i*) Continuous combustion
(*ii*) Intermittent combustion.

5. By fuel :

(*i*) Solid fuel (*ii*) Liquid fuel
(*iii*) Gaseous fuel.

5.9. CLASSIFICATION OF GAS TURBINES

The gas turbines are mainly divided into two groups :

1. Constant pressure combustion gas turbine

(*a*) Open cycle constant pressure gas turbine
(*b*) Closed cycle constant pressure gas turbine.

2. Constant volume combustion gas turbine

- In almost *all the fields open cycle gas turbine plants are used. Closed cycle plants were introduced at one stage because of their ability to burn cheap fuel.* In between their progress remained slow because of availability of cheap oil and natural gas. Because of rising oil prices, now again, the attention is being paid to closed cycle plants.

5.10. MERITS OF GAS TURBINES

(*i*) **Merits over I.C. engines :**

1. The mechanical efficiency of a gas turbine (95%) is quite high as compared with I.C. engine (85%) since the I.C. engine has many sliding parts.
2. A gas turbine does not require a flywheel as the torque on the shaft is continuous and uniform. Whereas a flywheel is a must in case of an I.C. engine.
3. The weight of gas turbine per kW developed is less than that of an I.C. engine.
4. The gas turbine can be driven at a very high (40000 r.p.m.) whereas this is not possible with I.C. engines.
5. The work developed by a gas turbine per kg of air is more as compared to an I.C. engine. This is due to the fact that gases can be expanded upto atmospheric pressure in case of a gas turbine whereas in an I.C. engine expansion upto atmospheric pressure is not possible.
6. The components of the gas turbine can be made lighter since the pressures used in it are very low, say 5 bar compared with I.C. engine, say 60 bar.

7. In the gas turbine the ignition and lubrication systems are much simpler as compared with I.C. engines.
8. Cheaper fuels such as paraffine type, residue oils or powdered coal can be used whereas special grade fuels are employed in petrol engine to check knocking or pinking.
9. The exhaust from gas turbine is less polluting comparatively since excess air is used for combustion.
10. Because of low specific weight the gas turbines are particularly suitable for use in aircrafts.

Demerits of gas turbines :

1. The thermal efficiency of a simple turbine cycle is low (15 to 20%) as compared with I.C. engines (25 to 30%).
2. With wide operating speeds the fuel control is comparatively difficult.
3. Due to higher operating speeds of the turbine, it is imperative to have a speed reduction device.
4. It is difficult to start a gas turbine as compared to an I.C. engine.
5. The gas turbine blades need a special cooling system.

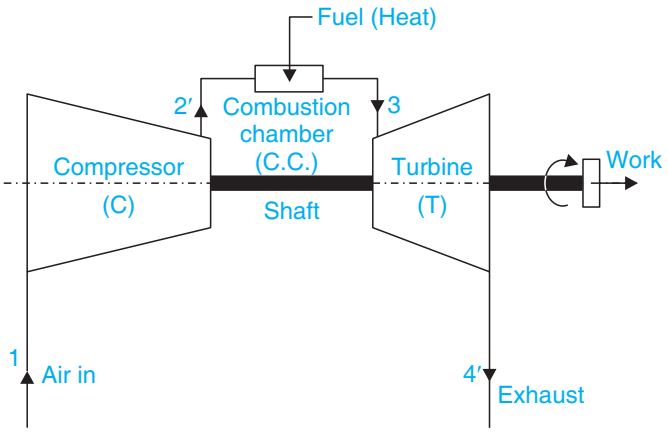


Fig. 5.3. Open cycle gas turbine.

6. One of the main demerits of a gas turbine is its *very poor thermal efficiency at part loads,* as the quantity of air remains same irrespective of load, and output is reduced by reducing the quantity of fuel supplied.
7. Owing to the use of nikel-chromium alloy, the manufacture of the blades is difficult and costly.
8. For the same output the gas turbine produces five times exhaust gases than I.C. engine.
9. Because of prevalence of high temperature (1000 K for blades and 2500 K for combustion chamber) and centrifugal force the life of the combustion chamber and blades is short/small.

(*ii*) Merits over steam turbines :

The gas turbine entails the following *advantages over steam turbines* :

1. Capital and running cost less.
2. For the same output the space required is far less.
3. Starting is more easy and quick.
4. Weight per H.P. is far less.
5. Can be installed anywhere.
6. Control of gas turbine is much easier.
7. Boiler along with accessories not required.

5.11. CONSTANT PRESSURE COMBUSTION GAS TURBINES

5.11.1. Open Cycle Gas Turbines

Refer to Fig. 5.3. The fundamental gas turbine unit is one operating on the open cycle in which a rotary compressor and a turbine are mounted on a common shaft. Air is drawn into the compressor and after compression passes to a combustion chamber. Energy is supplied in the combustion chamber by spraying fuel into the air stream, and the resulting hot gases expand through the turbine to the atmosphere. In order to achieve net work output from the unit, the turbine must develop more gross work output than is required to drive the compressor and to overcome mechanical losses in the drive. The products of combustion coming out from the turbine are exhausted to the atmosphere as they cannot be used any more. The working fluids (air and fuel) must be replaced continuously as they are exhausted into the atmosphere.

If pressure loss in the combustion chamber is neglected, this cycle may be drawn on a *T-s* diagram as shown in Fig. 5.4.

Line 1-2′ represents : *irreversible adiabatic compression.*

Line 2′-3 represents : *constant pressure heat supply in the combustion chamber.*

Line 3-4′ represents : *irreversible adiabatic expansion.*

Line 1-2 represents : *ideal isentropic compression.*

Line 3-4 represents : *ideal isentropic expansion.*

Assuming change in kinetic energy between the various points in the cycle to be negligibly small compared with enthalpy changes and then applying the flow equation to each part of cycle, for unit mass, we have

Work input (compressor) $= c_p (T_2' - T_1)$

Heat supplied (combustion chamber) $= c_p (T_3 - T_2')$

Work output (turbine) $= c_p (T_3 - T_4')$

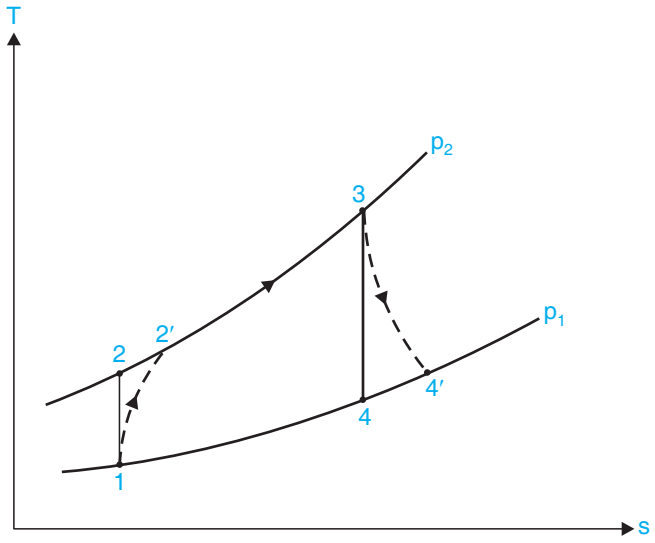


Fig. 5.4

$\therefore$ Net work output

= Work output – work input

$= c_p (T_3 - T_4') - c_p (T_2' - T_1)$

and $\eta_{thermal} = \dfrac{\text{Net work output}}{\text{Heat supplied}}$

$= \dfrac{c_p (T_3 - T_4') - c_p (T_2' - T_1)}{c_p (T_3 - T_2')}$

Compressor isentropic efficiency, $\eta_{comp.}$

$= \dfrac{\text{Work input required in isentropic compression}}{\text{Actual work required}}$

$= \dfrac{c_p (T_2 - T_1)}{c_p (T_2' - T_1)} = \dfrac{T_2 - T_1}{T_2' - T_1}$ ...(5.1)

Turbine isentropic efficiency, $\eta_{turbine}$

$= \dfrac{\text{Actual work output}}{\text{Isentropic work output}}$

$= \dfrac{c_p (T_3 - T_4')}{c_p (T_3 - T_4)} = \dfrac{T_3 - T_4'}{T_3 - T_4}$ ...(5.2)

Note. With the variation in temperature, the value of the specific heat of a real gas varies, and also in the open cycle, the specific heat of the gases in the combustion chamber and in turbine is different from that in the compressor because fuel has been added and a chemical change has taken place. Curves showing the variation of c_p with temperature and air/fuel ratio can be used, and a suitable mean value of c_p and hence γ can be found out. It is usual in gas turbine practice to assume fixed mean value of c_p and γ for the expansion process, and fixed mean values of c_p and γ for the compression process. In an open cycle gas turbine unit the mass flow of gases in turbine is greater than that in compressor due to mass of fuel burned, but it is possible to neglect mass of fuel, since the air/fuel ratios used are large. Also, in many cases, air is bled from the compressor for cooling purposes, or in the case of air craft at high altitudes, bled air is used for de-icing and cabin air-conditioning. This amount of air bled is approximately the same as the mass of fuel injected therein.

5.11.2. Methods for Improvement of Thermal Efficiency of Open Cycle Gas Turbine Plant

The following methods are employed to increase the specific output and thermal efficiency of the plant :

1. Intercooling
2. Reheating
3. Regeneration.

1. Intercooling. A compressor in a gas turbine cycle utilises the major percentage of power developed by the gas turbine. The work required by the compressor can be reduced by compressing the air in two stages and incorporating an intercooler between the two as shown in Fig. 5.5. The corresponding *T-s* diagram for the unit is shown in Fig. 5.6 (*a*). The actual processes take place as follows :

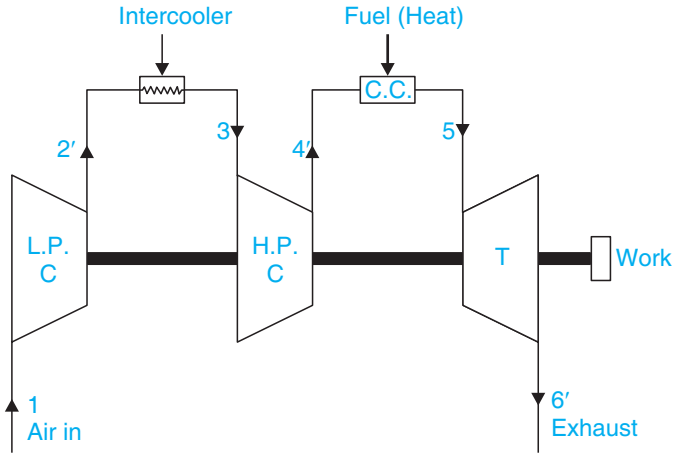


Fig. 5.5. Turbine plant with intercooler.

1-2′ : *L.P. (Low pressure) compression*

2′-3 : *Intercooling*

3-4′ : H.P. (High pressure) compression

4′-5 : C.C. (Combustion chamber)–heating

5-6′ : T (Turbine)–expansion

The ideal cycle for this arrangement is 1-2-3-4-5-6 ; the compression process without intercooling is shown as 1-*L*′ in the actual case, and 1-*L* in the ideal isentropic case.

Now, work input (with intercooling)

$= c_p (T_2' - T_1) + c_p (T_4' - T_3)$ ...(5.3)

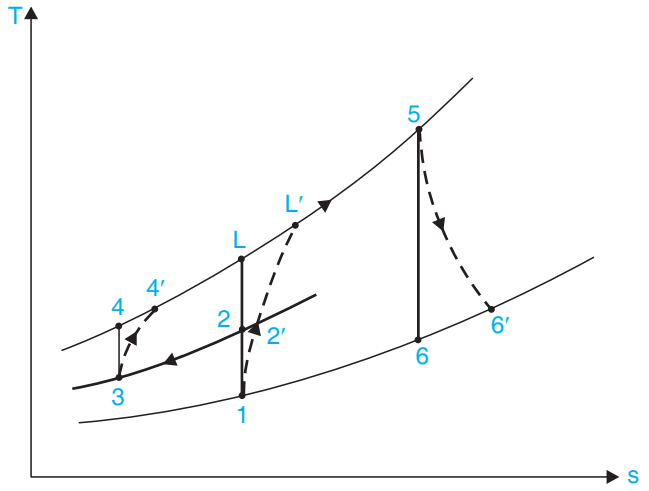


Fig. 5.6. (*a*) *T-s* diagram for the unit.

Work input (without intercooling)

$$= c_p(T_L' - T_1) = c_p(T_2' - T_1) + c_p(T_L' - T_2') \quad ...(5.4)$$

By comparing equation (5.4) with equation (5.3) it can be observed that the *work input with intercooling is less than the work input with no intercooling*, when $c_p(T_4' - T_3)$ is *less* than $c_p(T_L' - T_2')$. This is so if it is assumed that isentropic efficiencies of the two compressors, operating separately, are each equal to the isentropic efficiency of the single compressor which would be required if no intercooling were used. Then $(T_4' - T_3) < (T_L' - T_2')$ since the pressure lines diverge on the *T-s* diagram from left to the right.

Again, work ratio

$$= \frac{\text{Net work output}}{\text{Gross work output}}$$

$$= \frac{\text{Work of expansion} - \text{Work of compression}}{\text{Work of expansion}}$$

From this we may conclude that *when the compressor work input is reduced then the work ratio is increased*.

However the heat supplied in the combustion chamber when intercooling is used in the cycle, is given by,

Heat supplied *with* intercooling = $c_p(T_5 - T_4')$

Also the heat supplied when intercooling is *not* used, with the same maximum cycle temperature T_5, is given by

Heat supplied *without* intercooling = $c_p(T_5 - T_L')$

Thus, the *heat supplied when intercooling is used is greater than with no intercooling. Although the net work output is increased by intercooling it is found in general that the increase in heat to be supplied causes the thermal efficiency to decrease.* When intercooling is used a supply of cooling water must be readily available. The additional bulk of the unit may offset the advantage to be gained by increasing the work ratio.

In Fig. 5.6 (*b*) is shown that the intercooling has marked effect on thermal efficiency only at high pressure ratio.

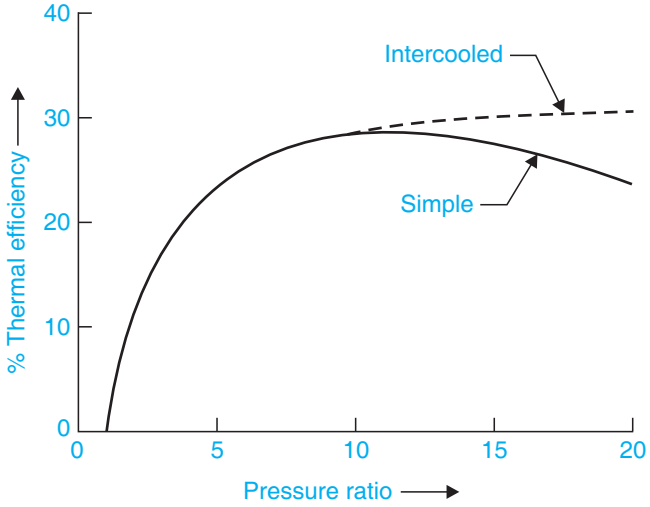


Fig. 5.6 (*b*)

2. Reheating. The output of a gas turbine can be amply improved by expanding the gases in two stages with a reheater between the two as shown in Fig. 5.7. The H.P. turbine drives the compressor and the L.P. turbine provides the useful power output. The corresponding *T-s* diagram is shown in Fig. 5.8 (*a*). The line 4′-*L*′ represents the expansion in the L.P. turbine if reheating is not employed.

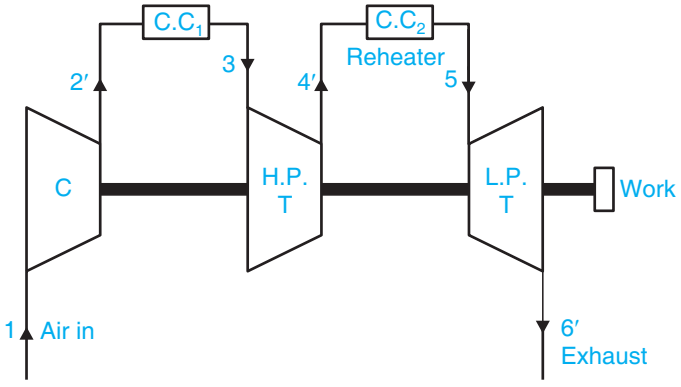


Fig. 5.7. Gas turbine with reheater.

Neglecting mechanical losses the work output of the H.P. turbine must be exactly equal to the work input required for the compressor

i.e., $c_{pa}(T_2' - T_1) = c_{pg}(T_3 - T_4')$

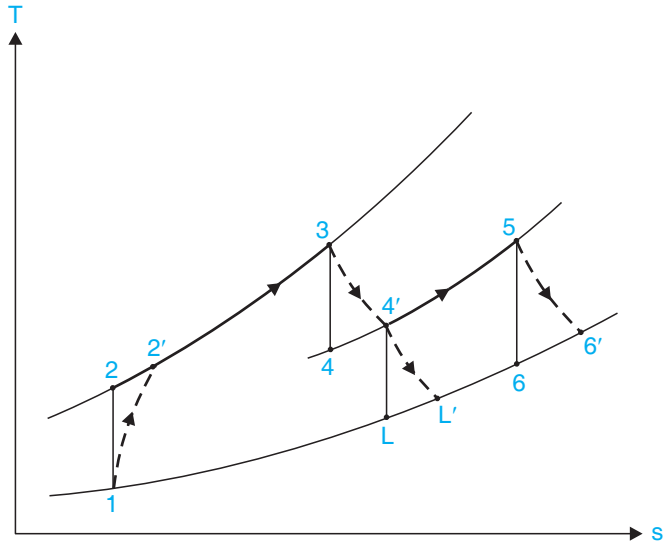


Fig. 5.8. (*a*) *T-s* diagram for the unit.

The work output (net output) of L.P. turbine is given by:

Net work output (with reheating)

$$= c_{pg} (T_5 - T_6')$$

and, Net work output (without reheating)

$$= c_{pg} (T_4' - T_L')$$

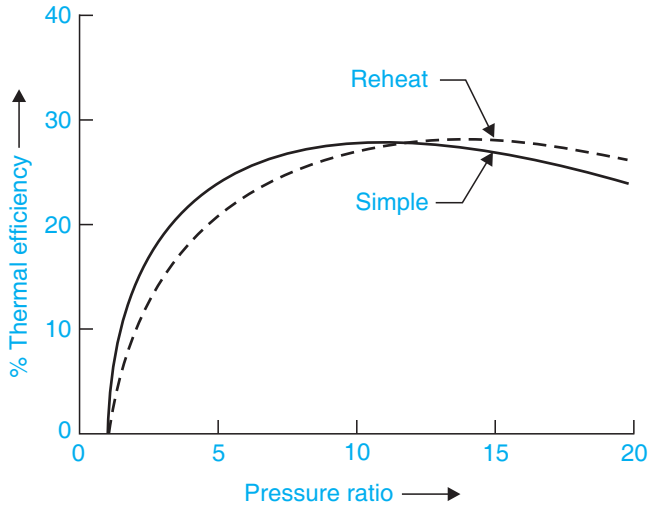


Fig. 5.8 (*b*)

Since the pressure lines diverge to the right on *T-s* diagram it can be seen that the temperature difference $(T_5 - T_6')$ is always *greater* than $(T_4' - T_L')$, so that *reheating increases the net work output.*

Although net work is increased by reheating the heat to be supplied is also increased, and the net effect *can be to reduce the thermal efficiency* [Fig. 5.8 (*b*)]

Heat supplied $= c_{pg} (T_3 - T_2') + c_{pg} (T_5 - T_4')$.

Note. c_{pa} and c_{pg} stand for specific heats of air and gas respectively at constant pressure.

3. Regeneration. The exhaust gases from a gas turbine carry a large quantity of heat with them since their temperature is far above the ambient temperature. They can be used to heat the air coming from the compressor thereby reducing the mass of fuel supplied in the combustion chamber. Fig. 5.9 shows a gas turbine plant *with a regenerator*. The corresponding *T-s* diagram is shown in Fig. 5.10. 2′-3 represents the heat flow into the compressed air during its passage through the heat exchanger and 3-4 represents the heat taken in from the combustion of fuel. Point 6 represents the temperature of exhaust gases at discharge from the heat exchanger. The maximum temperature to which the air could be heated in the heat exchanger is ideally that of exhaust gases, but less than this is obtained in practice because a temperature gradient must exist for an unassisted transfer of energy. The effectiveness of the heat exchanger is given by :

Effectiveness,

$$\varepsilon = \frac{\text{Increase in enthalpy per kg of air}}{\text{Available increase in enthalpy per kg of air}}$$

$$= \frac{(T_3 - T_2')}{(T_5' - T_2')} \qquad ...(5.5)$$

(assuming c_{pa} and c_{pg} to be equal)

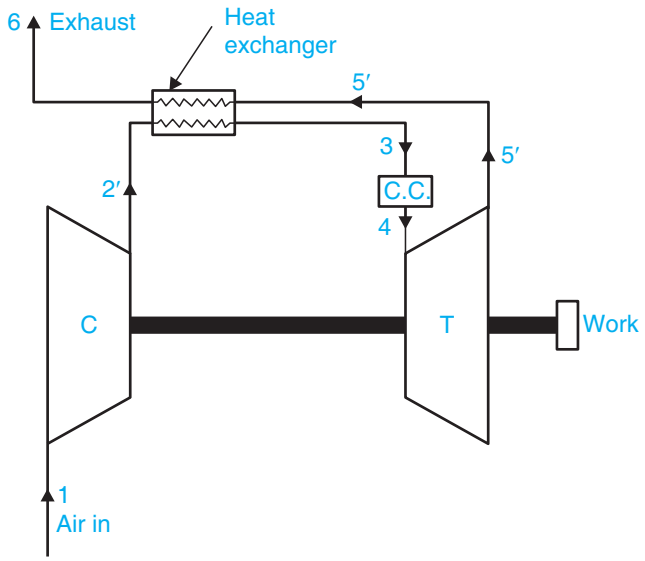


Fig. 5.9. Gas turbine with regenerator.

Fig. 5.10 (*b*) shows that the regenerative cycle has higher efficiency than the simple cycle only at low pressure ratios. At pressure ratios above a certain limit the efficiency of the regenerative cycle drops since in that case the regenerator will cool the compressed air entering the combustion chamber instead of heating it.

A heat exchanger is usually used in large gas turbine units for marine propulsion or industrial power.

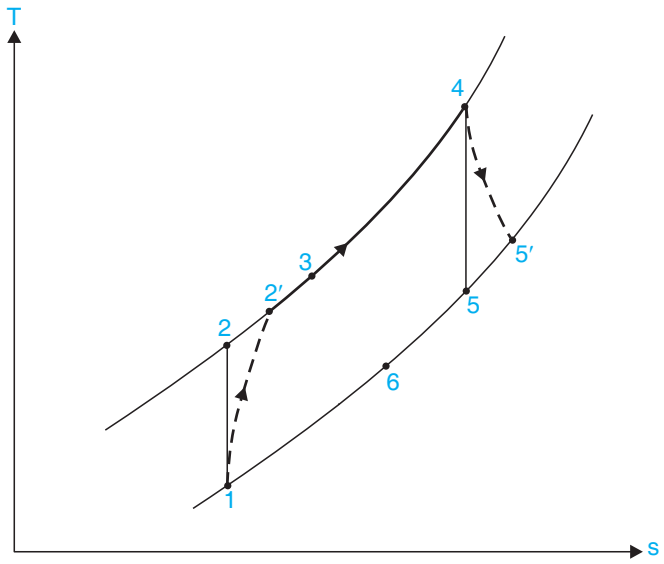


Fig. 5.10. (*a*) *T-s* diagram for the unit.

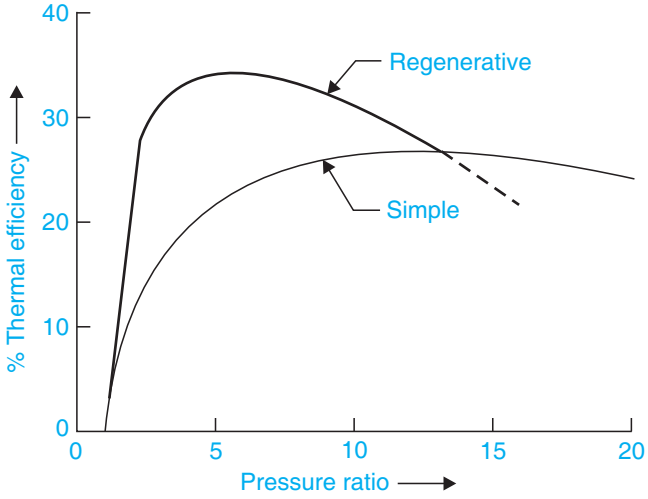


Fig. 5.10 (*b*)

5.11.3. Closed Cycle Gas Turbine

(Constant pressure or joule cycle).

Fig. 5.11 shows a gas turbine operating on a constant pressure cycle in which the closed system consists of air behaving as an ideal gas. The various operations are as follows : Refer to Figs. 5.12 and 5.13.

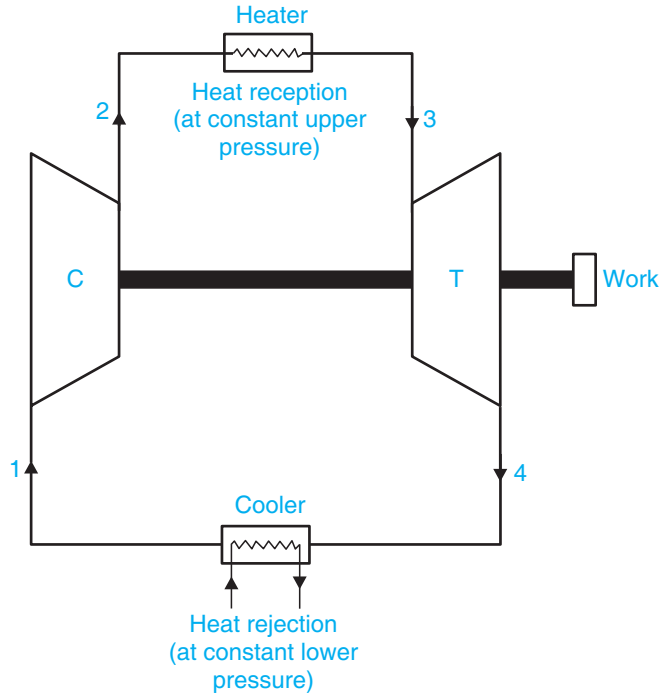


Fig. 5.11. Closed cycle gas turbine.

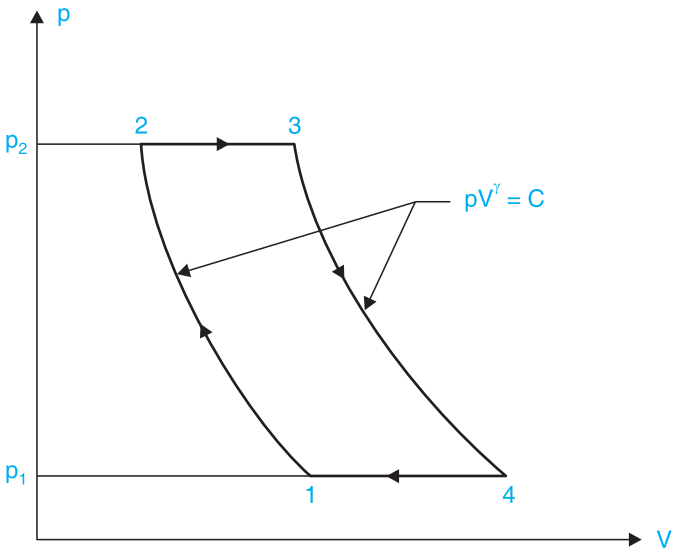


Fig. 5.12. *p-V* diagram.

Operation 1-2 : The air is compressed isentropically from the lower pressure p_1 to the upper pressure p_2, the temperature rising from T_1 to T_2. No heat flow occurs.

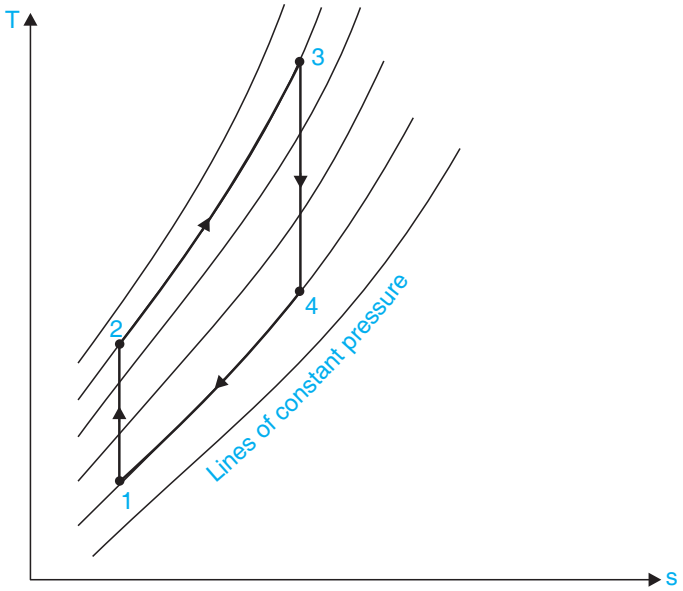


Fig. 5.13. *T-s* diagram.

Operation 2-3 : Heat flows into the system increasing the volume from V_2 to V_3 and temperature from T_2 to T_3 whilst the pressure remains constant at p_2. Heat received = $mc_p\,(T_3 - T_2)$.

Operation 3-4 : The air is expanded isentropically from p_2 to p_1, the temperature falling from T_3 to T_4. No heat flow occurs.

Operation 4-1 : Heat is rejected from the system as the volume decreases from V_4 to V_1 and the temperature from T_4 to T_1 whilst the pressure remains constant at p_1. Heat rejected = $mc_p\,(T_4 - T_1)$.

$$\eta_{\text{air-standard}} = \frac{\text{Work done}}{\text{Heat received}}$$

$$= \frac{\text{Heat received cycle} - \text{Heat rejected cycle}}{\text{Heat received cycle}}$$

$$= \frac{mc_p(T_3 - T_2) - mc_p(T_4 - T_1)}{mc_p(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

Now, from isentropic expansion

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = T_1\,(r_p)^{\frac{\gamma-1}{\gamma}}, \text{ where } r_p = \text{pressure ratio}$$

Similarly $$\frac{T_3}{T_4} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{or} \quad T_3 = T_4\,(r_p)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \quad \eta_{\text{air-standard}} = 1 - \frac{T_4 - T_1}{T_4(r_p)^{\frac{\gamma-1}{\gamma}} - T_1(r_p)^{\frac{\gamma-1}{\gamma}}}$$

$$= 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}} \qquad \ldots(5.6)$$

The expression shows that the *efficiency of the ideal joule cycle increases with the pressure ratio. The absolute limit of upper pressure is determined by the limiting temperature of the material of the turbine at the point at which this temperature is reached by the compression process alone, no further heating of the gas in the combustion chamber would be permissible and the work of expansion would ideally just balance the work of compression so that no excess work would be available for external use.*

We as designers are always interested in the percentage of work developed by the turbine available for electric generation.

$$\therefore \text{ Work ratio} = \frac{W_{\text{net}}}{W_{\text{turbine}}}$$

$$= \frac{W_{\text{turbine}} - W_{\text{comp.}}}{W_{\text{turbine}}} = 1 - \frac{W_{\text{comp.}}}{W_{\text{turbine}}}$$

$$= 1 - \frac{m_{cp}\,(T_2 - T_1)}{m_{cp}\,(T_3 - T_4)} = 1 - \frac{T_2 - T_1}{T_3 - T_4}$$

$$= 1 - \frac{T_1\,(r_p)^{\left(\frac{\gamma-1}{\gamma}\right)} - T_1}{T_3 - \frac{T_3}{(r_p)^{\left(\frac{\gamma-1}{\gamma}\right)}}} = 1 - \frac{T_1}{T_3}\,(r_p)^{\left(\frac{\gamma-1}{\gamma}\right)}$$

$$\ldots(5.7)$$

The *'work ratio' increases with increase in turbine inlet temperature, decrease in compressor inlet temperature and decrease in pressure ratio of the cycle.* The compressor inlet temperature is always atmospheric temperature particularly in open cycle plant and turbine inlet temperature is limited by metallurgical considerations. *The highest temperature ever used for gas turbine power plants is about 1000 K.*

From the eqn. (5.7), it is obvious that the maximum possible pressure ratio for the fixed temperature T_1 and T_3 is given by:

$$(r_p)_{max} = \left(\frac{T_3}{T_1}\right)^{\left(\frac{\gamma}{\gamma-1}\right)} \qquad \ldots(5.8)$$

because, the value of r_p greater than this gives the negative value of work ratio which is impossible for power developing system. Thus, the maximum value of r_p to be used for finding the maximum possible efficiency in eqn. (5.6) is given by eqn. (5.8).

Now we shall prove that the **pressure ratio for maximum work is a function of the limiting temperature ratio.**

Work output during the cycle

= Heat received / cycle – heat rejected / cycle

$= mc_p (T_3 - T_2) - mc_p (T_4 - T_1)$

$= mc_p (T_3 - T_4) - mc_p (T_2 - T_1)$

$= mc_p T_3 \left(1 - \frac{T_4}{T_3}\right) - T_1 \left(\frac{T_2}{T_1} - 1\right)$

In case of a given turbine the minimum temperature T_1 and the maximum temperature T_3 are prescribed, T_1 being the temperature of the atmosphere and T_3 the maximum temperature which the metals of turbine would withstand. Consider the specific heat at constant pressure c_p to be constant. Then,

Since, $$\frac{T_3}{T_4} = (r_p)^{\frac{\gamma - 1}{\gamma}} = \frac{T_2}{T_1}$$

Using the constant $'z' = \frac{\gamma - 1}{\gamma}$,

We have, work output/cycle

$$W = K \left[T_3 \left(1 - \frac{1}{r_p{}^z}\right) - T_1 (r_p{}^z - 1) \right]$$

Differentiating with respect to r_p

$$\frac{dW}{dr_p} = K \left[T_3 \times \frac{z}{r_p (z+1)} - T_1 z r_p{}^{(z-1)} \right]$$

= 0 for a maximum

$$\therefore \quad \frac{zT_3}{r_p{}^{(z+1)}} = T_1 z (r_p)^{(z-1)}$$

$$\therefore \quad r_p{}^{2z} = \frac{T_3}{T_1}$$

$$\therefore \quad r_p = \left(\frac{T_3}{T_1}\right)^{1/2z} \quad i.e., \quad r_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma - 1)}} \qquad ...(5.9)$$

Thus the *pressure ratio for maximum work is a function on the limiting temperature ratio.*

Comparing eqns. (5.8) and (5.9), we get

$$r_p = \sqrt{(r_p)_{max}} \qquad ...(5.10)$$

- Fig. 5.14 shows an arrangement of closed cycle stationary gas turbine plant in which air is continuously circulated. This ensures that the air is not polluted by the addition of combustion waste product, since the heating of air is carried out in the form of heat exchanger shown in the diagram as air heater. The air exhausted from the power turbine is cooled before readmission to L.P. compressor. The various operations as indicated on *T-s* diagram (Fig. 5.15) are as follows :

Operation 1-2′ : Air is compressed from p_1 to p_x in the L.P. compressor.

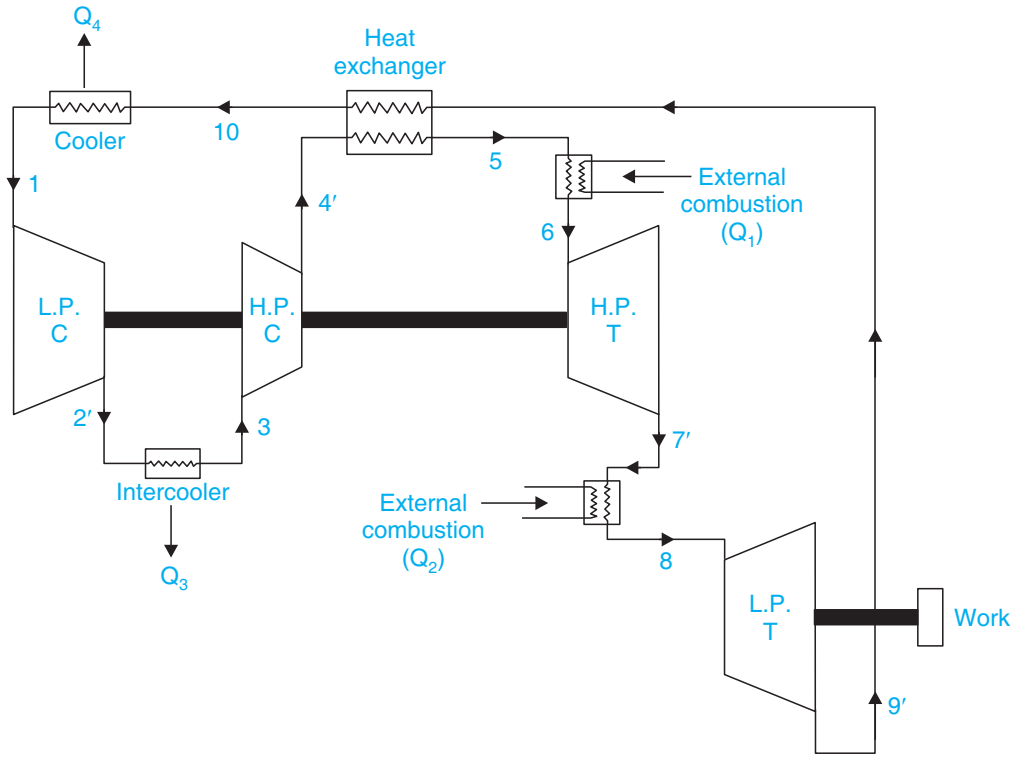


Fig. 5.14. Closed cycle gas turbine plant.

Operation 2′-3 : Air is cooled in the intercooler at constant pressure p_x.

Operation 3-4′ : Air is compressed in the H.P. compressor from p_x to p_2.

Operation 4′-5 : High pressure air is heated at constant pressure by exhaust gases from power turbine in the heat exchanger to T_5.

Operation 5-6 : High pressure air further heated at constant pressure to the maximum temperature T_6 by an air heater (through external combustion).

Operation 6-7′ : The air is expanded in the H.P. turbine from p_2 to p_x producing work to drive the compressor.

Operation 7′-8 : Exhaust air from the H.P. turbine is heated at constant pressure in the air heater (through external combustion) to the maximum temperature T_8 (= T_6).

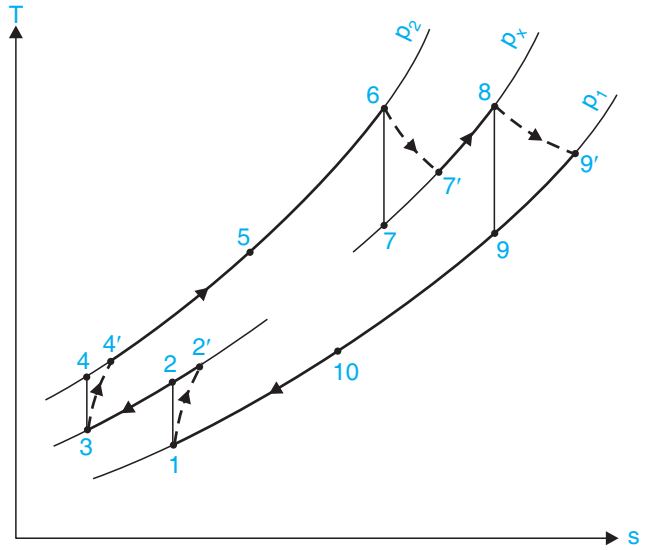


Fig. 5.15. *T-s* diagram for the plant.

Operation 8-9′ : The air is expanded in the L.P. turbine from p_x to p_1, producing energy for a flow of work externally.

Operation 9′-10 : Air from L.P. turbine is passed to the heat exchanger where energy is transferred to the air delivered from the H.P. compressor. The temperature of air leaving the heat exchanger and entering the cooler is T_{10}.

Operation 10-1 : Air cooled to T_1 by the cooler before entering the L.P. compressor.

The energy balance for the whole plant is as follows:

$$Q_1 + Q_2 - Q_3 - Q_4 = W$$

- In a closed cycle plant, in practice, the control of power output is achieved by varying the mass flow by the use of a reservoir in the circuit. The *reservoir maintains the design pressure and temperature and therefore achieves an approximately constant level of efficiency for varying* loads.
- In this cycle, since it is closed, *gases other than air with favourable properties can be used* ; furthermore it is possible to burn solid fuels in the combustion heaters.
- Fig. 5.16 shows the *comparison of thermal efficiency between steam and closed cycle gas turbine plants.*

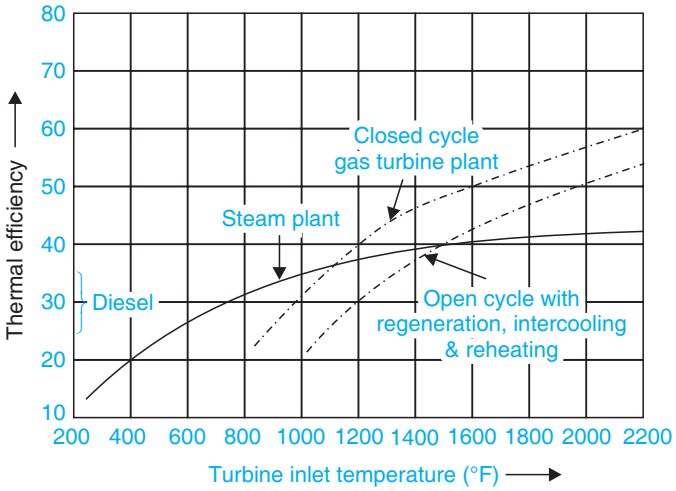


Fig. 5.16. Comparison of thermal efficiency between steam and closed cycle gas turbine plants.

— It is obvious from the figure that the gas turbine plant should be operated above 550°C to compete with the steam plants.

— Above 375°C, the gap between the steam cycle and gas turbine cycle efficiency widens.

— Above 550°C, the efficiency of the gas turbine plant increases 3 times as fast as the steam cycle efficiency for a given top temperature increase.

- *The major factor responsible for inefficiency in this cycle is the large irreversible temperature drop which occurs in the air heaters between the furnace and circulating gas.*

Note. **1.** In a closed cycle gas turbines, although air has been extensively used, the use of 'helium' which though of a lower density, has been inviting the attention of manufacturers for its use, for large output gas turbine units. *The specific heat of helium at constant pressure is about 'five times' that of air, therefore for each kg mass flow the heat drop and hence energy dealt with in helium machines is nearly five times of those in case of air.* The *surface area of the heat exchanger for helium can be kept as low as 1/3* of that *required for gas turbine plant using air as working medium.* For the same temperature ratio and for the plants of the same output the *cross-sectional area required for helium is much less than that for air.* It may therefore be concluded that the *size of helium unit is considerably small comparatively.*

2. Some gas turbine plants work on a combination of two cycles the open cycle and the closed cycle. Such a combination is called the ***semi-closed cycle.*** *Here a part of the working fluid is confined within the plant and another part flows from and to atmosphere.*

5.11.4. Merits and Demerits of Closed Cycle Turbine Over Open Cycle Turbine

Merits of closed cycle :

1. Higher thermal efficiency
2. Reduced size
3. No contamination
4. Improved heat transmission
5. Improved part load efficiency
6. Lesser fluid friction
7. No loss of working medium
8. Greater output
9. Inexpensive fuel.

Demerits of closed cycle :

1. Complexity
2. Large amount of cooling water is required. This limits its use to stationary installation or marine use where water is available in abundance.
3. Dependent system.
4. The weight of the system per kW developed is high comparatively, therefore not economical for moving vehicles.
5. Requires the use of a very large air heater.

5.12. CONSTANT VOLUME COMBUSTION TURBINES

Refer to Fig. 5.17. In a constant volume combustion turbine, the compressed air from an air compressor *C* is admitted into the combustion chamber *D* through the valve *A*. When

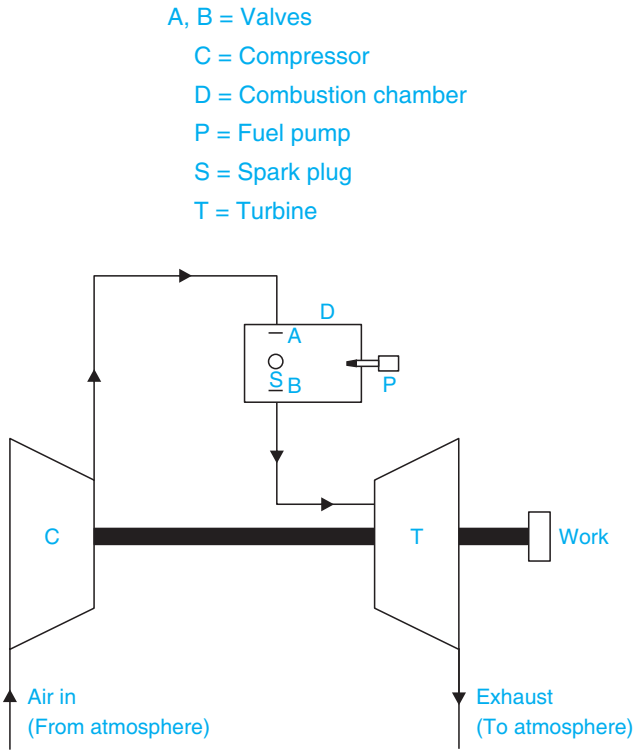


Fig. 5.17. Constant volume combustion gas turbine.

the valve *A* is closed, the fuel is admitted into the chamber by means of a fuel pump *P*. Then the mixture is ignited by means of a spark plug *S*. The combustion takes place at constant volume with increase of pressure. The valve *B* opens and the hot gases flow to the turbine *T*, and finally, they are discharged into atmosphere. The energy of the hot gases is thereby converted into mechanical energy. For

continuous running of the turbine these operations are repeated.

The main demerit associated with this type of turbine is that the *pressure difference and velocities of hot gases are not constant ; so the turbine speed fluctuates.*

5.13. GAS TURBINE FUELS

The various fuels used in gas turbines are enumerated and discussed as follows :

1. Gaseous fuels
2. Liquid fuels
3. Solid fuels.

1. Gaseous fuels. *Natural gas is the ideal fuel for gas turbines*, but this is not available everywhere.

Blast furnace gas and *producer gas* may also be used for gas turbine power plants.

2. Liquid fuels. Liquid fuels of petroleum origin such as distillate oils or residual oils are most commonly used for gas turbine plant. The essential qualities of these fuels include *proper volatility, viscosity and calorific value*. At the same time it *should be* free *from any contents of moisture* and *suspended impurities that would clog the small passages of the nozzles and damage valves and plungers of the fuel pumps.*

Minerals like *sodium, vanadium* and *calcium* prove *very harmful* for the *turbine blading* as these build deposits or corrode the blades. The sodium in ash should be less than 30% of the vanadium content as otherwise the ratio tends to be critical. The actual sodium content may be between 5 ppm to 10 ppm (part per million). If the vanadium is over 2 ppm, the magnesium in ash tends to become critical. *It is necessary that the magnesium in ash is least three times the quantity of vanadium.* The content of calcium and lead should not be over 10 ppm and 5 ppm respectively.

Sodium is removed from residual oils by mixing with 5% of water and then double centrifuging when sodium leaves with water. Magnesium is added to the washed oil in the form of epsom salts, before the oil is sent into the combustor. This checks the corrosive action of vanadium. Residual oils burn with less ease than distillate oils and the latter are often used to start the unit from cold, after which the residual oils are fed in the combustor. In cold conditions residual oils need to be preheated.

3. Solid fuels. The use of solid fuels such as coal in pulverised form in gas turbines present several difficulties most of which have been only partially overcome yet. The pulverising plant for coal in gas turbine applications is much lighter and smaller than its counterpart in steam generators. *Introduction of fuel in the combustion chamber of a gas turbine is required to be done against a high pressure whereas the pressure in the furnace of a steam plant is atmospheric.* Furthermore, the *degree of completeness of combustion in gas turbine applications has to be very high as otherwise soot and dust in gas would deposit on the turbine blading.*

Some practical applications of solid fuel burning in turbine combustors have been commercially made available in recent years. In one such design finely crushed coal is used instead of pulverised fuel. This fuel is carried in steam of air tangentially into one end of a cylindrical furnace while gas comes out at the centre of opposite end. As the fuel particles roll around the circumference of the furnace they are burnt and a high temperature of about 1650°C is maintained which causes the mineral matter of fuel to be converted into a liquid slag. The slag covers the walls of the furnace and runs out through a top hole in the bottom. The result is that fly ash is reduced to a very small content in the gases. In *another design* a regenerator is used to transfer the heat to air, the combustion chamber being located on the outlet of the turbine, and the combustion is carried out in the turbine exhaust stream. The advantage is that only clean air is handled by the turbine.

5.14. EFFECT OF OPERATING VARIABLES ON THERMAL EFFICIENCY

The thermal efficiency of *actual open cycle* depends on the following *thermodynamic variables* :

(*i*) Pressure ratio

(*ii*) Turbine inlet temperature (T_3)

(*iii*) Compressor inlet temperature (T_1)

(*iv*) Efficiency of the turbine ($\eta_{turbine}$)

(*v*) Efficiency of the compressor (η_{comp}).

1. Effect of turbine inlet temperature and pressure ratio :

If the permissible turbine inlet-temperature (with the other variables being constant) of an *open cycle gas turbine power plant* is increased its *thermal efficiency* is *amply improved*. A practical limitation to increasing the turbine inlet temperature, however, is the ability of the material available for the turbine blading to *withstand the high rotative and thermal stresses.*

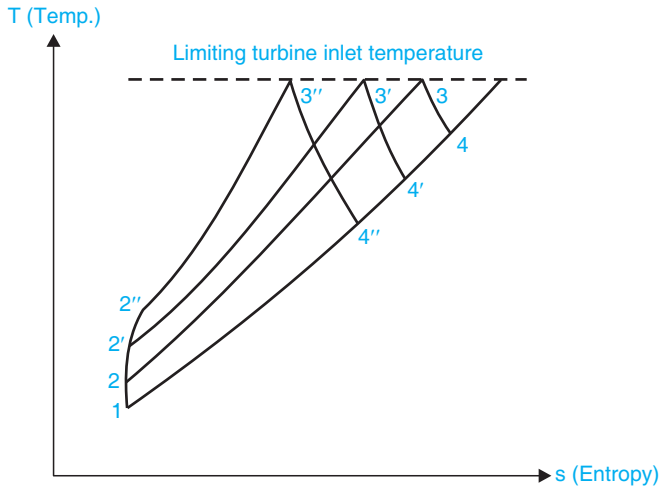


Fig. 5.18

— Refer to Fig. 5.18. For *a given turbine inlet temperature, as the pressure rate increases, the heat supplied as well as the heat rejected are reduced. But the rate of change of heat supplied is not the same as the rate of change heat rejected.* As a consequence, *there exists an optimum pressure ratio producing maximum thermal efficiency for a given turbine inlet temperature.*

— As the pressure ratio increases, the thermal efficiency also increases until it becomes maximum and then it drops off with a further increase in pressure ratio (Fig. 5.19). Further, as the turbine inlet temperature increases, the peaks of the curves flatten out giving a greater range of ratios of pressure optimum efficiency.

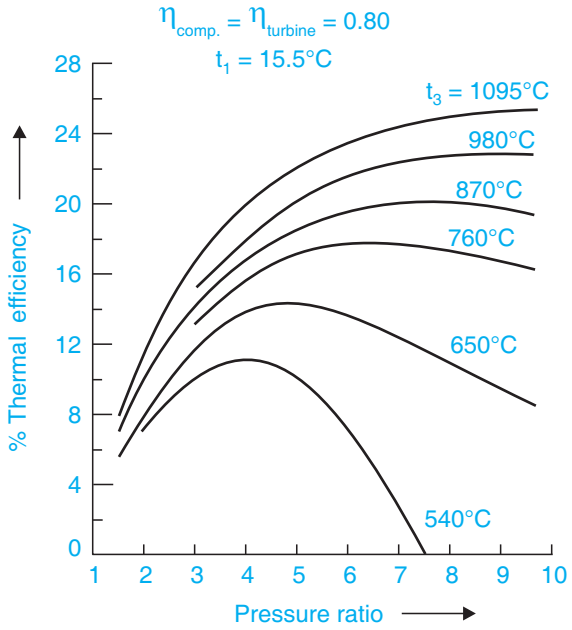


Fig. 5.19. Effect of pressure ratio and turbine inlet temperature.

Following particulars are worth noting :

Gas temperatures	*Efficiency (gas turbine)*
550 to 600°C	20 to 22%
900 to 1000°C	32 to 35%
Above 1300°C	more than 50%

2. Effect of turbine and compressor efficiencies :

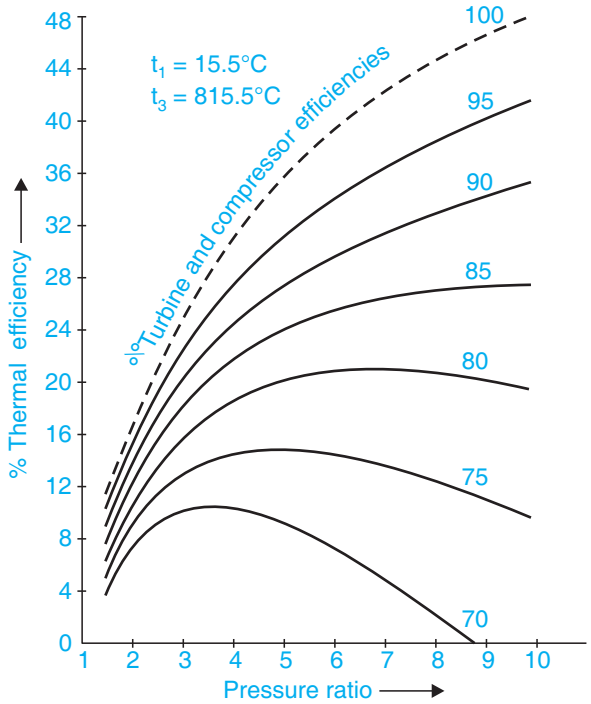


Fig. 5.20. Effect of component efficiency.

Refer to Fig. 5.20. The thermal efficiency of the actual gas turbine cycle is very sensitive to variations in the efficiencies of the compressor and turbine. There is a particular pressure ratio at which maximum efficiencies occur. For lower efficiencies, the peak of thermal efficiency occur at lower pressure ratios and vice versa.

3. Effect of compressor inlet temperature :

Refer to Fig. 5.21. *With the decrease in the compressor inlet temperature there is increase in the thermal efficiency of the plant.* Also, the peaks of thermal efficiency occurs at high pressure ratios and the curves become flatter giving thermal efficiency over a wider pressure ratio range.

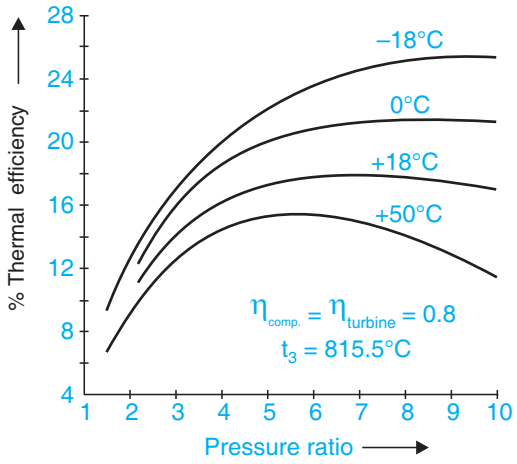


Fig. 5.21. Effect of compressor inlet temperature.

5.15. COMBINATION GAS TURBINE CYCLES

5.15.1. Combined Gas Turbine and Steam Power Plants

The characteristics of the gas turbine plants render these plants very well suited for use in combination with steam or hydro plants. These plants can be quickly started for emergency or peak load service. The combination *'gas-turbine-steam cycles' aim at utilising the heat of exhaust gases from the gas turbine and thus, improve the overall plant efficiency.*

Three popular designs of combination cycle comprise of :

1. Heating feed water with exhaust gases.
2. Employing the gases from a supercharged boiler to expand in the gas turbine.
3. Employing the gases as combustion air in the steam boiler.

1. Heating feed water with exhaust gases :

Refer to Fig. 5.22. By employing exhaust gases to heat the feed water it is possible to utilise the entire steam supply to the turbines to expand through entire range of expansion, and thus result in increasing the output of work, since bleeding would not be required.

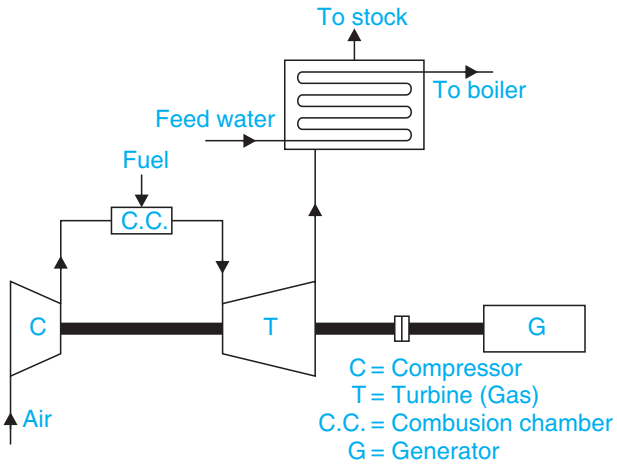


Fig. 5.22. Use of exhaust gases to heat feed water of steam cycle.

2. Employing the gases from a supercharged boiler to expand in the gas turbine :

Refer to Fig. 5.23. The supercharged boiler is good application of the combined gas turbine-steam cycle. In this arrangement of the boiler furnace works under a pressure of about 5 bar and the gases are expanded in the gas turbine, its exhaust being used to heat feed water before being discharged through the stack. The *heat transfer rate in this boiler is very high as compared to that in a conventional boiler due to higher pressure of gases ; and a smaller size of steam generator is needed* for the same steam raising capacity as of the conventional plant. Further more, since the gases in the furnace are already under pressure, *no induced draught or forced draught fans are needed* and there is saving in power consumption which would otherwise be spent in mechanical draught supply. Through this combination an *overall improvement in heat rate is to the extent of above 7 per cent.*

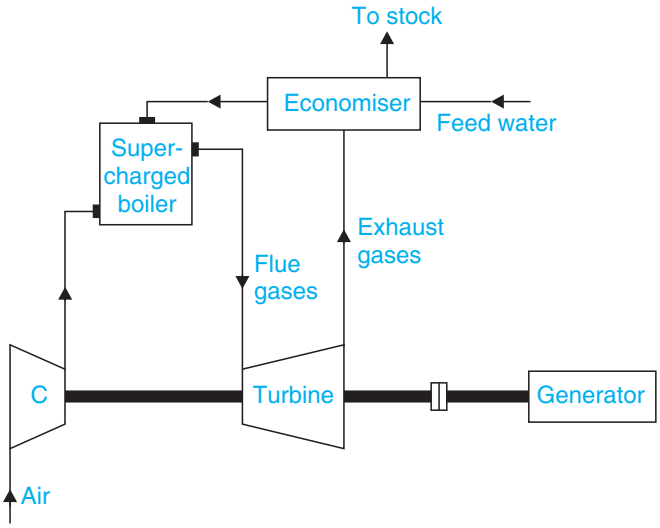


Fig. 5.23. Arrangement of supercharged boiler.

3. Employing the gases as combustion air in the steam boiler :

Refer to Fig. 5.24. When exhaust gases are used as preheated air for combustion in the boiler, an improvement of about 5 per cent in overall heat rate of the plant results. The boiler is fed with supplementary fuel and air, and is made larger than the conventional furnace. If only the turbine exhaust is used in the furnace without any supplementary fuel firing, the arrangement becomes a waste heat boiler.

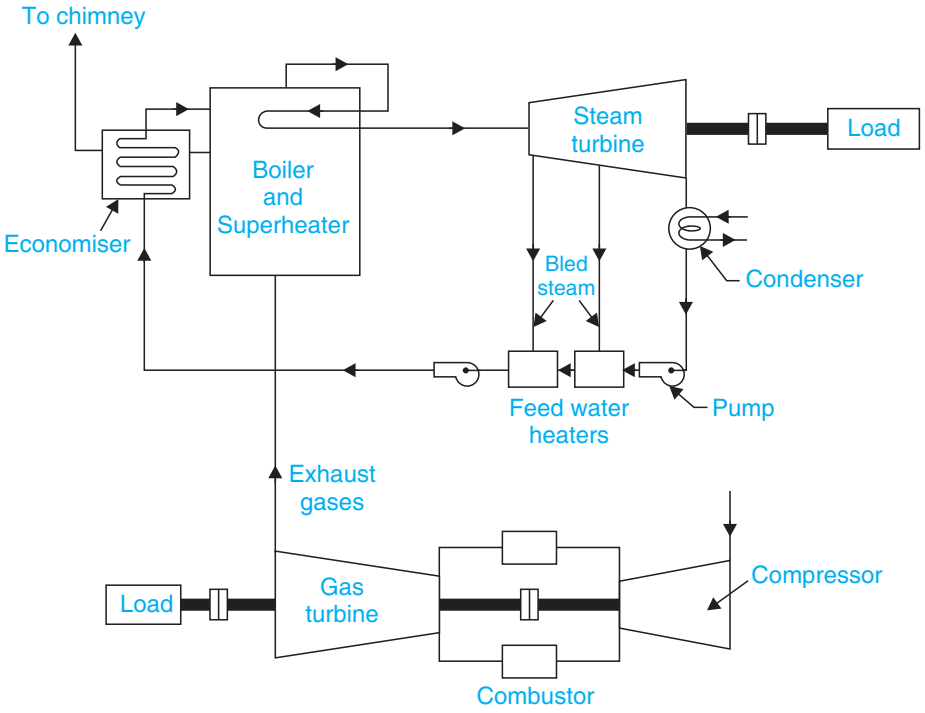


Fig. 5.24. Use of exhaust gases for combustion in the furnance of the steam plant.

— Fig. 5.25 shows the gain in heat rate due to combination cycle.

— Fig. 5.26 shows the comparison of a steam and closed cycle gas plant.

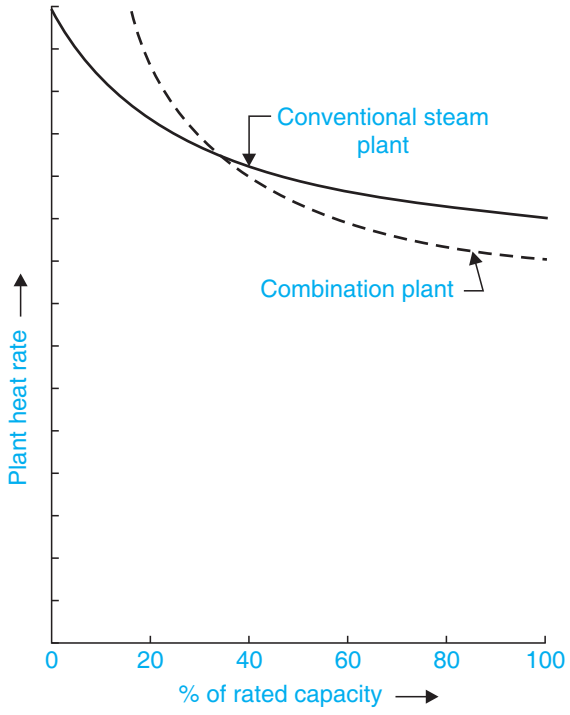


Fig. 5.25

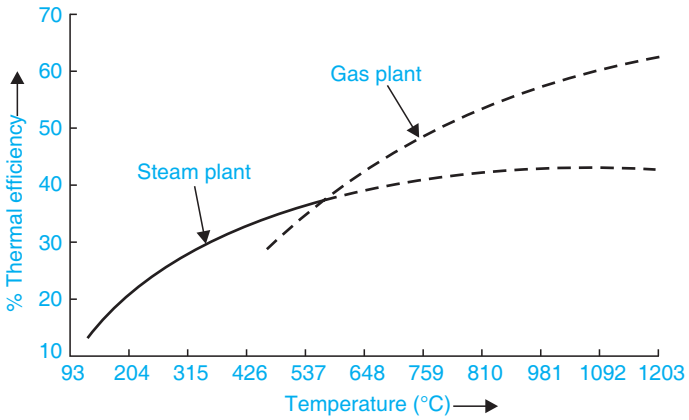


Fig. 5.26. Comparison between steam and closed cycle gas turbine plant.

5.15.2. Combined Gas Turbine and Diesel Power Plants

The performance of a diesel engine can be improved by combining it with an exhaust driven gas turbine. It can be achieved by the following *three* combinations :

1. Turbo-charging
2. Gas-generator
3. Compound engine.

1. Turbo-charging :

Refer to Fig. 5.27. This method is known as

supercharging. Here the exhaust of the diesel engine is expanded in the gas turbine and the work output of the gas turbine is utilised to run a compressor which supplies the pressurised air to the diesel engine to increase its output. The load is coupled to the diesel engine shaft and the output of the gas turbine is just sufficient to run the compressor.

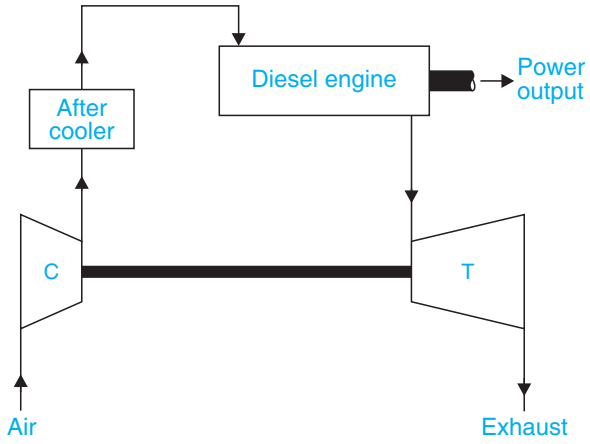


Fig. 5.27. Turbo-charging.

2. Gas-generator :

Fig. 5.28 shows the schematic arrangement. Here the compressor which supplies the compressed air to the diesel engine is not driven from gas turbine but from the diesel engine through some suitable drive. The output of the diesel engine is consumed in driving the air compressor and the gas turbine supplies the power.

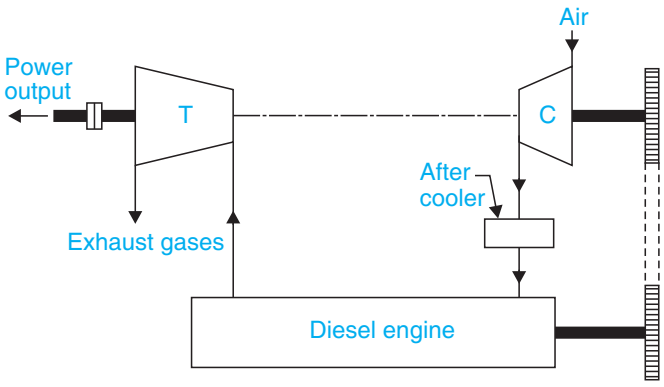


Fig. 5.28. Gas-generator.

3. Compound engine :

Refer to Fig. 5.29. In this arrangement the air compressor is driven from both diesel engine and gas turbine through a suitable gearing and the power output is taken from the diesel engine shaft.

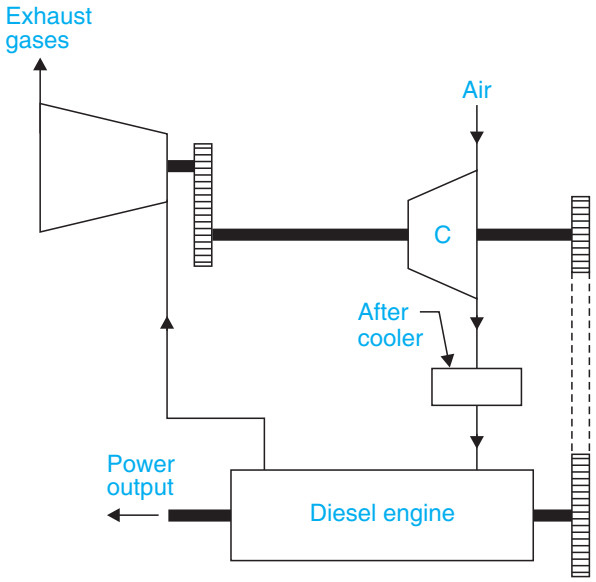


Fig. 5.29. Compound engine.

5.15.3. Advantages of Combined Cycle

1. Improved efficiency.
2. More suitable for rapid start and shut down.
3. Less cooling water requirement.
4. It gives high ratio of power output to occupied ground space.
5. The combined system offers self-sustaining feature.
6. The capital cost of combined plant with supplementary firing is slightly higher than a simple gas turbine plant and much below those of a classical steam plant of the same power capacity.

5.16. OPERATION OF A GAS TURBINE

The operation of a gas turbine includes the following :

1. Starting
2. Shut down

1. Starting of a gas turbine :

Starting of a gas turbine power plant requires an *auxiliary power source*, till the plants own compressor inducts air and compresses it to a pressure such that expansion from reasonable temperature will develop enough power to sustain operation. The *starter* may be (*i*) an I.C. engine, (*ii*) a steam turbine, (*iii*) an auxiliary electric motor or (*iv*) another gas turbine. It must be coupled to the turbo-compressor shaft with a disengaging or over-running clutch. A main generator or its direct connected exciter may be pressed into temporary service as a motor.

Starting procedure :

1. Run the unit and induct air.
2. Actuate the combustion ignition system and inject

the fuel. The fuel flow is controlled to obtain the necessary warm up.

3. Adjust the speed and voltage and synchronise the alternator.

4. Build up the load on the alternator by governor gear control.

2. Shut down of a gas turbine :

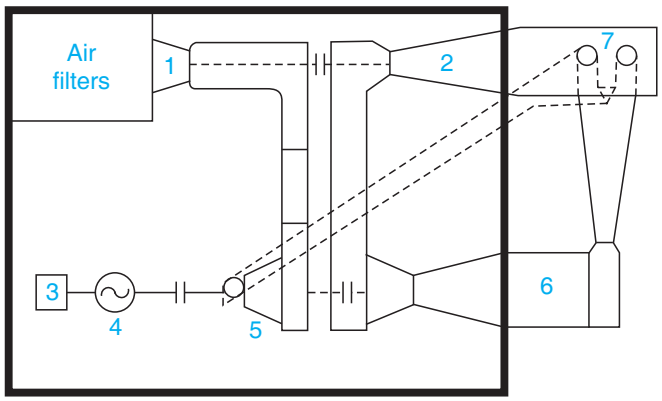
Shut down of a gas turbine occurs very quickly after the fuel is cut off from the combustor. A rapid shut down is desirable since it minimizes the *chilling effect* resulting from passing cold air through the hot turbine. Turning gears are usually employed, or alternatively the starting device may be operated at reduced speed to ensure symmetrical cooling of rotor. This avoids thermal '*kinking*' of the shaft.

5.17. GAS TURBINE POWER PLANT LAYOUT

The layout of a gas turbine plant exercises a very important effect on the overall performance of the plant, as it is possible to incur a loss to the extent of 20% of the power developed in the interconnecting ducts having a considerable number of sharp bends. Therefore, ample care should be taken in the design and layout of the air as well as gas circuits. Fig. 5.30 shows a schematic simplified diagram of a gas turbine power plant layout. The following points are worth noting :

— In this case the main building is the turbine house in which major portion of the plant as well as auxiliaries are installed. Usually it is similar to the steam plant house in many respects.

— The storage tanks containing fuel oil are arranged outside but adjoining the turbine house. In some installations even heat exchangers are also out of the doors.



1 = L.P. Compressor 2 = L.P. Turbine
3 = Starting motor 4 = Alternator
5 = H.P. Compressor 6 = Combustion chamber
7 = Heat exchangers

Fig. 5.30. Gas turbine power plant layout.

— Whereas the major portion of the total space is occupied by the intercoolers, combustion chambers, heat exchangers, waste heat boilers and interconnecting duct work, the rotating parts of the plant form a very small part of the total volume of the plant.

5.18. COMPONENTS OF A GAS TURBINE POWER PLANT

The main components of a gas turbine power plant are enumerated and discussed as follows :

1. Gas turbines
2. Compressors
3. Combustor
4. Intercoolers and regenerators.

1. Gas turbines :

A turbine basically employs vanes or blades mounted on a shaft and enclosed in a casing. The flow of fluid through the turbine in *most design is axial and tangential to the rotor* at a nearly constant or increasing radius. The basic requirements of the turbines are : (*i*) *Light weight,* (*ii*) *High efficiency,* (*iii*) *Reliability in operation, and* (*iv*) *Long working life*. Large work output can be obtained per stage with high blade speeds when the blades are designed to sustain higher stresses. *More stages of the turbine are always preferred in gas turbine power plant because it helps to reduce the stresses in the blades and increases the overall life of the turbine*.

It is essential to cool the gas turbine blades for long life as these are continuously subjected to high temperature gases. The blades can be cooled by different methods, the common method being the *air-cooling*. The air is passed through the holes provided through the blade.

The following **accessories** are fitted to the turbine :

(*i*) *Tachometer*. It shows the speed of the machine and also actuates the fuel regulator in case the speed shoots above or falls below the regulated speed, so that the fuel regulator admits less or more fuel into the combustor and varies the turbine power according to the demand. The tachometer is driven through a gear box.

(*ii*) *An overspeed governor.* The governor backs off fuel feed if exhaust temperature from the turbine exceeds the safe limit, thermal switches at the turbine exhaust acting on fuel control to maintain present maximum temperature.

(*iii*) *Lubricating oil pump.* It supplies oil to the bearings under pressure.

(*iv*) Starting motor or engine

(*v*) Starting set-up gear

(*vi*) Oil coolers

(*vii*) Filters

(*viii*) Inlet and exhaust mufflers.

2. Compressors :

The compressors which are commonly used are of the following two types :

1. Centrifugal type
2. Axial flow type

— The *'centrifugal compressor'* consists of an *impeller* and a *diffuser*. The *impeller imparts the high kinetic energy to the air* and *diffuser converts the kinetic energy into the pressure energy*. The pressure ratio of 2 to 3 is possible with single stage compressor and it can be increased upto 20 with 3-stage compressor. The compressors may have single or double inlet. The *single inlet* compressors are designed to handle the air in the range of 15 to 300 m^3/min. and *double inlets* are preferred above 300 m^3/min capacity. Fig. 5.31 shows a single stage centrifugal compressor.

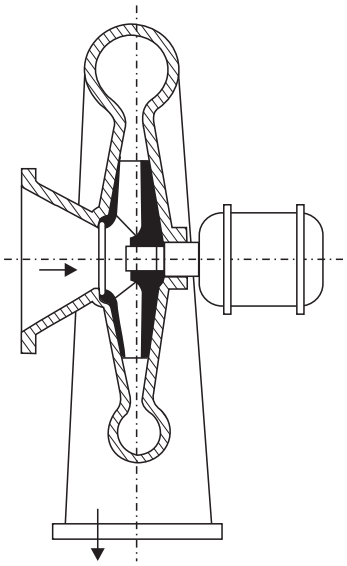


Fig. 5.31. Single stage centrifugal compressor.

In the centrifugal compressor :

(*i*) *Capacity* varies *directly as the speed ratio*.

(*ii*) *Total pressure* varies as the *square of speed ratio*.

(*iii*) *Power input* varies as the *cube of the speed ratio*.

(*iv*) Pressure is developed *independent of load*, but the *volume handled depends on the load.*

In a *multistage centrifugal compressor*, two or more impellers operating in series on a single shaft are provided in a single casing. The effect of multi-staging is to increase the delivery pressure of air as air compressed in one stage of machine is fed into the next stage for further compression and pressure is multiplied in each stage. The *efficiency of multistage compressor is lower than a single stage due to the losses*.

The centrifugal compressor is *superior to the axial flow machine in that a high pressure ratio can be obtained in a short rugged single stage machine, though at the cost of lower efficiency and increased frontal area*.

— The *'axial flow compressors'* are commonly *used in gas turbine installations*. An axial flow compressor consists of a series of rotor and stator stages with decreasing diameters along the flow of air. The blades are fixed on the rotors and rotors are fixed on the shaft. The stator blades are fixed on the stator casing. The stator blades guide the air flow to the next rotor stage coming from the previous rotor stage. The air flows along the axis of the rotor. The kinetic energy is given to the air as it passes through the rotor and part of it is converted into pressure. A multistage single flow axial compressor is shown in Fig. 5.32.

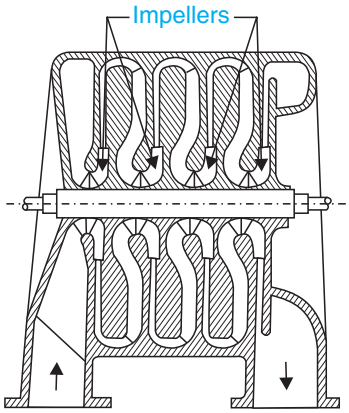


Fig. 5.32. Multistage single flow axial compressor.

An axial compressor is capable of *delivering constant volumes of air over varying discharge pressures*. These machines are well suited for large capacities at moderate pressures. If the impeller of a centrifugal compressor is designed to give an axial component of velocity at the exit, the design becomes a *mixed flow type*.

3. Combustor :

The primary function of the *combustor is to provides for the chemical reaction of the fuel and air being supplied by the compressor*. It must fulfil the following *conditions* :

(*i*) Combustion must take place at high efficiency because of the effect of the combustion efficiency on the thermal efficiency of the gas turbine cycle.

(*ii*) The pressure losses must be low.

(*iii*) Ignition must be reliable and accomplished with ease over a wide range of atmospheric condition especially in aircraft installation.

(*iv*) Through mixing of fuel and air.

(*v*) Carbon deposits must not be formed under any conditions.

The physical process of combustion may be divided into four important steps :

1. Formation of reactive mixture
2. Ignition
3. Flame propagation.
4. Cooling of combustion products with air. Atomisation should be done for perfect burning.

Fig. 5.33 shows an arrangement of a typical combustor design which employs an *outer cylindrical shell* with a *conical inner sleeve* which is provided with ports or slots along the length. At the cone apex is fitted a *nozzle* through which fuel is sprayed in a conical pattern into the sleeve and near this is an *igniting device* or spark plug. A fuel line conveys the fuel to the nozzle. A few air ports provided close to the situation of the nozzle supply the combustion air directly to the fuel and are fitted with vanes to produce a whirling motion of oil and thereby create turbulence. The rest of the air admitted ahead of combustion zone serves to cool the combustor and outlet gases. The combustor is best located between the compressor outlet and turbine inlet and takes the shape of a cylinder. Alternatively, the 'can' arrangement may be used in which the flow is divided to pass through a number of smaller cylindrical chambers. In this latter design the adjacent chambers may be interconnected through small tubes so that a simple igniting device fitted in one of the chambers serves all the chambers.

The *nozzle* sprays the fuel under pressure in an atomised conical spray. The fuel is delivered to the nozzle through the fuel line and flows out through tangential slots in the nozzle, thus being given a whirling motion in an annular chamber from where it passes out through a small orifice in the conical pattern of desired angle.

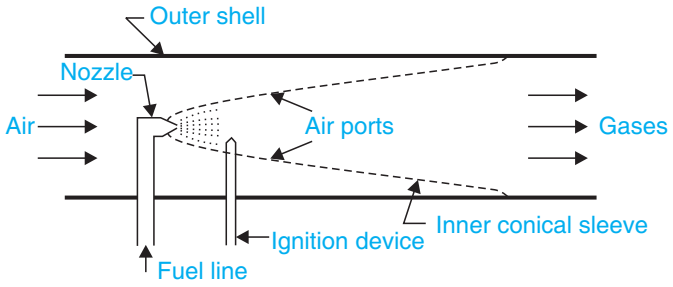


Fig. 5.33. Arrangement of a combustor.

4. Intercoolers and regenerators :

Intercoolers. In a gas turbine plant the *intercooler* is generally used when the pressure ratio used is sufficiently large and the compression is completed with two or more stages. The cooling of compressed air is generally done with the use of cooling water. A *cross-flow* type intercooler (Fig. 5.34) is generally preferred for effective heat transfer.

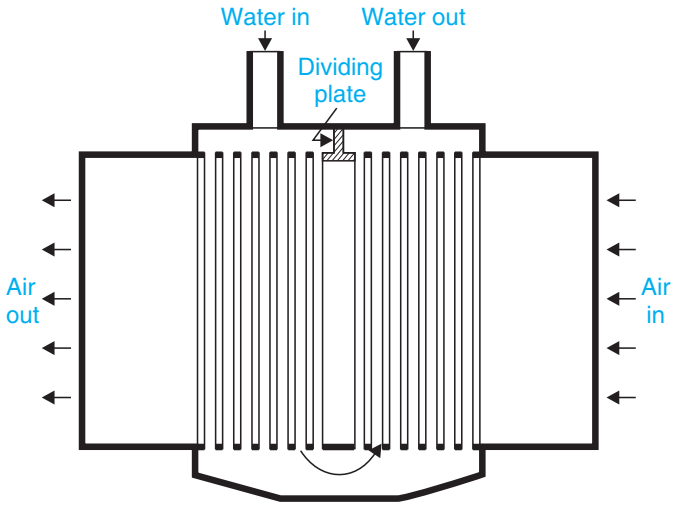


Fig. 5.34. Intercooler.

Regenerators. Refer to Fig. 5.35. In the regenerator heat transfer takes place between the exhaust gases and cool air. It is usually made in shell and tube construction with gas flowing inside the tubes and air outside the tubes, the two fluids being made to flow in opposite directions. Since the gas is bound to carry dust and deposit the same on the heat transfer surface, the internal flow through the tubes is convenient as the tube inside can be easily cleaned with brushes whereas it is very difficult to clean the outside surface of tubes. The effect of counterflow is the highest average temperature difference between the heating and heated medium with consequent high heat transfer between the two fluids. A number of baffles in the air put in the shell make the air to flow in contact with maximum heat transfer. However, *the pressure drop in both air and gas during the flow should be minimum possible*.

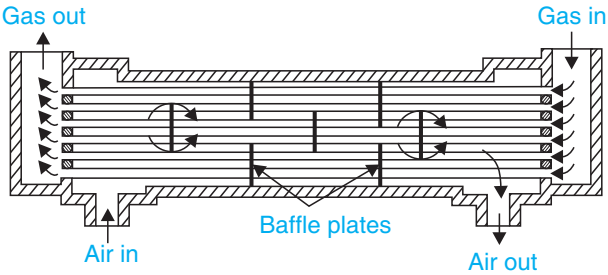
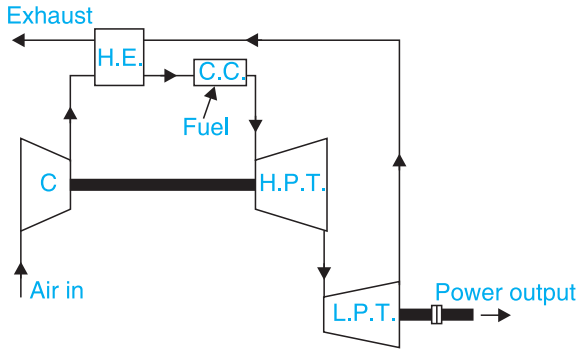


Fig. 5.35. Regenerator.

5.19. VARIOUS ARRANGEMENTS OF GAS TURBINE POWER PLANTS

The various arrangements of gas turbine plants are shown in Figs. 5.36 to 5.41.



H.P.T. = High pressure turbine C.C. = Combustion chamber
L.P.T. = Low pressure turbine C = Compressor
H.E. = Heat exchanger

Fig. 5.36. Open cycle gas turbine with separate power turbine.

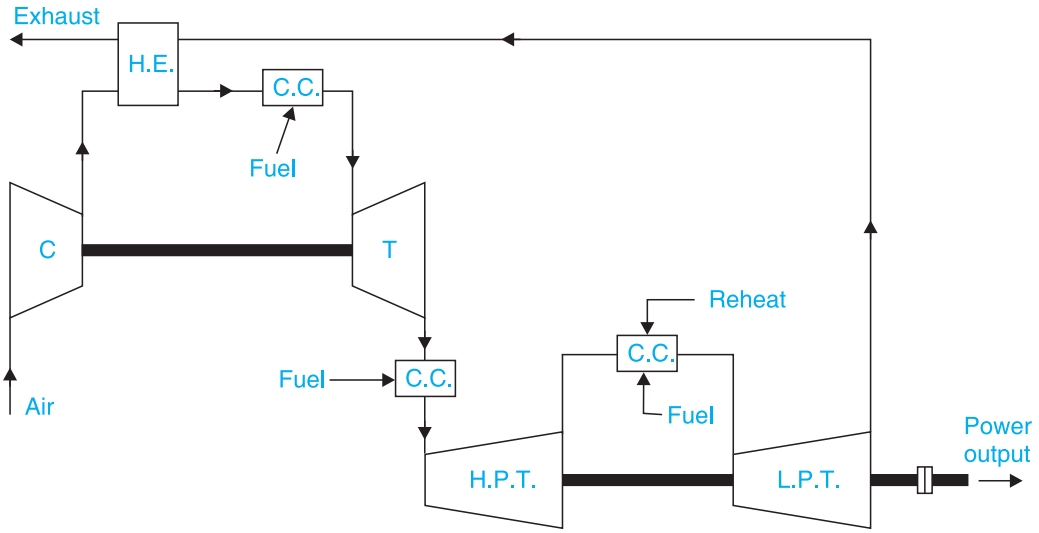
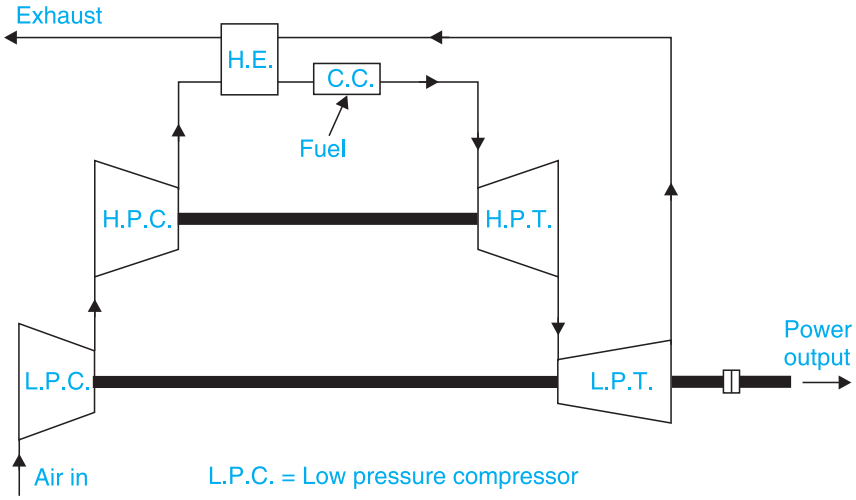


Fig. 5.37. Series flow gas turbine plant.



L.P.C. = Low pressure compressor
H.P.C. = High pressure compressor

Fig. 5.38. Parallel flow gas turbine plant.

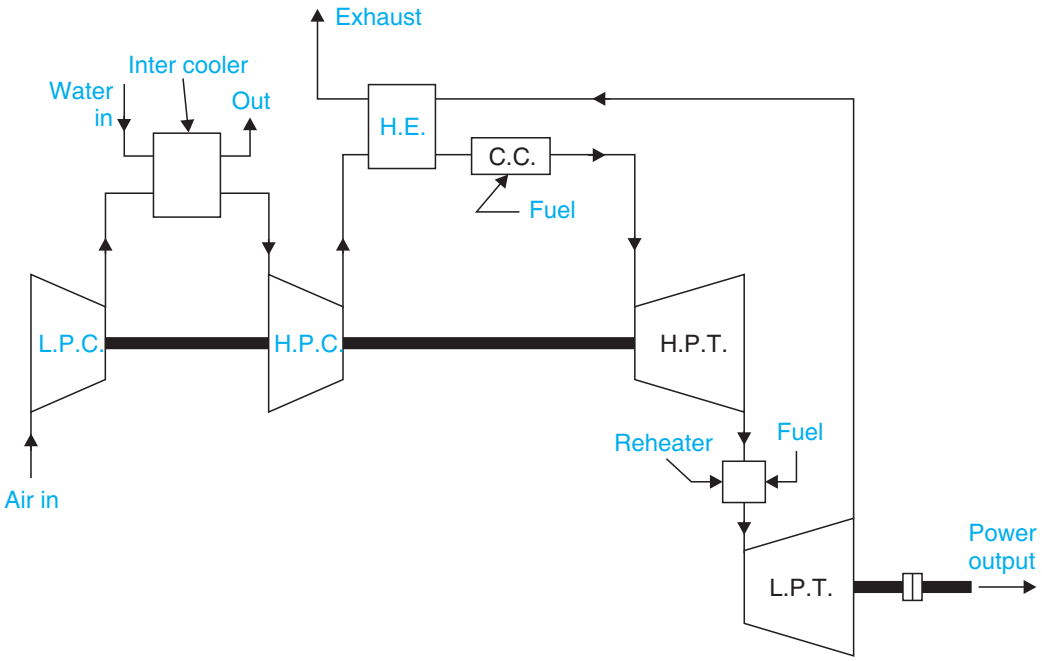


Fig. 5.39. Series flow plant with intercooled compression.

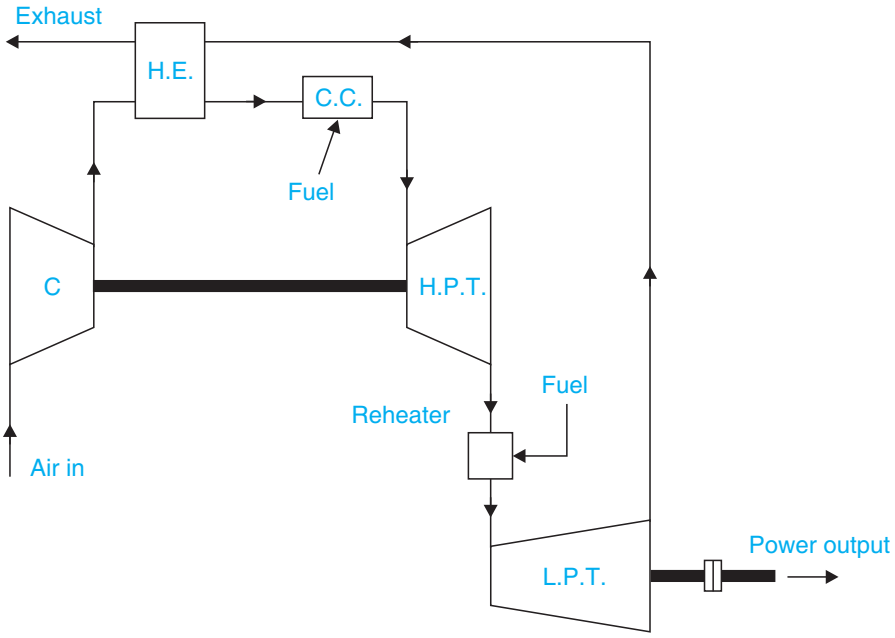


Fig. 5.40. Series flow plant with reheat between power turbine stages.

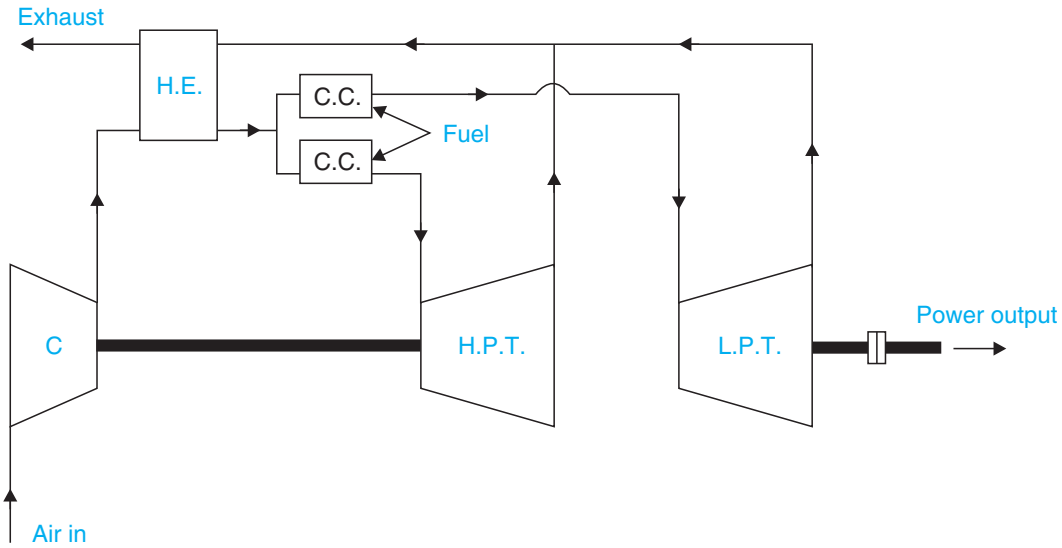


Fig. 5.41. Straight compound gas turbine plant.

5.20. EFFECT OF THERMODYNAMIC VARIABLES ON AIR RATE

The gas turbine plant size depends upon air rate. *The lower the air rate, the smaller the plant size*. The effect of the various thermodynamic variables on air rate is given in the Figs. 5.42 to 5.45.

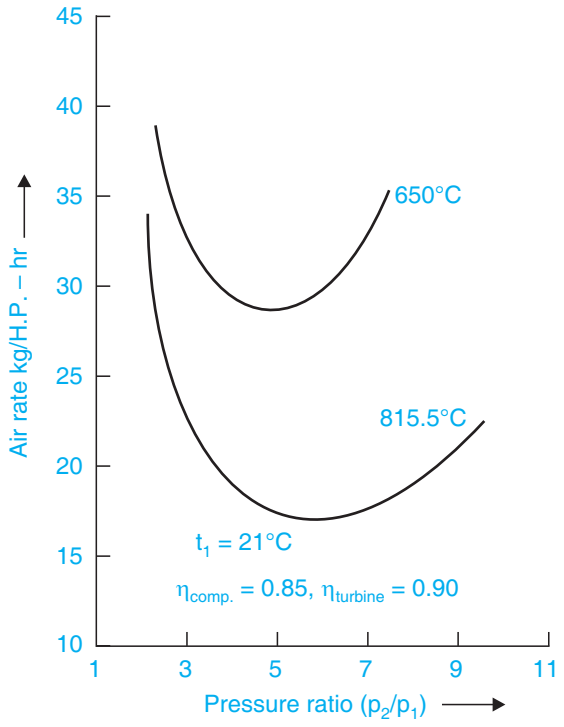


Fig. 5.42. Effect of turbine inlet temperature and pressure ratio on air rate.

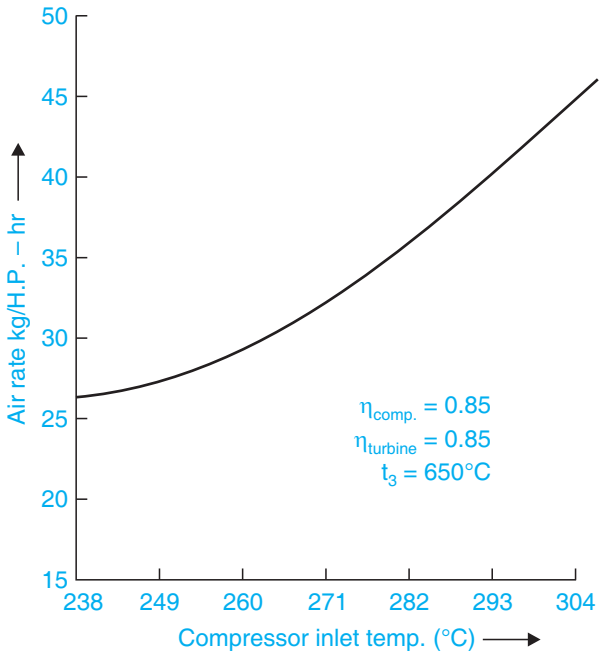


Fig. 5.43. Effect of the compressor inlet temperature on air rate.

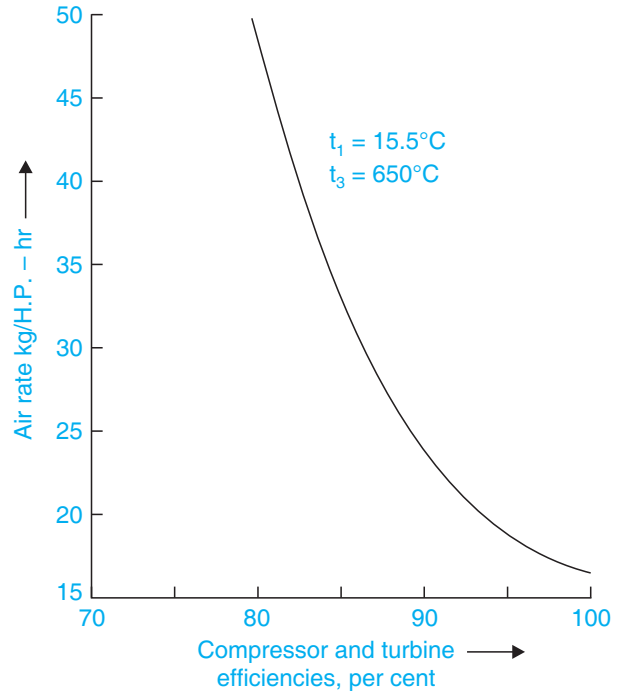


Fig. 5.44. Effect of compressor and turbine efficiencies on air rate.

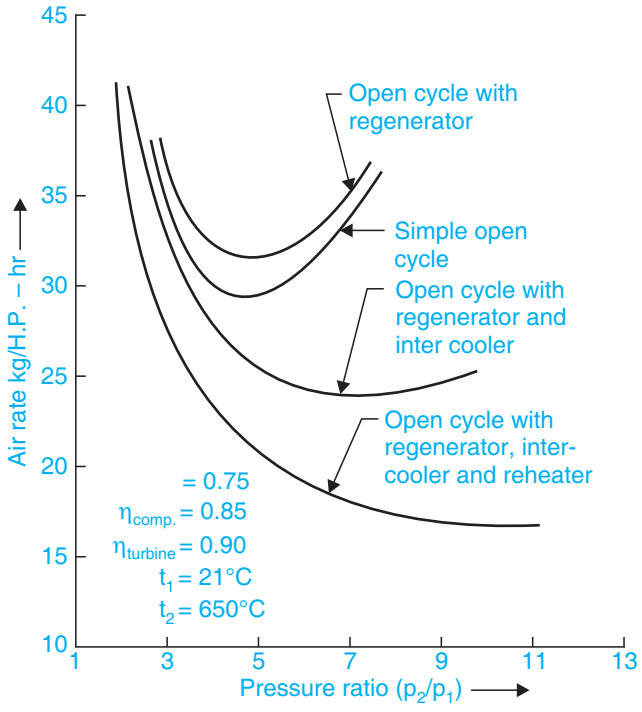


Fig. 5.45. Effect of thermal refinements on air rate.

5.21. FREE-PISTON ENGINE PLANT

Free-piston engine plants are the conventional gas turbine plants *with the difference that the air compressor and combustion chamber are replaced by a free piston engine.* The working of such a plant is explained in Fig. 5.46.

Refer to Fig. 5.46. A free-piston engine unit comprises of five cylinders with two assemblies of pistons that move opposite to each other. The pistons are powered by a diesel cylinder located in the centre. Each assembly has a diesel piston at the centre of the unit. These are rigidly connected to large-diameter pistons reciprocating in the large air-compressor cylinders. Each assembly has air-cushion cylinders at the end.

Refer to Fig. 5.46 (*a*) :

— The pistons are at their innermost position.

— The diesel cylinder has charge of compressed air at about 100 bar ready for firing.

— The air-compression cylinders are filled with air at atmospheric pressure ; the inlet valves IV_1 and IV_2 have just closed. The air trapped in the *air-cushion cylinders*, also called *bounce cylinders,* is at its lowest pressure.

— The discharge values DV_1 and DV_2 in the *air compression cylinders* are held shut by the high-pressure air in the compressed-air receiver that connects the air compression cylinders and the diesel cylinders.

— The compressed air-charge in the diesel cylinder is at high temperature from work of compression, so that a charge of fuel injected immediately ignites and burns. The resulting sudden rise of pressure in the diesel cylinder forces the pistons apart. As they move apart, the exhaust port *leading to the turbine* uncovers first. The combustion products at a pressure of 3 to 6 bar and temperature of about 550°C rush out *through the exhaust to the turbine.* As the pistons continue to move to their outermost positions, the inlet port from the compressed-air receiver is uncovered and compressed air from the receiver enters the diesel cylinder to scavenge out the combustion products and fill the cylinder with a fresh charge of air [Fig. 5.46 (*b*)]. During this outward stroke, the air in the cushion cylinders has been compressed. This air now expands and pushes on the end pistons to return the assemblies back to the innermost position, in turn compressing the fresh air charge trapped in the diesel cylinder by the opposed piston closing on each other.

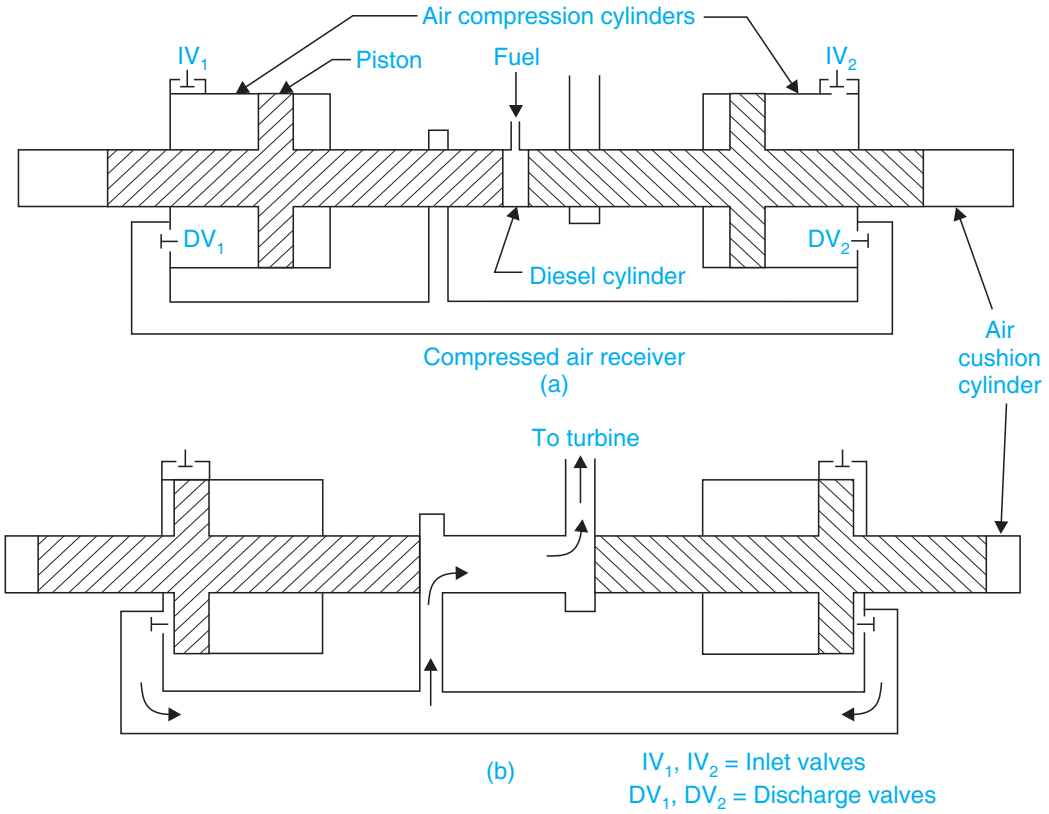


Fig. 5.46. Free-piston engine plant.

— *Thermal efficiencies of 35%* and more can be developed by these plants. This can be achieved *because the 1900°C combustion gas in the diesel cylinder does work directly on the pistons in compressing air. The higher the temperature of gases doing work, the more efficient the process.*

Note. The temperature to the tune of 1900°C can be tolerated because *it appears only instantaneously at ignition and cylically*. During most of the cycle the cylinder is being cooled by relatively cooler air charges and expanding combustion products. In addition, the diesel cylinder walls are cooled by a water jacket. The materials problem of the gas turbine is alleviated considerably by being required to handle temperatures of 550°C.

Advantages of Free-piston Engine Arrangement :

1. Less air rate as compared to a conventional gas turbine.
2. It is possible to achieve efficiency more than 40 per cent.
3. Lighter and smaller than a diesel engine of the same capacity.
4. The gas turbine is about one third the size of the turbine for a simple open gas turbine plant.
5. The free-piston is vibrationless.

Disadvantages :

1. Starting and control problems.
2. Synchronization problem not yet fully overcome.

5.22. RELATIVE THERMAL EFFICIENCIES OF DIFFERENT CYCLES

Fig. 5.47 shows the graphs between turbine inlet temperatures and thermal efficiency for different cycles and which are self explanatory.

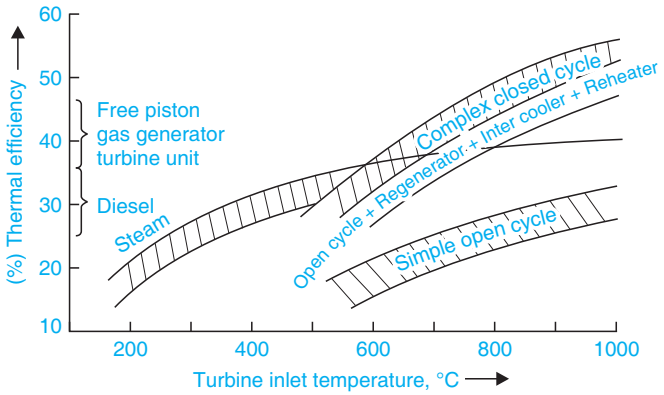


Fig. 5.47. Relative thermal efficiencies of different cycles.

WORKED EXAMPLES

Example 5.1. *The air enters the compressor of an open cycle constant pressure gas turbine at a pressure of 1 bar and temperature of 20°C. The pressure of the air after compression is 4 bar. The isentropic efficiencies of compressor and turbine are 80% and 85% respectively. The air-fuel ratio used is 90 : 1. If flow rate of air is 3.0 kg/s, find :*

(i) Power developed.

(ii) Thermal efficiency of the cycle.

Assume c_p = 1.0 kJ/kg K and γ = 1.4 for air and gases.

Calorific value of fuel = 41800 kJ/kg.

Solution. *Given* : $p_1 = 1$ bar ; $T_1 = 20 + 273 = 293$ K

$p_2 = 4$ bar ; $\eta_{compressor} = 80\%$;

$\eta_{turbine} = 85\%$

Air-fuel ratio = 90 : 1 ; Air flow rate,

$m_a = 3.0$ kg/s

(i) Power developed, P :

Refer to Fig. 5.48 (*b*)

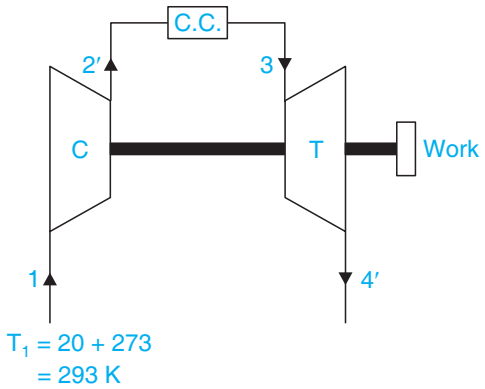
$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4}{1}\right)^{\frac{1.4-1}{1.4}} = 1.486$$

$$\therefore \quad T_2 = (20 + 273) \times 1.486 = 435.4 \text{ K}$$

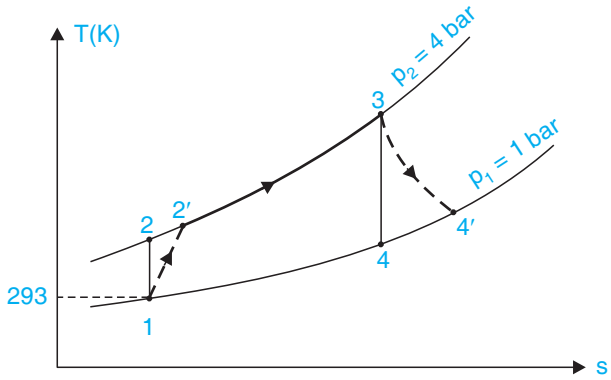
$$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{435.4 - 293}{T_2' - 293}$$

$$\therefore \quad T_2' = \frac{435.4 - 293}{0.8} + 293 = 471 \text{ K}$$



(a)



(b)

Fig. 5.48

Heat supplied by fuel = Heat taken by burning gases

$$m_f \times C = (m_a + m_f)\, c_p (T_3 - T_2')$$

(where m_a = mass of air, m_f = mass of fuel)

$$\therefore \quad C = \left(\frac{m_a}{m_f} + 1\right) c_p (T_3 - T_2')$$

$$\therefore \quad 41800 = (90 + 1) \times 1.0 \times (T_3 - 471)$$

i.e.,

$$T_3 = \frac{41800}{91} + 471 = 930 \text{ K}$$

Again,

$$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{4}\right)^{\frac{0.4}{0.4}} = 0.672$$

$$\therefore \quad T_4 = 930 \times 0.672 = 624.9 \text{ K}$$

$$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.85 = \frac{930 - T_4'}{930 - 624.9}$$

$$\therefore \quad T_4' = 930 - 0.85\,(930 - 624.9)$$

$$= 670.6 \text{ K}$$

$$W_{turbine} = m_g \times c_p \times (T_3 - T_4')$$

(where m_g is the mass of hot gases formed per kg of air)

$$\therefore \quad W_{turbine} = \left(\frac{90+1}{90}\right) \times 1.0 \times (930 - 670.6)$$

$$= 262.28 \text{ kJ/kg of air.}$$

$$W_{compressor} = m_a \times c_p \times (T_2' - T_1)$$

$$= 1 \times 1.0 \times (471 - 293)$$

$$= 178 \text{ kJ/kg of air}$$

$$W_{net} = W_{turbine} - W_{compressor}$$

$$= 262.28 - 178 = 84.28 \text{ kJ/kg of air.}$$

Hence, *power developed,*

$$P = 84.28 \times 3$$

$$= \mathbf{252.84\ kW/kg\ of\ air.} \quad \textbf{(Ans.)}$$

(*ii*) Thermal efficiency of cycle, $\eta_{thermal}$:

Heat supplied per kg of air passing through combustion chamber

$$= \frac{1}{90} \times 41800 = 464.44 \text{ kJ/kg of air}$$

$$\therefore \ \eta_{thermal} = \frac{\text{Work output}}{\text{Heat supplied}} = \frac{84.28}{464.44}$$

$$= 0.1814 \text{ or } \mathbf{18.14\%}. \quad \textbf{(Ans.)}$$

Example 5.2. *A gas turbine unit has a pressure ratio of 6 : 1 and maximum cycle temperature of 610°C. The isentropic efficiencies of the compressor and turbine are 0.80 and 0.82 respectively. Calculate the power output in kilowatts of an electric generator geared to the turbine when the air enters the compressor at 15°C at the rate of 16 kg/s.*

Take c_p = 1.005 kJ/kg K and γ = 1.4 for the compression process, and take c_p = 1.11 kJ/kg K and γ = 1.333 for the expansion process.

Solution. *Given* : $T_1 = 15 + 273 = 288$ K ;

$$T_3 = 610 + 273 = 883 \text{ K} ; \ \frac{p_2}{p_1} = 6,$$

$$\eta_{compressor} = 0.80 ; \ \eta_{turbine} = 0.82 ;$$

Air flow rate = 16 kg/s

For compression process :

$$c_p = 1.005 \text{ kJ/kg K}, \ \gamma = 1.4$$

For expansion process :

$$c_p = 1.11 \text{ kJ/kg K}, \ \gamma = 1.333$$

In order to evaluate the net work output it is necessary to calculate temperatures T_2' and T_4'. To calculate these temperatures we must first calculate T_2 and then use the isentropic efficiency.

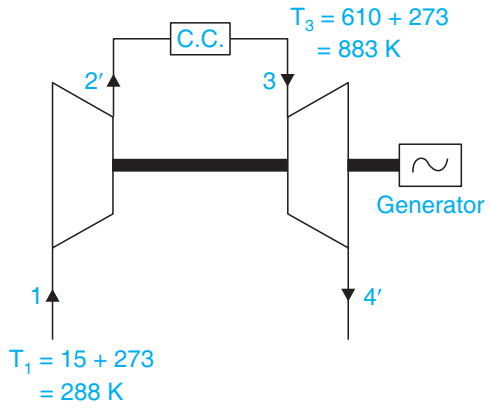
For an isentropic process,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = (6)^{\frac{1.4-1}{1.4}} = 1.67$$

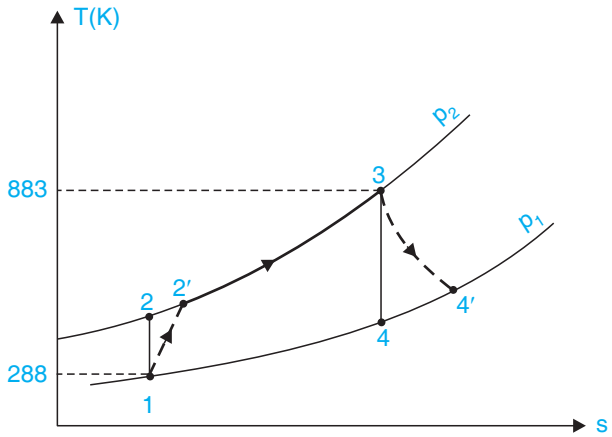
$$\therefore \quad T_2 = 288 \times 1.67 = 481 \text{ K}$$

$$\text{Also, } \eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{481 - 288}{T_2' - T_1}$$



(a)



(b)

Fig. 5.49

$$\therefore \quad T_2' = \frac{481 - 288}{0.8} + 288 = 529 \text{ K}$$

Similarly for the turbine,

$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = (6)^{\frac{1.333-1}{1.333}} = 1.565$$

$$\therefore \quad T_4 = \frac{T_3}{1.565} = \frac{883}{1.565} = 564 \text{ K}$$

$$\text{Also, } \eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4} = \frac{883 - T_4'}{883 - 564}$$

$$\therefore \quad 0.82 = \frac{883 - T_4'}{883 - 564}$$

$$\therefore \quad T_4' = 883 - 0.82\ (883 - 564) = 621.4 \text{ K}$$

Hence, Compressor work input,

$$W_{compressor} = c_p\ (T_2' - T_1)$$

$$= 1.005\ (529 - 288) = 242.2 \text{ kJ/kg}$$

Turbine work output,

$$W_{turbine} = c_p\,(T_3 - T_4') = 1.11\,(883 - 621.4) = 290.4 \text{ kJ/kg.}$$

$\therefore$ Net work output,

$$W_{net} = W_{turbine} - W_{compressor} = 290.4 - 242.2 = 48.2 \text{ kJ/kg}$$

Power in kilowatts

$$= 48.2 \times 16 = \mathbf{771.2\ kW.} \quad \textbf{(Ans.)}$$

Example 5.3. *Calculate the thermal efficiency and work ratio of the plant is example 5.2, assuming that c_p for the combustion process is 1.11 kJ/kg K.*

Solution. Heat supplied $= c_p(T_3 - T_2') = 1.11\,(883 - 529) = 392.9$ kJ/kg

$$\eta_{thermal} = \frac{\text{Net work output}}{\text{Heat supplied}} = \frac{48.2}{392.9} = 0.1226 \text{ or } \mathbf{12.26\%.} \quad \textbf{(Ans.)}$$

Now, *Work ratio* $= \dfrac{\text{Net work output}}{\text{Gross work output}} = \dfrac{48.2}{W_{turbine}} = \dfrac{48.2}{290.4} = \mathbf{0.166.}$ **(Ans.)**

Example 5.4. *In a constant pressure open cycle gas turbine air enters at 1 bar and 20°C and leaves the compressor at 5 bar. Using the following data ; Temperature of gases entering the turbine = 680°C, pressure loss in the combustion chamber = 0.1 bar, $\eta_{compressor}$ = 85%, $\eta_{turbine}$ = 80%, $\eta_{combustion}$ = 85%, γ = 1.4 and c_p = 1.024 kJ/kg K for air and gas, find :*

(i) The quantity of air circulation if the plant develops 1065 kW.

(ii) Heat supplied per kg of air circulation.

(iii) The thermal efficiency of the cycle.

Mass of the fuel may be neglected.

Solution. *Given* : p_1 = 1 bar, p_2 = 5 bar,

$p_3 = 5 - 0.1 = 4.9$ bar, p_4 = 1 bar,

$T_1 = 20 + 273 = 293$ K,

$T_3 = 680 + 273 = 953$ K,

$\eta_{compressor}$ = 85%, $\eta_{turbine}$ = 80%,

$\eta_{combustion}$ = 85%.

For air and gases : c_p = 1.024 kJ/kg K, γ = 1.4

Power developed by the plant, P = 1065 kW.

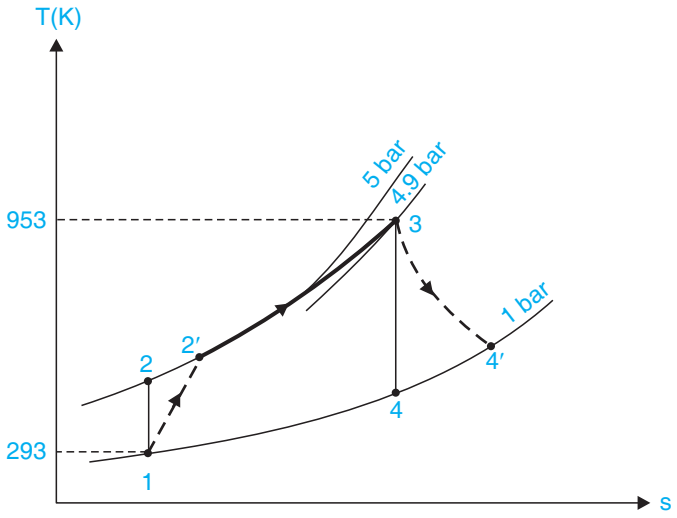


Fig. 5.50

(i) The quantity of air circulation, m_a :

For *isentropic compression 1-2*,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5}{1}\right)^{\frac{1.4-1}{1.4}} = 1.584$$

$\therefore$ $T_2 = 293 \times 1.584 = 464$ K

Now, $\eta_{compressor} = \dfrac{T_2 - T_1}{T_2' - T_1}$

i.e., $0.85 = \dfrac{464 - 293}{T_2' - 293}$

$\therefore$ $T_2' = \dfrac{464 - 293}{0.85} + 293 = 494$ K

For *isentropic expansion process 3-4*,

$$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{4.9}\right)^{\frac{1.4-1}{1.4}} = 0.635$$

$\therefore$ $T_4 = 953 \times 0.635 = 605$ K

Now, $\eta_{turbine} = \dfrac{T_3 - T_4'}{T_3 - T_4}$

$$0.8 = \frac{953 - T_4'}{953 - 605}$$

$\therefore$ $T_4' = 953 - 0.8(953 - 605) = 674.6$ K

$W_{compressor} = c_p\,(T_2' - T_1) = 1.024\,(494 - 293) = 205.8$ kJ/kg

$W_{turbine} = c_p\,(T_3 - T_4') = 1.024\,(953 - 674.6) = 285.1$ kJ/kg.

$\therefore$ $W_{net} = W_{turbine} - W_{compressor} = 285.1 - 205.8 = 79.3$ kJ/kg of air

If the mass of air flowing is m_a kg/s, the power developed by the plant is given by

$$P = m_a \times W_{net} \text{ kW}$$

$$1065 = m_a \times 79.3$$

$$\therefore \quad m_a = \frac{1065}{79.3} = 13.43 \text{ kg.}$$

i.e., **Quantity of air circulation = 13.43 kg. (Ans.)**

(ii) Heat supplied per kg of air circulation :

Actual heat supplied per kg of air circulation

$$= \frac{c_p\,(T_3 - T_2')}{\eta_{combustion}} = \frac{1.024\,(953 - 494)}{0.85}$$

$$= 552.9 \text{ kJ/kg.}$$

(iii) Thermal efficiency of the cycle, $\eta_{thermal}$:

$$\eta_{thermal} = \frac{\text{Work output}}{\text{Heat supplied}} = \frac{79.3}{552.9}$$

$$= \mathbf{0.1434} \quad \text{or} \quad \mathbf{14.34\%.} \quad \textbf{(Ans.)}$$

Example 5.5. *Air is drawn in a gas turbine unit at 15°C and 1.01 bar and pressure ratio is 7 : 1. The compressor is driven by the H.P. turbine and L.P. turbine drives a separate power shaft. The isentropic efficiencies of compressor, and the H.P. and L.P. turbines are 0.82, 0.85 and 0.85 respectively. If the maximum cycle temperature is 610°C, calculate :*

(i) The pressure and temperature of the gases entering the power turbine.

(ii) The net power developed by the unit per kg/s mass flow.

(iii) The work ratio.

(iv) The thermal efficiency of the unit.

Neglect the mass of fuel and assume the following :

For compression process c_{pa} = 1.005 kJ/kg K and γ = 1.4

For combustion and expansion processes : c_{pg} = 1.15 kJ/kg K and γ = 1.333.

Solution. *Given* : $T_1 = 15 + 273 = 288$ K,

$$p_1 = 1.01 \text{ bar, Pressure ratio} = \frac{p_2}{p_1} = 7,$$

$$\eta_{compressor} = 0.82,\ \eta_{turbine}\ (\text{H.P.}) = 0.85,$$

$$\eta_{turbine}\ (\text{L.P.}) = 0.85,$$

Maximum cycle temperature,

$$T_3 = 610 + 273 = 883 \text{ K}$$

(i) Pressure and temperature of the gases entering the power turbine, p_4' and T_4' :

Considering *isentropic compression 1-2*, we get

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} = (7)^{\frac{1.4 - 1}{1.4}} = 1.745$$

$$\therefore \quad T_2 = 288 \times 1.745 = 502.5 \text{ K}$$

Also, $\eta_{compressor} = \dfrac{T_2 - T_1}{T_2' - T_1}$

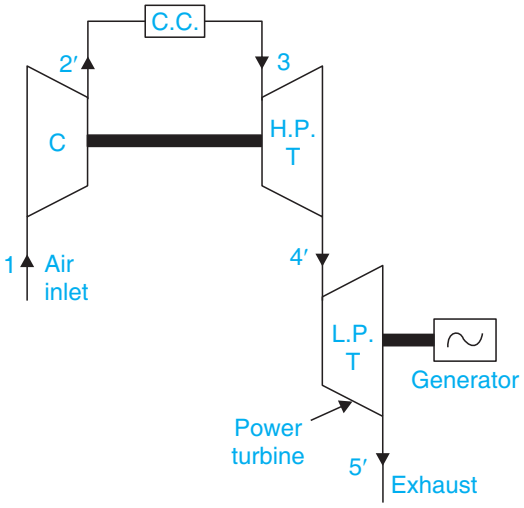
$$0.82 = \frac{502.5 - 288}{T_2' - 288}$$

$$\therefore \quad T_2' = \frac{502.5 - 288}{0.82} + 288 = 549.6 \text{ K}$$

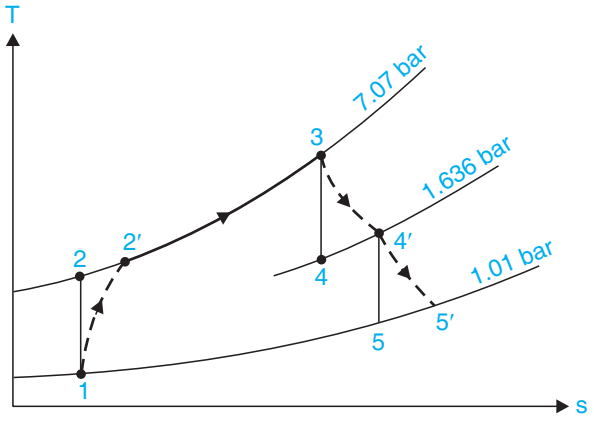
$$W_{compressor} = c_{pa}(T_2' - T_1)$$

$$= 1.005 \times (549.6 - 288)$$

$$= 262.9 \text{ kJ/kg}$$



(a)



(b)

Fig. 5.51

Now, the *work output of H.P. turbine = Work input to compressor*

$$\therefore \quad c_{pg}(T_3 - T_4') = 262.9$$

i.e., $1.15(883 - T_4') = 262.9$

$$\therefore \quad T_4' = 883 - \frac{262.9}{1.15} = 654.4 \text{ K}$$

i.e., *Temperature of gases entering the power turbine* **= 654.4 K.** **(Ans.)**

Again, for H.P. turbine :

$$\eta_{\text{turbine}} = \frac{T_3 - T_4'}{T_3 - T_4} \quad \textit{i.e.,} \quad 0.85 = \frac{883 - 654.4}{883 - T_4}$$

$$\therefore \quad T_4 = 883 - \left(\frac{883 - 654.4}{0.85}\right) = 614 \text{ K}$$

Now, considering *isentropic expansion process 3-4*, we get

$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma - 1}{\gamma}}$$

or, $$\frac{p_3}{p_4} = \left(\frac{T_3}{T_4}\right)^{\frac{\gamma}{\gamma - 1}} = \left(\frac{883}{614}\right)^{\frac{1.33}{0.33}} = 4.32$$

i.e., $$p_4 = \frac{p_3}{4.32} = \frac{7.07}{4.32} = 1.636 \text{ bar}$$

i.e., *Pressure of gases entering the power turbine* **= 1.636 bar.** **(Ans.)**

(*ii*) Net power developed per kg/s mass flow, P :

To find the power output it is now necessary to calculate T_5'.

The pressure ratio, $\frac{p_4}{p_5}$, is given by $\frac{p_4}{p_3} \times \frac{p_3}{p_5}$

i.e., $$\frac{p_4}{p_5} = \frac{p_4}{p_3} \times \frac{p_2}{p_1} = \frac{7}{4.32} = 1.62$$
$$(\because \quad p_2 = p_3 \text{ and } p_5 = p_1)$$

Then, $$\frac{T_4'}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma - 1}{\gamma}} = (1.62)^{\frac{0.33}{1.33}} = 1.27$$

$$\therefore \quad T_5 = \frac{T_4'}{1.127} = \frac{654.4}{1.127} = 580.6 \text{ K.}$$

Again, for L.P. turbine

$$\eta_{\text{turbine}} = \frac{T_4' - T_5'}{T_4' - T_5}$$

i.e., $$0.85 = \frac{654.4 - T_5'}{654.4 - 580.6}$$

$$\therefore \quad T_5' = 654.4 - 0.85\ (654.4 - 580.6)$$
$$= 591.7 \text{ K}$$

$$W_{\text{L.P. turbine}} = c_{pg}\ (T_4' - T_5') = 1.15\ (654.4 - 591.7)$$
$$= 72.1 \text{ kJ/kg}$$

Hence *net power output* (per kg/s mass flow)

= 72.1 kW. **(Ans.)**

(*iii*) Work ratio :

$$\textit{Work ratio} = \frac{\text{Net work output}}{\text{Gross work output}} = \frac{72.1}{72.1 + 262.9}$$
$$= \mathbf{0.215.} \quad \textbf{(Ans.)}$$

(*iv*) Thermal efficiency of the unit, η_{thermal} :

Heat supplied $= c_{pg}(T_3 - T_2') = 1.15\ (883 - 549.6)$
$= 383.4$ kJ/kg

$$\therefore \quad \eta_{\text{thermal}} = \frac{\text{Net work output}}{\text{Heat supplied}} = \frac{72.1}{383.4}$$

$$= 0.188 \text{ or } \mathbf{18.8\%.} \quad \textbf{(Ans.)}$$

Example 5.6. *In a gas turbine the compressor takes in air at a temperature of 15°C and compresses it to four times the initial pressure with an isentropic efficiency of 82%. The air is then passed through a heat exchanger heated by the turbine exhaust before reaching the combustion chamber. In the heat exchanger 78% of the available heat is given to the air. The maximum temperature after constant pressure combustion is 600°C, and the efficiency of the turbine is 70%. Neglecting all losses except those mentioned, and assuming the working fluid throughout the cycle to have the characteristic of air find the efficiency of the cycle.*

Assume R = 0.287 kJ/kg K and γ = 1.4 for air and constant specific heats throughout.

Solution. *Given* : $T_1 = 15 + 273 = 288$ K,

Pressure ratio, $\frac{p_2}{p_1} = \frac{p_3}{p_4} = 4$, $\eta_{\text{compressor}} = 82\%$.

Effectiveness of the heat exchanger, $\varepsilon = 0.78$,

$\eta_{\text{turbine}} = 70\%$, Maximum temperature,

$T_3 = 600 + 273 = 873$ K.

Efficiency of the cycle η_{cycle} :

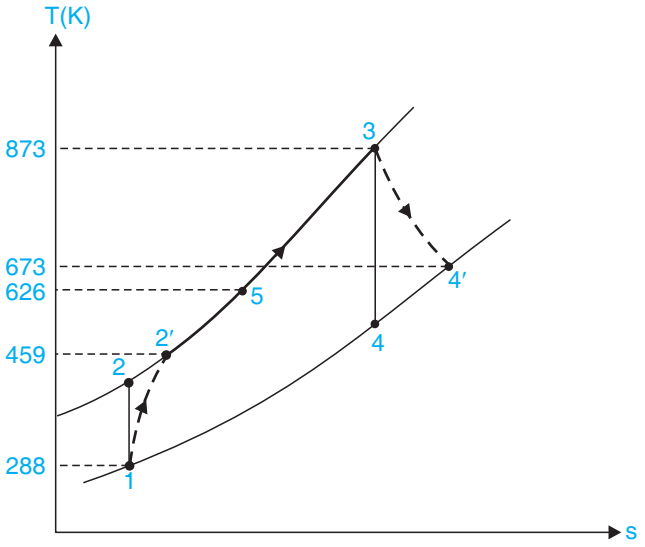


Fig. 5.52

Considering the *isentropic compression 1-2*, we get

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{1.4-1}{1.4}} = 1.486$$

$$\therefore \quad T_2 = 288 \times 1.486 = 428 \text{ K}$$

Now, $\eta_{compressor} = \dfrac{T_2 - T_1}{T_2' - T_1}$

i.e., $0.82 = \dfrac{428 - 288}{T_2' - 288}$

$$\therefore \quad T_2' = \frac{428 - 288}{0.82} + 288 = 459 \text{ K}$$

Considering the isentropic expansion process 3-4, we have

$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{1.4-1}{1.4}} = 1.486$$

$$\therefore \quad T_4 = \frac{T_3}{1.486} = \frac{873}{1.486} = 587.5 \text{ K.}$$

Again, $\eta_{turbine} = \dfrac{T_3 - T_4'}{T_3 - T_4} = \dfrac{873 - T_4'}{873 - 587.5}$

i.e., $0.70 = \dfrac{873 - T_4'}{873 - 587.5}$

$$\therefore \quad T_4' = 873 - 0.7(873 - 587.5) = 673 \text{ K}$$

$$W_{compressor} = c_p(T_2' - T_1)$$

But $$c_p = R \times \frac{\gamma}{\gamma - 1} = 0.287 \times \frac{1.4}{1.4 - 1}$$

$$= 1.0045 \text{ kJ/kg K}$$

$$\therefore \quad W_{compressor} = 1.0045(459 - 288) = 171.7 \text{ kJ/kg}$$

$$W_{turbine} = c_p(T_3 - T_4') = 1.0045(873 - 673)$$

$$= 200.9 \text{ kJ/kg}$$

$$\therefore \quad \text{Net work} = W_{turbine} - W_{compressor}$$

$$= 200.9 - 171.7 = 29.2 \text{ kJ/kg.}$$

Effectiveness for heat exchanger,

$$\varepsilon = \frac{T_5 - T_2'}{T_4' - T_2'}$$

i.e., $0.78 = \dfrac{T_5 - 459}{673 - 459}$

$$\therefore \quad T_5 = (673 - 459) \times 0.78 + 459 = 626 \text{ K}$$

$\therefore$ Heat supplied by fuel per kg

$$= c_p(T_3 - T_5) = 1.0045(873 - 626)$$

$$= 248.1 \text{ kJ/kg}$$

$$\therefore \quad \eta_{cycle} = \frac{\text{Net work done}}{\text{Heat supplied by the fuel}}$$

$$= \frac{29.2}{248.1} = 0.117 \text{ or } \mathbf{11.7\%}. \quad \textbf{(Ans.)}$$

Example 5.7. *A gas turbine employs a heat exchanger with a thermal ratio of 72%. The turbine operates between the pressures of 1.01 bar and 4.04 bar and ambient temperature is 20°C. Isentropic efficiencies of compressor and turbine are 80 and 85% respectively. The pressure drop on each side of the heat exchanger is 0.05 bar and in the combustion chamber 0.14 bar. Assume combustion efficiency to be unity and calorific value of the fuel to be 41800 kJ/kg calculate the increase in efficiency due to heat exchanger over that for simple cycle.*

Assume c_p is constant throughout and is equal to 1.024 kJ/kg K, and assume $\gamma = 1.4$.

For simple cycle the air-fuel ratio is 90 : 1, and for the heat exchange cycle the turbine entry temperature is the same as for a simple cycle.

Solution. Simple Cycle. Refer to Fig. 5.53.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4}{1}\right)^{\frac{1.4-1}{1.4}} = 1.486$$

$$\therefore \quad T_2 = 293 \times 1.486 = 435.4$$

Also, $\eta_{compressor} = \dfrac{T_2 - T_1}{T_2' - T_1}$

$$0.8 = \frac{435.4 - 293}{T_2' - 293}$$

$$\therefore \quad T_2' = \frac{435.4 - 293}{0.8} + 293 = 471 \text{ K}$$

Now, $m_f \times C = (m_a + m_f) \times c_p \times (T_3 - T_2')$

[m_a = mass of air, m_f = mass of fuel]

$$\therefore \quad T_3 = \frac{m_f \times C}{c_p\,(m_a + m_f)} + T_2'$$

$$= \frac{1 \times 41800}{1.024\,(90 + 1)} + 471 = 919.5 \text{ K}$$

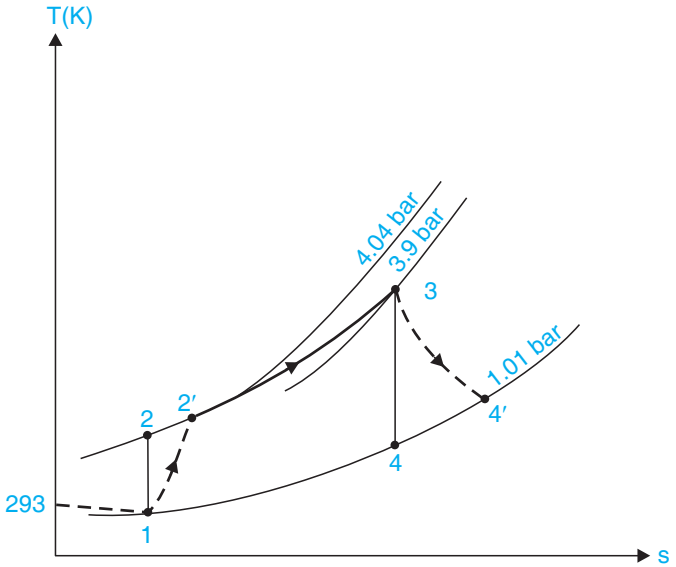


Fig. 5.53

Also, $$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}}$$

or $$T_4 = T_3 \times \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}}$$

$$= 919.5 \times \left(\frac{1.01}{3.9}\right)^{\frac{1.4-1}{1.4}} = 625 \text{ K}$$

Again, $$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$\therefore \quad 0.85 = \frac{919.5 - T_4'}{919.5 - 625}$$

$$\therefore \quad T_4' = 919.5 - 0.85(919.5 - 625)$$

$$= 669 \text{ K}$$

$$\eta_{thermal} = \frac{(T_3 - T_4') - (T_2' - T_1)}{(T_3 - T_2')}$$

$$= \frac{(919.5 - 669) - (471 - 293)}{(919.5 - 471)}$$

$$= \frac{72.5}{448.5}$$

$$= 0.1616 \text{ or } \mathbf{16.16\%}. \quad \textbf{(Ans.)}$$

Heat Exchanger Cycle. Refer to Fig. 5.54 (*a, b*)

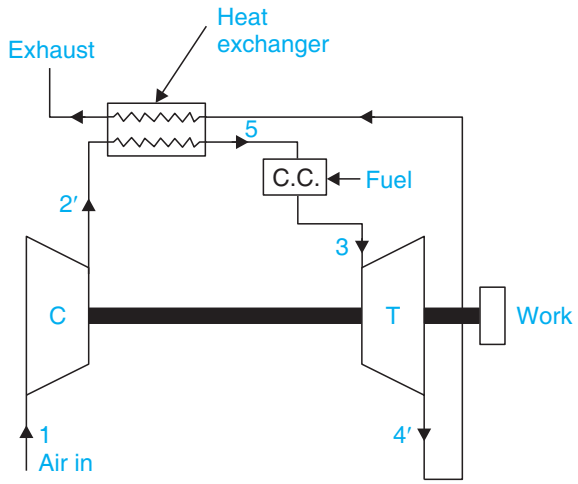
$T_2' = 471$ K (as for simple cycle)

$T_3 = 919.5$ K (as for simple cycle)

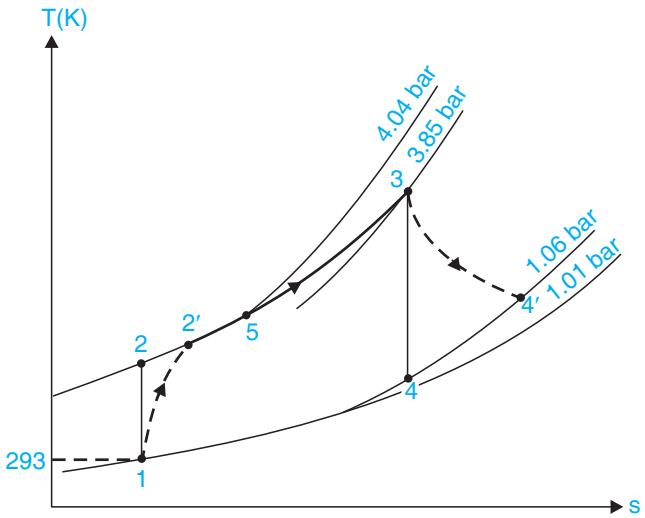
To find T_4' :

$p_3 = 4.04 - 0.14 - 0.05 = 3.85$ bar

$p_4 = 1.01 + 0.05 = 1.06$ bar



(a)



(b)

Fig. 5.54

$$\therefore \quad \frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.06}{3.85}\right)^{\frac{1.4-1}{1.4}} = 0.69$$

i.e., $$T_4 = 919.5 \times 0.69 = 634 \text{ K}$$

$$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4} \; ; \quad 0.85 = \frac{919.5 - T_4'}{919.5 - 634}$$

$$\therefore \quad T_4' = 919.5 - 0.85\,(919.5 - 634) = 677 \text{ K}$$

To find T_5 :

Thermal ratio (or effectiveness),

$$\varepsilon = \frac{T_5 - T_2'}{T_4' - T_2'} \quad \therefore \quad 0.72 = \frac{T_5 - 471}{677 - 471}$$

$$\therefore \quad T_5 = 0.72(677 - 471) + 471 = 619 \text{ K}$$

$$\eta_{thermal} = \frac{(T_3 - T_4') - (T_2' - T_1)}{(T_3 - T_5)}$$

$$= \frac{(919.5 - 677) - (471 - 293)}{(919.5 - 619)} = \frac{64.5}{300.5}$$

$$= 0.2146 \text{ or } \mathbf{21.46\%}$$

$\therefore$ **Increase in thermal efficiency**

$= 21.46 - 16.16 = \mathbf{5.3\%}$. **(Ans.)**

Example 5.8. *A 5400 kW gas turbine generating set operates with two compressor stages ; the overall pressure ratio is 9 : 1. A high pressure turbine is used to drive the compressors, and a low-pressure turbine drives the generator. The temperature of the gases at entry to the high pressure turbine is 625°C and the gases are reheated to 625°C after expansion in the first turbine. The exhaust gases leaving the low-pressure turbine are passed through a heat exchanger to heat the air leaving the high pressure stage compressor. The compressors have equal pressure ratios and intercooling is complete between the stages. The air inlet temperature to the unit is 20°C. The isentropic efficiency of each compressor stage is 0.8, and the isentropic efficiency of each turbine stage is 0.85, the heat exchanger thermal ratio is 0.8. A mechanical efficiency of 95% can be assumed for both the power shaft and compressor turbine shaft. Neglecting all pressure losses and changes in kinetic energy calculate :*

(i) The thermal efficiency ;

(ii) Work ratio of the plant ;

(iii) The mass flow in kg/s.

Neglect the mass of the fuel and assume the following :

For air : c_{pa} = 1.005 kJ/kg K and γ = 1.4

For gases in the combustion chamber and in turbines and heat exchanger, c_{pg} = 1.15 kJ/kg K and γ = 1.333.

Solution. Refer to Fig. 5.55.

Given : $T_1 = 20 + 273 = 293$ K,

$T_6 = T_8 = 625 + 273 = 898$ K

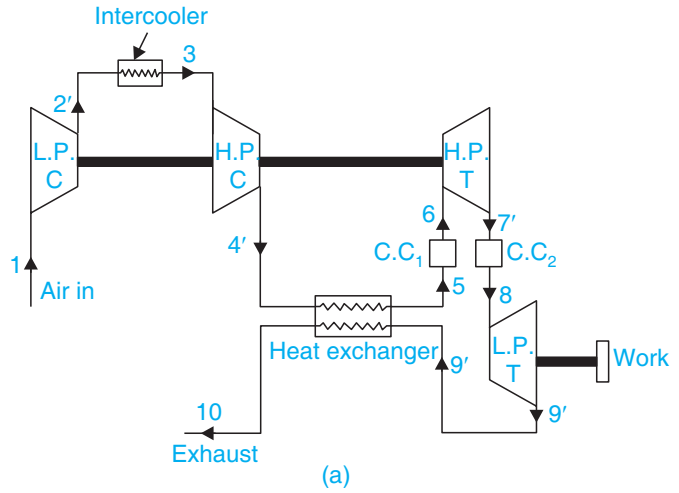
Efficiency of each compressor stage = 0.8

$\eta_{mech.} = 0.95$, $\varepsilon = 0.8$

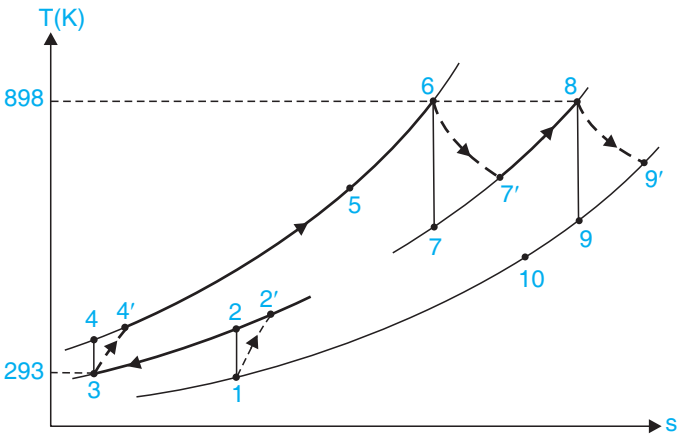
(i) Thermal efficiency, $\eta_{thermal}$:

Since the pressure ratio and the isentropic efficiency of each compressor is the same then the work input required for each compressor is the same since both compressor have the same air inlet temperature *i.e.*, $T_1 = T_3$ and $T_2' = T_4'$.

Also, $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}}$ and $\frac{p_2}{p_1} = \sqrt{9} = 3$



(a)



(b)

Fig. 5.55

$$\therefore \quad T_2 = (20 + 273) \times (3)^{\frac{1.4 - 1}{1.4}}$$

$$= 401 \text{ K}$$

Now, $\eta_{compressor}$ (L.P.) $= \frac{T_2 - T_1}{T_2' - T_1}$

$$0.8 = \frac{401 - 293}{T_2' - 293}$$

i.e., $$T_2' = \frac{401 - 298}{0.8} + 293$$

$$= 428 \text{ K}$$

Work input per compressor stage

$$= c_{pa}(T_2' - T_1)$$

$$= 1.005\ (428 - 293)$$

$$= 135.6 \text{ kJ/kg}$$

The H.P. turbine is required to drive both compressors and to overcome mechanical friction.

i.e., Work output of H.P. turbine $= \dfrac{2 \times 135.6}{0.95}$

$= 285.5$ kJ/kg

$\therefore \quad c_{pg}\,(T_6 - T_7') = 285.5$

i.e., $1.15\,(898 - T_7') = 285.5$

$\therefore \quad T_7' = 898 - \dfrac{285.5}{1.15} = 650$ K

Now, $\eta_{\text{turbine (H.P.)}} = \dfrac{T_6 - T_7'}{T_6 - T_7}$;

$0.85 = \dfrac{898 - 650}{898 - T_7}$

$\therefore \quad T_7 = 898 - \left(\dfrac{898 - 650}{0.85}\right)$

$= 606$ K

Also, $\dfrac{T_6}{T_7} = \left(\dfrac{p_6}{p_7}\right)^{\frac{\gamma - 1}{\gamma}}$

or $\dfrac{p_6}{p_7} = \left(\dfrac{T_6}{T_7}\right)^{\frac{\gamma}{\gamma - 1}} = \left(\dfrac{898}{606}\right)^{\frac{1.333}{0.333}} = 4.82$

Then, $\dfrac{p_8}{p_9} = \dfrac{9}{4.82} = 1.86$

Again, $\dfrac{T_8}{T_9} = \left(\dfrac{p_8}{p_9}\right)^{\frac{\gamma - 1}{\gamma}} = (1.86)^{\frac{1.333 - 1}{1.333}} = 1.16$

$\therefore \quad T_9 = \dfrac{T_8}{1.16} = \dfrac{898}{1.16} = 774$ K

Also, $\eta_{\text{turbine (L.P.)}} = \dfrac{T_8 - T_9'}{T_8 - T_9}$; $0.85 = \dfrac{898 - T_9'}{898 - 774}$

$\therefore \quad T_9' = 898 - 0.85\,(898 - 774) = 792.6$ K

$\therefore$ Net work output $= c_{pg}(T_8 - T_9') \times 0.95$

$= 1.15\,(898 - 792.6) \times 0.95$

$= 115.15$ kJ/kg

Thermal ratio or effectiveness of heat exchanger,

$$\varepsilon = \frac{T_5 - T_4'}{T_9' - T_4'} = \frac{T_5 - 428}{792.6 - 428}$$

i.e., $0.8 = \dfrac{T_5 - 428}{792.6 - 428}$

$\therefore \quad T_5 = 0.8\,(792.6 - 428) + 428$

$= 719.7$ K

Now, Heat supplied

$= c_{pg}(T_6 - T_5) + c_{pg}(T_8 - T_7')$

$= 1.15\,(898 - 719.7) + 1.15\,(898 - 650)$

$= 490.2$ kJ/kg

$\therefore \quad \eta_{\text{thermal}} = \dfrac{\text{Net work output}}{\text{Heat supplied}} = \dfrac{115.15}{490.2}$

$= 0.235$ or **23.5%.** **(Ans.)**

(ii) **Work ratio :**

Gross work of the plant

$= W_{\text{turbine (H.P.)}} + W_{\text{turbine (L.P.)}}$

$= 285.5 + \dfrac{115.15}{0.95} = 406.7$ kJ/kg

$\therefore$ **Work ratio**

$= \dfrac{\text{Net work output}}{\text{Gross work output}} = \dfrac{115.15}{406.7}$

$=$ **0.283.** **(Ans.)**

(iii) **Mass flow, $\dot{m}$:**

Let the mass flow be $\dot{m}$, then

$\dot{m} \times 115.15 = 4500$

$\therefore \quad \dot{m} = \dfrac{4500}{115.15} = 39.08$ kg/s

i.e., **Mass flow = 39.08 kg/s.** **(Ans.)**

Example 5.9. *In a closed cycle gas turbine there is two-stage compressor and a two-stage turbine. All the components are mounted on the same shaft. The pressure and temperature at the inlet of the first-stage compressor are 1.5 bar and 20°C. The maximum cycle temperature and pressure are limited to 750°C and 6 bar. A perfect intercooler is used between the two-stage compressors and a reheater is used between the two turbines. Gases are heated in the reheater to 750°C before entering into the L.P. turbine. Assuming the compressor and turbine efficiencies as 0.82, calculate :*

(i) The efficiency of the cycle without regenerator.

(ii) The efficiency of the cycle with a regenerator whose effectiveness is 0.70.

(iii) The mass of the fluid circulated if the power developed by the plant is 350 kW.

The working fluid used in the cycle is air. For air : $\gamma = 1.4$ *and* $c_p = 1.005$ *kJ/kg K.*

Solution. *Given :* $T_1 = 20 + 273 = 293$ K,

$T_5 = T_7 = 750 + 273 = 1023$ K,

$p_1 = 1.5$ bar,

$p_2 = 6$ bar, $\eta_{\text{compressor}} = \eta_{\text{turbine}} = 0.82$,

Effectiveness of regenerator, $\varepsilon = 0.70$, Power developed, $P = 350$ kW.

For air : $c_p = 1.005$ kJ/kg, K, $\gamma = 1.4$

As per given conditions : $T_1 = T_3$, $T_2' = T_4'$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}}$$

and $$p_x = \sqrt{p_1 p_2} = \sqrt{1.5 \times 6} = 3 \text{ bar}$$

Now, $$T_2 = T_1 \times \left(\frac{p_2}{T_1}\right)^{\frac{\gamma - 1}{\gamma}}$$

$$= 293 \times \left(\frac{3}{1.5}\right)^{\frac{1.4 - 1}{1.4}} = 357 \text{ K}$$

$$\eta_{\text{compressor (L.P.)}} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.82 = \frac{357 - 293}{T_2' - 293}$$

$$\therefore \quad T_2' = \frac{357 - 293}{0.82} + 293 = 371 \text{ K}$$

i.e., $$T_2' = T_4' = 371 \text{ K}$$

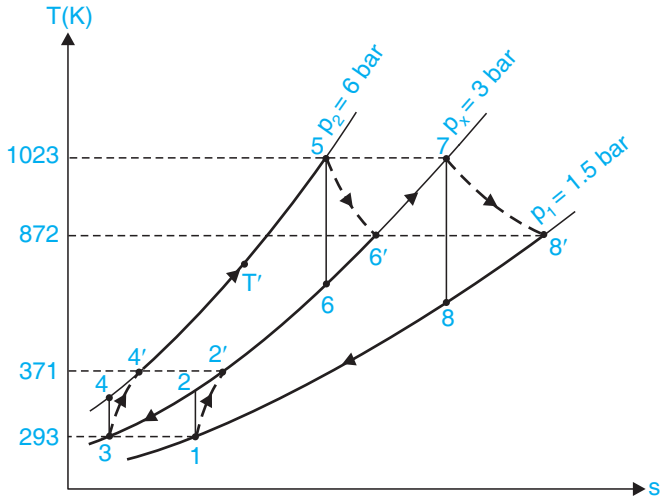


Fig. 5.56

Now, $$\frac{T_5}{T_6} = \left(\frac{p_5}{p_6}\right)^{\frac{\gamma - 1}{\gamma}} = \left(\frac{p_2}{p_x}\right)^{\frac{1.4 - 1}{1.4}}$$

$$\left[\because \quad p_5 = p_2 \quad p_6 = p_x\right]$$

$$\frac{1023}{T_6} = \left(\frac{6}{3}\right)^{0.286} = 1.219$$

$$\therefore \quad T_6 = \frac{1023}{1.219} = 839 \text{ K}$$

$$\eta_{\text{turbine (H.P.)}} = \frac{T_5 - T_6'}{T_5 - T_6}$$

$$0.82 = \frac{1023 - T_6'}{1023 - 839}$$

$$\therefore \quad T_6' = 1023 - 0.82\,(1023 - 839) = 872 \text{ K}$$

$$T_8' = T_6' = 872 \text{ K} \quad \text{as} \quad \eta_{\text{turbine (H.P.)}} = \eta_{\text{turbine (L.P.)}}$$

and $$T_7 = T_5 = 1023 \text{ K}$$

Effectiveness of regenerator, $$\varepsilon = \frac{T' - T_4'}{T_8' - T_4'}$$

where T' is the temperature of air coming out of regenerator

$$\therefore \quad 0.70 = \frac{T' - 371}{872 - 371}$$

i.e., $$T' = 0.70\,(872 - 371) + 371 = 722 \text{ K}$$

Net work available,

$$W_{\text{net}} = [W_{T(\text{L.P.})} + W_{T(\text{L.P.})}] - [W_{C(\text{H.P.})} + W_{C(\text{L.P.})}]$$

$$= 2\,[W_{T(\text{L.P.})} - W_{C(\text{L.P.})}]$$

as the *work developed by each turbine is same and work absorbed by each compressor is same.*

$$\therefore \quad W_{\text{net}} = 2c_p\,[(T_5 - T_6') - (T_2' - T_1)]$$

$$= 2 \times 1.005\,[(1023 - 872) - (371 - 293)]$$

$$= 146.73 \text{ kJ/kg of air}$$

Heat supplied per kg of air *without regenerator*

$$= c_p(T_5 - T_4') + c_p(T_7 - T_6')$$

$$= 1.005\,[(1023 - 371) + (1023 - 872)]$$

$$= 807 \text{ kJ/kg of air}$$

Heat supplied per kg of air *with regenerator*

$$= c_p(T_5 - T') + c_p(T_7 - T_6')$$

$$= 1.005\,[(1023 - 722) + (1023 - 872)]$$

$$= 454.3 \text{ kJ/kg}$$

(*i*) $\eta_{\text{thermal (without regenerator)}}$

$$= \frac{146.73}{807} = 0.182 \text{ or } \mathbf{18.2\%}. \quad \textbf{(Ans.)}$$

(*ii*) $\eta_{\text{thermal (with regenerator)}}$

$$= \frac{146.73}{454.3} = 0.323 \text{ or } \mathbf{32.3\%}. \quad \textbf{(Ans.)}$$

(*iii*) Mass of fluid circulated, $\dot{m}$:

Power developed,

$$P = 146.73 \times \dot{m} \text{ kW}$$

$$\therefore \quad 350 = 146.73 \times \dot{m}$$

i.e., $$\dot{m} = \frac{350}{146.73} = 2.38 \text{ kg/s}$$

i.e., **Mass of fluid circulated = 2.38 kg/s.** **(Ans.)**

☞**Example 5.10.** *The air in a gas turbine plant is taken in L.P. compressor at 293 K and 1.05 bar and after compression it is passed through intercooler where its*

temperature is reduced to 300 K. The cooled air is further compressed in H.P. unit and then passed in the combustion chamber where its temperature is increased to 750°C by burning the fuel. The combustion products expand in H.P. turbine which runs the compressor and further expansion is continued in L.P. turbine which runs the alternator. The gases coming out from L.P. turbine are used for heating the incoming air from H.P. compressor and then expanded to atmosphere.

Pressure ratio of each compressor = 2, isentropic efficiency of each compressor stage = 82%, isentropic efficiency of each turbine stage = 82%, effectiveness of heat exchanger = 0.72, air flow = 16 kg/s, calorific value of fuel = 42000 kJ/kg, c_v (for gas) = 1.0 kJ/kg K, c_p (gas) = 1.15 kJ/kg K, γ (for air) = 1.4, γ (for gas) = 1.33.

Neglecting the mechanical, pressure and heat losses of the system and fuel mass also, determine the following :

(i) The power output.

(ii) Thermal efficiency.

(iii) Specific fuel consumption.

Solution. *Given :* $T_1 = 293$ K, $T_3 = 300$ K, $\frac{p_2}{p_1} = \frac{p_4}{p_3} = 2$,

$T_6 = 750 + 273 = 1023$ K,

$\eta_{compressor} = 82\%$, $\eta_{turbine} = 82\%$, $\varepsilon = 0.72$,

$\dot{m}_a = 16$ kg/s, $C = 42000$ kJ/kg,

$c_{pa} = 1.0$ kJ/kg K, $c_{pg} = 1.15$ kJ/kg K,

γ (for air) = 1.4, γ (for gas) = 1.33.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = (2)^{\frac{1.4-1}{1.4}} = 1.219$$

$$\therefore \quad T_2 = 293 \times 1.219 = 357 \text{ K}$$

Also, $$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$\therefore \quad 0.82 = \frac{357 - 293}{T_2' - 293}$$

$$\therefore \quad T_2' = \left(\frac{357 - 293}{0.82}\right) + 293 = 371 \text{ K}$$

Similarly, $$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = (2)^{\frac{1.4-1}{1.4}} = 1.219$$

$$\therefore \quad T_4 = 300 \times 1.219 = 365.7 \text{ K}$$

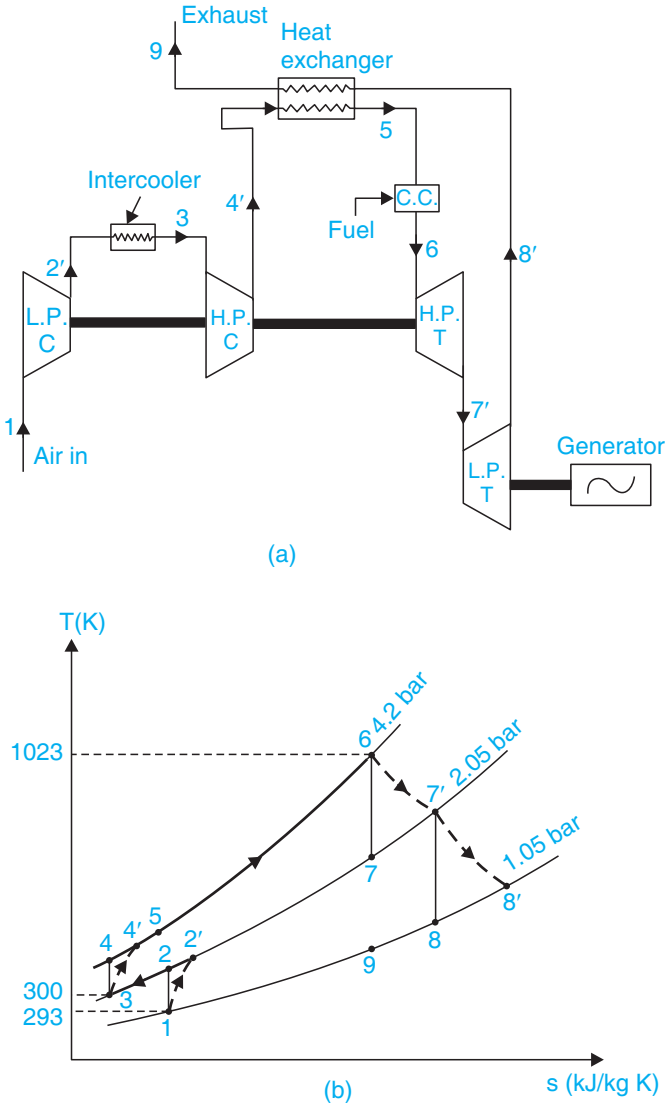


Fig. 5.57

and $$\eta_{compressor} = \frac{T_4 - T_3}{T_4' - T_3}$$

$$\therefore \quad 0.82 = \frac{365.7 - 300}{T_4' - 300}$$

i.e., $$T_4' = \left(\frac{365.7 - 300}{0.82}\right) + 300 = 380 \text{ K}$$

Work output of H.P. turbine = Work input to compressor.

Neglecting mass of fuel we can write

$$c_{pg}(T_6 - T_7') = c_{pa}[(T_2' - T_1) + (T_4' - T_3)]$$

$$1.15(1023 - T_7') = 1.0[(371 - 293) + (380 - 300)]$$

or $$1.15(1023 - T_7') = 158$$

$$\therefore \quad T_7' = 1023 - \frac{15.8}{1.15} = 886 \text{ K}$$

Also, $\eta_{\text{turbine (H.P.)}} = \dfrac{T_6 - T_7'}{T_6 - T_7}$

i.e., $$0.82 = \frac{1023 - 886}{1023 - T_7}$$

$$\therefore \quad T_7 = 1023 - \left(\frac{1023 - 886}{0.82}\right) = 856 \text{ K}$$

Now, $$\frac{T_6}{T_7} = \left(\frac{p_6}{p_7}\right)^{\frac{\gamma - 1}{\gamma}}$$

$$\therefore \quad \frac{p_6}{p_7} = \left(\frac{T_6}{T_7}\right)^{\frac{\gamma}{\gamma - 1}} = \left(\frac{1023}{856}\right)^{\frac{1.33}{1.33 - 1}} = 2.05$$

i.e., $$p_7 = \frac{p_6}{2.05} = \frac{4.2}{2.05} = 2.05 \text{ bar}$$

[$\because$ $p_6 = 1.05 \times 4 = 4.2$ bar]

$$\frac{T_7'}{T_8} = \left(\frac{p_7}{p_8}\right)^{\frac{\gamma - 1}{\gamma}} = \left(\frac{2.05}{1.05}\right)^{\frac{1.33 - 1}{1.33}} = 1.18$$

$$T_8 = \frac{T_7'}{1.18} = \frac{886}{1.18} = 751 \text{ K}$$

Again, $\eta_{\text{turbine (L.P.)}} = \dfrac{T_7' - T_8'}{T_7' - T_8}$

$$0.82 = \frac{886 - T_8'}{886 - 751}$$

$$\therefore \quad T_8' = 886 - 0.82\,(886 - 751) = 775 \text{ K}$$

(*i*) Power output :

Net power output $= c_{pg}\,(T_7' - T_8')$

$= 1.15\,(886 - 775) = 127.6$ kJ/kg

$\therefore$ Net output per second

$= \dot{m} \times 127.6$

$= 16 \times 127.6 = 2041.6$ kJ/s

$=$ **2041.6 kW.** **(Ans.)**

(*ii*) Thermal efficiency :

Effectiveness of heat exchanger,

$$\varepsilon = \frac{T_5 - T_4'}{T_8' - T_4'}$$

i.e., $$0.72 = \frac{T_5 - 380}{775 - 380}$$

$$\therefore \quad T_5 = 0.72(775 - 380) + 380 = 664 \text{ K}$$

Heat supplied in combustion chamber per second

$= \dot{m}_a\, c_{pg}\,(T_6 - T_5)$

$= 16 \times 1.15(1023 - 664)$

$= 6605.6$ kJ/s

$$\therefore \quad \eta_{\text{thermal}} = \frac{2041.6}{6605.6}$$

$= 0.309$ or **30.9%.** **(Ans.)**

(*iii*) Specific fuel consumption :

If m_f is the mass of fuel supplied per kg of air, then

$$m_f \times 42000 = 1.15(1023 - 664)$$

$$\therefore \quad \frac{1}{m_f} = \frac{42000}{1.15(1023 - 664)} = \frac{101.7}{1}$$

$\therefore$ Air-fuel ratio = 101.7 : 1

$\therefore$ Fuel supplied per hour

$$= \frac{16 \times 3600}{101.7} = 566.37 \text{ kg/h}$$

$\therefore$ **Specific fuel consumption**

$$= \frac{566.37}{2041.6} = \textbf{0.277 kg/kWh.} \quad \textbf{(Ans.)}$$

☞Example 5.11. *Air is taken in a gas turbine plant at 1.1 bar 20°C. The plant comprises of L.P. and H.P. compressors and L.P. and H.P. turbines. The compression in L.P. stage is upto 3.3 bar followed by intercooling to 27°C. The pressure of air after H.P. compressor is 9.45 bar. Loss in pressure during intercooling is 0.15 bar. Air from H.P. compressor is transferred to heat exchanger of effectiveness 0.65 where it is heated by the gases from L.P. turbine. After heat exchanger the air passes through combustion chamber. The temperature of gases supplied to H.P. turbine is 700°C. The gases expand in H.P. turbine to 3.62 bar and air then reheated to 670°C before expanding in L.P. turbine. The loss of pressure in reheater is 0.12 bar. Determine :*

(i) The overall efficiency (ii) The work ratio

(iii) Mass flow rate when the power generated is 6000 kW.

Assume : Isentropic efficiency of compression in both stages = 0.82.

Isentropic efficiency of expansion in turbines = 0.85.

For air : $c_p = 1.005$ kJ/kg K, $\gamma = 1.4$.

For gases : $c_p = 1.15$ kJ/kg K, $\gamma = 1.33$.

Neglect the mass of fuel.

Solution. *Given* : $T_1 = 20 + 273 = 293$ K,

$p_1 = 1.1$ bar, $p_2 = 3.3$ bar,

$T_3 = 27 + 273 = 300$ K,

$p_3 = 3.3 - 0.15 = 3.15$ bar,

$p_4 = p_6 = 9.45$ bar, $T_6 = 973$ K,

$T_8 = 670 + 273 = 943$ K,

$p_8 = 3.5$ bar,

$\eta_{\text{compressors}} = 82\%$, $\eta_{\text{turbines}} = 85\%$,

Power generated = 6000 kW,

Effectiveness, $\varepsilon = 0.65$, $c_{pa} = 1.005$ kJ/kg K,

$\gamma_{\text{air}} = 1.44$, $c_{pg} = 1.15$ kJ/kg K

and $\gamma_{\text{gases}} = 1.33$.

Refer to Fig. 5.58

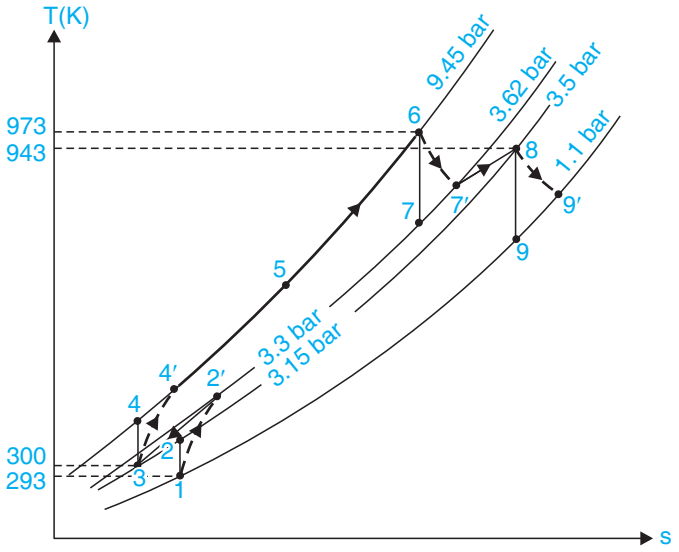


Fig. 5.58

Now, $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.3}{1.1}\right)^{\frac{1.4-1}{1.4}} = 1.369$

$\therefore \quad T_2 = 293 \times 1.369 = 401 \text{ K}$

$\eta_{\text{compressor (L.P.)}} = 0.82 = \frac{T_2 - T_1}{T_2' - T_1} = \frac{401 - 293}{T_2' - 293}$

$\therefore \quad T_2' = \left(\frac{401 - 293}{0.82}\right) + 293 = 425 \text{ K}$

Again, $\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{9.45}{3.15}\right)^{\frac{1.4-1}{1.4}} = 1.369$

$\therefore \quad T_4 = 300 \times 1.369 = 411 \text{ K}$

Now, $\eta_{\text{compressor (H.P.)}} = \frac{T_4 - T_3}{T_4' - T_3}$

$0.82 = \frac{411 - 300}{T_4' - 300}$

$\therefore \quad T_4' = \left(\frac{411 - 300}{0.82}\right) + 300 = 435 \text{ K}$

Similarly, $\frac{T_6}{T_7} = \left(\frac{p_6}{p_7}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{9.45}{3.62}\right)^{\frac{1.33-1}{1.33}} = 1.268$

$\therefore \quad T_7 = \frac{T_6}{1.268} = \frac{973}{1.268} = 767 \text{ K}$

Also, $\eta_{\text{turbine (H.P.)}} = \frac{T_6 - T_7'}{T_6 - T_7}$

$0.85 = \frac{973 - T_7'}{973 - 767}$

$\therefore \quad T_7' = 973 - 0.85(973 - 767) = 798 \text{ K}$

Again, $\frac{T_8}{T_9} = \left(\frac{p_8}{p_9}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.5}{1.1}\right)^{\frac{1.33-1}{1.33}} = 1.332$

$\therefore \quad T_9 = \frac{T_8}{1.332} = \frac{943}{1.332} = 708 \text{ K}$

$\eta_{\text{turbine (L.P.)}} = \frac{T_8 - T_9'}{T_8 - T_9}$

$0.85 = \frac{943 - T_9'}{943 - 708}$

$\therefore \quad T_9' = 943 - 0.85(943 - 708) = 743 \text{ K}.$

Effectiveness of heat exchanger,

$\varepsilon = 0.65 = \frac{T_5 - T_4'}{T_9' - T_4'}$

i.e., $0.65 = \frac{T_5 - 435}{743 - 435}$

$\therefore \quad T_5 = 0.65(743 - 435) + 435 = 635 \text{ K}$

$W_{\text{turbine (H.P.)}} = c_{pg}(T_6 - T_7')$
$= 1.15(973 - 798)$
$= 201.25 \text{ kJ/kg of gas}$

$W_{\text{turbine (L.P.)}} = c_{pg}(T_8 - T_9')$
$= 1.15(943 - 743)$
$= 230 \text{ kJ/kg of gas}$

$W_{\text{compressor (L.P.)}} = c_{pa}(T_2' - T_1)$
$= 1.005(425 - 293)$
$= 132.66 \text{ kJ/kg of air}$

$W_{\text{compressor (H.P.)}} = c_{pa}(T_4' - T_3)$
$= 1.005(435 - 300)$
$= 135.67 \text{ kJ/kg of air}$

Heat supplied $= c_{pg}(T_6 - T_5) + c_{pg}(T_8 - T_7')$
$= 1.15(973 - 635) + 1.15(943 - 798) = 555.45 \text{ kJ/kg of gas}$

(*i*) Overall efficiency η_{overall} :

$\eta_{\text{overall}} = \frac{\text{Net work done}}{\text{Heat supplied}}$

$= \frac{[W_{\text{turbine (H.P.)}} + W_{\text{turbine (L.P.)}}] - [W_{\text{comp. (L.P.)}} + W_{\text{comp. (H.P.)}}]}{\text{Heat supplied}}$

$= \frac{(201.25 + 230) - (132.66 + 135.67)}{555.45}$

$= \frac{162.92}{555.45} = 0.293 \text{ or } \mathbf{29.3\%}.$ **(Ans.)**

(*ii*) Work ratio :

$\textit{Work ratio} = \frac{\text{Net work done}}{\text{Turbine work}}$

$$= \frac{[W_{turbine\,(H.P.)} + W_{turbine\,(L.P.)}] - [W_{comp.\,(L.P.)} + W_{comp.\,(H.P.)}]}{[W_{turbine\,(H.P.)} + W_{turbine\,(L.P.)}]}$$

$$= \frac{(201.25 + 230) - (132.66 + 135.67)}{(201.25 + 230)}$$

$$= \frac{162.92}{431.25} = 0.377.$$

i.e., *Work ratio* = **0.377.** **(Ans.)**

(iii) **Mass flow rate, $\dot{m}$:**

Net work done = 162.92 kJ/kg.

Since mass of fuel is neglected, for 6000 kW, mass flow rate,

$$\dot{m} = \frac{6000}{162.92} = 36.83 \text{ kg/s}$$

i.e., *Mass flow rate* = **36.83 kg/s.** **(Ans.)**

ADDITIONAL / TYPICAL EXAMPLES

Example 5.12. *A gas turbine plant consists of two turbines. One compressor turbine to drive compressor and other power turbine to develop power output and both are having their own combustion chambers which are served by air directly from the compressor. Air enters the compressor at 1 bar and 288 K and is compressed to 8 bar with an isentropic efficiency of 76%. Due to heat added in the combustion chamber, the inlet temperature of gas to both turbines is 900°C. The isentropic efficiency of turbines is 86%. The mass flow rate of air at the compressor is 23 kg/s. The calorific value of fuel is 4200 kJ/kg. Calculate the output of the plant and the thermal efficiency if mechanical efficiency is 95% and generator efficiency is 96%. Take c_p = 1.005 kJ/kg K and γ = 1.4 for air and c_{pg} = 1.128 kJ/kg K and γ = 1.34 for gases.* **(M.U.)**

Solution. *Given* : p_1 = 1 bar ; T_1 = 288 K ;

p_2 = 8 bar, $\eta_{(isen)}$ = 76% ;

T_3 = 900°C or 1173 K,

$\eta_{T(isen.)}$ = 86%, m_a = 23 kg/s ;

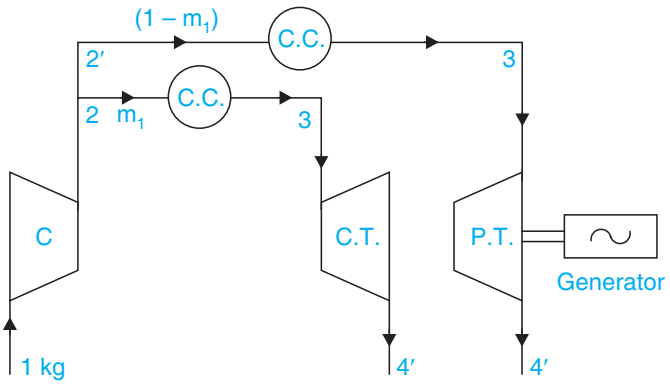
C.V. = 4200 kJ/kg ;

$\eta_{mech.}$ = 95% ; $\eta_{gen.}$ = 96% ;

c_p = 1.005 kJ/kg ; γ_a = 1.4 ;

c_{pg} = 1.128 kJ/kg K ; γ_g = 1.34.

The arrangement of the plant and the cycle are shown in Fig. 5.59 (*a*), (*b*) respectively.



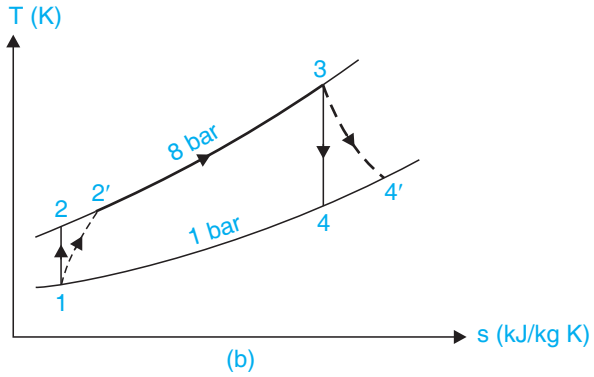


Fig. 5.59

Considering *isentropic compression process 1-2*, we have

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} = \left(\frac{8}{1}\right)^{\frac{1.4 - 1}{1.4}} = 1.811$$

$$\therefore \quad T_2 = 288 \times 1.811 = 521.6 \text{ K}$$

Also, $$\eta_{C(isen.)} = \frac{T_2 - T_1}{T_2' - T_1}$$

or $$0.76 = \frac{521.6 - 288}{T_2' - 288}$$

or $$T_2' = \frac{521.6 - 288}{0.76} + 288 = 595.4 \text{ K}$$

Considering *isentropic expansion process 3-4*, we have

$$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma - 1}{\gamma}} = \left(\frac{1}{8}\right)^{\frac{1.34 - 1}{1.34}} = 0.59$$

$$\therefore \quad T_4 = 1173 \times 0.59 = 692.1 \text{ K}$$

Also, $$\eta_{T(isen.)} = \frac{T_3 - T_4'}{T_3 - T_4}$$

or $$0.86 = \frac{1173 - T_4'}{1173 - 692.1}$$

$$\therefore \quad T_4' = 1173 - 0.86(1173 - 692.1)$$
$$= 759.4 \text{ K}$$

Consider 1 kg of air flow through compressor.

$$W_{\text{compressor}} = c_p (T_2' - T_1) = 1.005(595.4 - 288)$$
$$= 308.9 \text{ kJ}$$

This is equal to work of compressor turbine.

$$\therefore \quad 308.9 = m_1 \times c_{pg} (T_3 - T_4'),$$

neglecting fuel mass

or $$m_1 = \frac{308.9}{1.128\,(1173 - 759.4)} = 0.662 \text{ kg}$$

and flow through the power turbine

$$= 1 - m_1 = 1 - 0.662 = 0.338 \text{ kg}$$

$$\therefore \quad W_{PT} = (1 - m_1) \times c_{pg}(T_3 - T_4')$$
$$= 0.338 \times 1.128\,(1173 - 759.4)$$
$$= 157.7 \text{ kJ}$$

$\therefore$ **Power output**

$$= 23 \times 157.7 \times \eta_{\text{mech.}} \times \eta_{\text{gen.}}$$
$$= 23 \times 157.7 \times 0.95 \times 0.96$$
$$= \mathbf{3307.9\ kJ.} \quad \textbf{(Ans.)}$$

$$Q_{\text{input}} = c_{pg} T_3 - c_{pa} T_2'$$
$$= 1.128 \times 1173 - 1.005 \times 595.4$$
$$= 724.7 \text{ kJ/kg of air}$$

Thermal efficiency,

$$\eta_{\text{th}} = \frac{157.7}{724.7} \times 100 = \mathbf{21.76\%.} \quad \textbf{(Ans.)}$$

Example 5.13. *(a) Why are the back work ratios relatively high in gas turbine plants compared to those of steam power plants ?*

(b) In a gas turbine plant compression is carried out in two stages with perfect intercooling and expansion in one stage turbine. If the maximum temperature (T_{max} K) and minimum temperature (T_{min}K) in the cycle remain constant, show that for maximum specific output of the plant, the optimum overall pressure ratio is given by

$$r_{opt.} = \left(\eta_T \cdot \eta_C \cdot \frac{T_{max}}{T_{min}} \right)^{\frac{2\gamma}{3(\gamma - 1)}}$$

where γ = *Adiabatic index ;* η_T = *Isentropic efficiency of the turbine.*

η_C = *Isentropic efficiency of compressor.* **(N.U.)**

Solution. (*a*) **Back work ratio** may be defined as *the ratio of negative work to the turbine work in a power plant.* In gas turbine plants, air is compressed from the turbine exhaust pressure to the combustion chamber pressure. This work is given by $-\int v dp$. As the specific volume of air is very high (even in closed cycle gas turbine plants), the compressor work required is very high, and also *bulky compressor is required*. In steam power plants, the turbine exhaust is changed to liquid phase in the condenser. The pressure of condensate is raised to boiler pressure by condensate extraction pump and boiler feed pump in series since the specific volume of water is very small as compared to that of air, the pump work ($-\int v dp$), is also very small. From the above reasons, the back work ratio

$$= \frac{-\int v dp}{\text{Turbine work}}$$

for gas *turbine plants is relatively high compared to that for steam power plants.*

(*b*) Refer to Fig. 5.60.

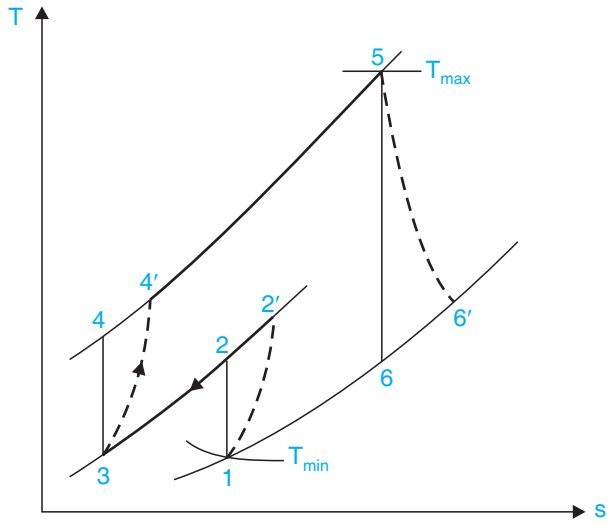


Fig. 5.60

Assuming optimum pressure ratio in each stage of the compressors as $\sqrt{r}$, we have

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma - 1}{\gamma}}$$

or $$T_2 = T_{\text{min}} \times (r)^{\frac{\gamma - 1}{2\gamma}}$$

$$W_{\text{compressor}} = 2[c_p (T_2' - T_1)]$$

For both compressors

$$= 2c_p \frac{T_2 - T_1}{\eta_C} = \frac{2c_p}{\eta_C} T_{\min} \left[(r)^{\frac{\gamma - 1}{2\gamma}} - 1 \right],$$

as $T_1 = T_{\min}$

Also, $$\frac{T_5}{T_6} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma - 1}{\gamma}} = (r)^{\frac{\gamma - 1}{2\gamma}}$$

$$\therefore \quad T_6 = \frac{T_5}{(r)^{\gamma - 1/\gamma}} = \frac{T_{\max}}{(r)^{\gamma - 1/\gamma}}, \text{ as } T_5 = T_{\max}$$

$$W_{\text{turbine}} = c_p (T_5 - T_6') = c_p \left[T_{\max} - \frac{T_{\max}}{(r)^{\gamma - 1/\gamma}} \right] \eta_T,$$

as $$\eta_T = \frac{T_5 - T_6'}{T_5 - T_6}$$

$$= c_p T_{\max} \left[1 - \frac{1}{(r)^{\gamma - 1/\gamma}} \right] \eta_T$$

$$W_{\text{net}} = W_{\text{turbine}} - W_{\text{compressor}}$$

$$= c_p \eta_T T_{\max} \left[1 - \frac{1}{(r)^{\gamma - 1/\gamma}} \right] - \frac{2c_p}{\eta_C} T_{\min} \left[(r)^{\frac{\gamma - 1}{2\gamma}} - 1 \right]$$

For maximum work output,

$$\frac{dW_{\text{net}}}{dr} = 0$$

or $$- c_p \eta_T T_{\max} \left(- \frac{\gamma - 1}{\gamma} \right) (r)^{-\left(\frac{\gamma - 1}{\gamma} \right) - 1}$$

$$- \frac{2c_p}{\eta_C} T_{\min} \left(\frac{\gamma - 1}{2\gamma} \right) (r)^{\frac{\gamma - 1}{2\gamma} - 1} = 0$$

or $$\eta_T \eta_C \frac{T_{\max}}{T_{\min}} = (r)^{3(\gamma - 1)/2\gamma}, \text{ on simplification.}$$

Hence, the optimum pressure ratio is

$$r_{\text{opt}} = \left[\eta_T \cdot \eta_C \cdot \frac{T_{\max}}{T_{\min}} \right]^{\frac{2\gamma}{3(\gamma - 1)}}. \quad \textbf{Proved.}$$

Example 5.14. *A gas turbine power plant of 12 MW capacity working on closed cycle, using air as working medium, is to be designed for maximum specific work output. Find the cost of energy generated if the plant is running at designed capacity. Use the following data :*

The temperature of air at inlet = 298 K
The maximum temperature in the cycle = 950 K
Isentropic efficiency of compressor = 82%
Isentropic efficiency of turbine = 88%
Mechanical efficiency = 94%
Generation efficiency = 94%
Combustion efficiency = 95%
Percentage of heat developed in the combustion chamber given to the air working into the system = 90%
Effectiveness of regenerator = 0.68
Cost of fuel used = ₹ 4500 per tonne
Calorific value of fuel used = 41000 kJ/kg
All other charges including profit per hour = ₹ 3500/hour

Neglect heat and pressure losses in the system. Take c_p for air = 1.005 kJ/kg K.

Solution. *Given :* $T_1 = 298$ K ; $T_4 = 950$ K ;
$\eta_{\text{comp.}} = 82\%$; $\eta_{\text{turbine}} = 88\%$;
$\eta_{\text{mech.}} = 94\%$;
$\eta_{\text{gen.}} = 94\%$; $\eta_{\text{comb.}} = 95\%$;
$\in = 0.68$;
Cost of fuel used = ₹ 4500 per tonne ;
$C = 41000$ kJ/kg ;
Other charges = ₹ 3500 per hour.

Cost of energy generated :

The schematic arrangement of the plant and its corresponding *T-s* diagram are shown in Fig. 5.61 (*a*) and (*b*) respectively.

As the plant is designed for maximum specific output,

$$r_p = \frac{p_2}{p_1} = \left(\eta_C \times \eta_T \times \frac{T_3}{T_1} \right)^{\left[\frac{\gamma}{2(\gamma - 1)} \right]}$$

$$= \left(0.82 \times 0.88 \times \frac{950}{298} \right)^{\left[\frac{1.4}{2(1.4 - 1)} \right]}$$

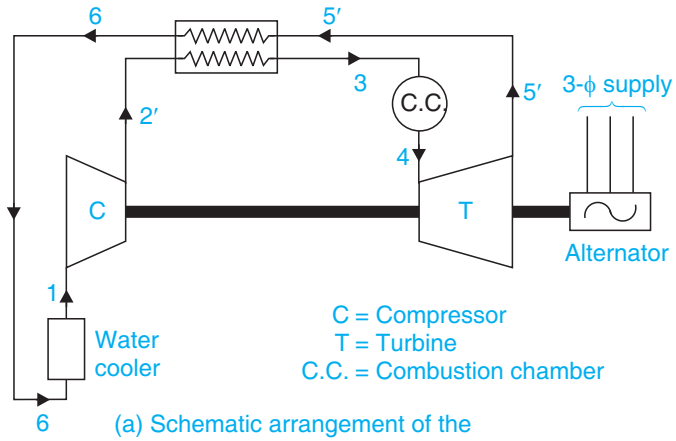
$$= (2.3)^{1.75} = 4.3$$

Compressor :

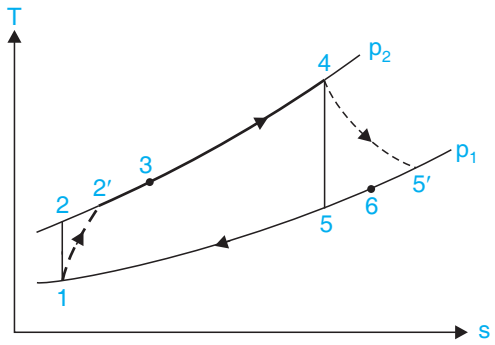
$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma - 1}{\gamma}} = (4.3)^{\frac{1.4 - 1}{1.4}} = 1.517$$

$$\therefore \quad T_2 = 298 \times 1.517 = 452 \text{ K}$$

$$\eta_C = 0.82 = \frac{T_2 - T_1}{T_2' - T_1} = \frac{452 - 298}{T_2' - 298}$$



(a) Schematic arrangement of the gas turbine plant



(b) T-s diagram

Fig. 5.61

$$\therefore \quad T_2' = 298 + \frac{452 - 298}{0.82} = 485.8 \text{ K}$$

Turbine :

$$\frac{T_4}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma - 1}{\gamma}} = (4.3)^{\frac{1.4 - 1}{1.4}} = 1.517$$

$$\therefore \quad T_5 = \frac{T_4}{1.57} = \frac{950}{1.517} = 626.2 \text{ K}$$

$$\eta_T = 0.88 = \frac{T_4 - T_5'}{T_4 - T_5} = \frac{950 - T_5'}{950 - 626.2}$$

$$\therefore \quad T_{5'} = 950 - 0.88\,(950 - 626.2) = 665 \text{ K}$$

Work developed per hour (neglecting fuel mass)

$= m_a \times c_{pa}\,[(T_4 - T_{5'}) - (T_{2'} - T_1)] \times \eta_{\text{mech.}} \times \eta_{\text{gen.}}$

$= 12 \times 10^3$ kW

where m_a is the mass of air passed per second.

$$m_a \times 1.005\,[(950 - 665) - (485.8 - 298)] \times 0.94 \times 0.94 = 12 \times 10^3$$

$$86.31\, m_a = 12 \times 10^3$$

$$\therefore \quad m_a = 139.03 \text{ kg/s}$$

Heat exchanger :

Effectiveness of heat exchanger,

$$\in = \frac{T_3 - T_{2'}}{T_{5'} - T_{2'}} \quad \text{(neglecting fuel mass)}$$

$$\therefore \quad 0.68 = \frac{T_3 - 485.8}{665 - 485.8}$$

or $$T_3 = 485.8 + 0.68\,(665 - 485.8) = 607.6 \text{ K}$$

Combustion chamber :

Considering the combustion process in combustion chamber, we have :

Now, $m_f \times C \times \eta_{\text{comb.}} \times 0.9 = m_a\, c_{pa}\,(T_4 - T_3)$

where m_f is the mass of fuel burned per sec.

or $m_f \times 41000 \times 0.95 \times 0.9 = 139.03 \times 1.005\,(950 - 607.6)$

$$\therefore \quad m_f = 1.365 \text{ kg/s}$$

$$\text{Cost of fuel} = \frac{1.365 \times 3600}{1000} \times 4500 = ₹\ 17690.4/\text{h}$$

Total cost per hour = Cost of fuel / hour

+ All other charges including profit per hour

= 17690.4 + 3500 = ₹ 21190.4/h

$$\therefore \quad \textit{Cost of energy generated} = \frac{21190.4}{12 \times 10^3}$$

= **₹ 1.76/kWh.** **(Ans.)**

Example 5.15. *A gas turbine power plant works on constant pressure open cycle. It consists of compressor, generator, combustion chamber and turbine (the compressor, turbine and generator mounted on the same shaft). The following data is given for this plant :*

The pressure and temperature of air entering into the compressor = *1 bar, 25°C*

The pressure of air leaving the compressor = *4 bar*

Isentropic efficiency of the compressor = *82 per cent*

Isentropic efficiency of the turbine = *86 per cent*

Effectiveness of the regenerator = *72 per cent*

Pressure loss in regenerator along air side = *0.08 bar*

Pressure loss in regenerator along gas side = *0.08 bar*

Pressure loss in the combustion chamber = *0.04 bar*

Combustion efficiency = *92 per cent*

Mechanical efficiency = *94 per cent*
Generation efficiency = *94 per cent*
Calorific value of fuel used = *40000 kJ/kg*
Flow of air = *24 kg/s*
Atmospheric pressure = *1.03 bar*
The maximum temperature of the cycle = *690°C*

Determine the following :

(i) The power available at the generator terminals,
(ii) The overall efficiency of the plant, and
(iii) The specific fuel consumption.

Take $\gamma = 1.4$ *for air and gases.*

$c_{pa} = 1$ *kJ/kg K* ; $c_{pg} = 1.1$ *kJ/kg K.*

Solution. *Given :* $p_1 = 1$ bar ;

$T_1 = 25 + 273 = 298$ K ;

$p_2 = p_{2'} = 4$ bar ;

$\eta_C = 82\%$; $\eta_T = 86\%$;

$\in = 0.72$; $\eta_{comb.} = 92\%$;

$\eta_{mech.} = 94\%$; $\eta_{gen.} = 94\%$;

$C = 40000$ kJ/kg ;

$m_a = 24$ kg/s ; $p_{atm.} = 1.03$ bar ;

$T_4 = 690 + 273 = 963$ K.

The schematic arrangement of the plant and its corresponding *T-s* diagram are shown in Fig. 5.62 (*a*) and (*b*) respectively.

Pressure at the inlet to the turbine,

$$p_4 = 4 - (0.08 + 0.04) = 3.88 \text{ bar}$$

Pressure at exit of the turbine,

$$p_5 = 1.03 + 0.08 = 1.11 \text{ bar}$$

Compressor :

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4}{1}\right)^{\frac{1.4-1}{1.4}} = 1.486$$

$$\therefore \quad T_2 = T_1 \times 1.486 = 298 \times 1.486 = 442.8 \text{ K}$$

$$\eta_{comp.} = 0.82 = \frac{T_2 - T_1}{T_{2'} - T_1} = \frac{442.8 - 298}{T_{2'} - 298}$$

$$\therefore \quad T_{2'} = 298 + \frac{442.8 - 298}{0.82} = 474.6 \text{ K}$$

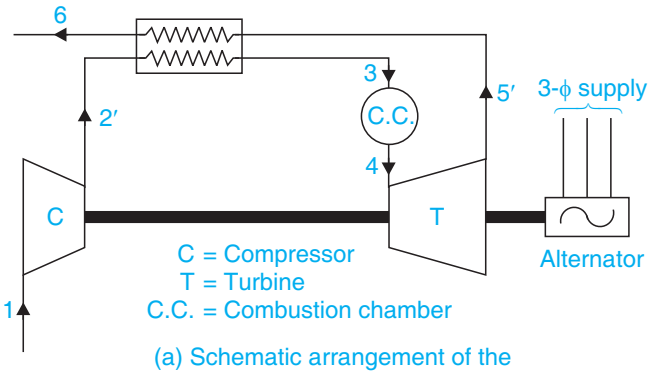
Turbine :

$$\frac{T_4}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.88}{1.11}\right)^{\frac{1.4-1}{1.4}} = 1.43$$

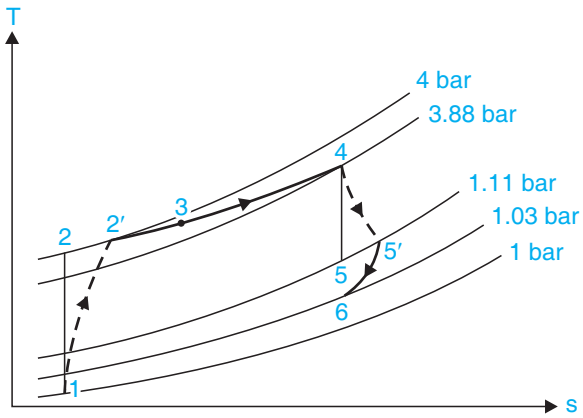
$$\therefore \quad T_5 = \frac{T_4}{1.43} = \frac{963}{1.43} = 673.4 \text{ K}$$

$$\eta_{turbine} = 0.86 = \frac{T_4 - T_{5'}}{T_4 - T_5} = \frac{963 - T_{5'}}{963 - 673.4}$$

$$\therefore \quad T_{5'} = 963 - 0.86\,(963 - 673.4) = 713.9 \text{ K}$$



(a) Schematic arrangement of the gas turbine plant



(b) T-s diagram

Fig. 5.62

Combustion Chamber :

Considering the combustion process in combustion chamber, we have

$$m_f \times C \times \eta_{comb.} = (m_a + m_f)\, c_{pg}\, (T_4 - T_3)$$

$$\therefore \quad C \times \eta_{comb.} = \left(\frac{m_a}{m_f} + 1\right) c_{pg}\, (T_4 - T_3)$$

or $$40000 \times 0.92 = \left(\frac{m_a}{m_f} + 1\right) \times 1.1\,(963 - T_3)$$

or $$\frac{m_a}{m_f} = \frac{40000 \times 0.92}{1.1(963 - T_3)} - 1 = \frac{33455}{(963 - T_3)} - 1 \qquad \ldots(1)$$

Also, effectiveness of the regenerator,

$$\in = \frac{m_a\, c_{pa}\, (T_3 - T_{2'})}{(m_a + m_f)\, c_{pg}\, (T_{5'} - T_{2'})}$$

or $$0.72 = \frac{1(T_3 - 474.6)}{\left(1 + \frac{m_f}{m_a}\right) \times 1.11 (713.9 - 474.6)}$$

or $$\frac{m_f}{m_a} = \frac{(T_3 - 474.6)}{0.72 \times 1.11 (713.9 - 474.6)} - 1$$

$$= \frac{(T_3 - 474.6)}{191.2} - 1 = \frac{T_3 - 665.8}{191.2}$$

or $$\frac{m_a}{m_f} = \frac{191.2}{T_3 - 665.8} \quad ...(2)$$

From eqns. (1) and (2), we get

$$\frac{33455}{963 - T_3} - 1 = \frac{191.2}{T_3 - 665.8}$$

or $$\frac{33455 - (963 - T_3)}{963 - T_3} = \frac{191.2}{T_3 - 665.8}$$

$$\frac{32492 + T_3}{963 - T_3} = \frac{191.2}{T_3 - 665.8}$$

$$(32492 + T_3)(T_3 - 665.8) = 191.2(963 - T_3)$$

$$32492\ T_3 - 21633174 + T_3^2 - 665.8\ T_3 = 184126 - 191.2\ T_3$$

$$T_3^2 + 32017\ T_3 - 21817300 = 0$$

$$\therefore \quad T_3 = \frac{-32017 \pm \sqrt{(32017)^2 + 4 \times 21817300}}{2}$$

$$= \frac{-32017 \pm 33352}{2} = 667.5 \text{ K}$$

i.e., $$T_3 = 667.5 \text{ K}$$

and $$\frac{m_a}{m_f} = 112 : 1.$$

(*i*) The power available at generator terminals:

$$W_{comp.} = 1 \times c_{pa} (T_{2'} - T_1) = 1 (474.6 - 298)$$

$$= 176.6 \text{ kJ/kg or air}$$

$$W_{turbine} = (1 + m_f) \times c_{pg} \times (T_4 - T_{5'})$$

$$= \left(1 + \frac{1}{112}\right) \times 1.1 (963 - 713.9)$$

$$= 276.4 \text{ kJ/kg of air}$$

$$W_{net} = W_{turbine} - W_{comp.}$$

$$= 276.4 - 176.6 = 99.8 \text{ kJ/kg of air}$$

Work available per kg of air at the terminals of generator

$$= 99.8 \times \eta_{mech.} \times \eta_{gen.}$$

$$= 99.8 \times 0.94 \times 0.94 = 88.18 \text{ kJ/kg}$$

Power available at the generator terminal

$$= \frac{24 \times 88.18}{1000} = \mathbf{2.116\ MW.} \quad \textbf{(Ans.)}$$

(*ii*) Overall efficiency of the plant, $\eta_{overall}$:

$$\eta_{overall} = \frac{88.18}{\frac{1}{112} \times 40000} \times 100 = \mathbf{24.69\%.} \quad \textbf{(Ans.)}$$

(*iii*) Specific fuel consumption :

Fuel required per hour $= (24 \times 3600) \times \frac{1}{112}$

$= 771.43$ kg/h

$\therefore$ Specific fuel consumption

$$= \frac{771.43}{2.116 \times 1000} = \mathbf{0.364\ kg/kWh.} \quad \textbf{(Ans.)}$$

Example 5.16. *The following data relate to a gas turbine plant :*

Power developed = 5 MW

Inlet pressure and temperature of air to the compressor = 1 bar, 30°C

Pressure ratio of the cycle = 5

Isentropic efficiency of the compressor = 80 per cent

Isentropic efficiency of both turbines = 85 per cent

Maximum temperature in both turbines = 550°C

c_{pa} *= 1.0 kJ/kg K ;*

c_{pg} *= 1.15 kJ/kg K ;*

γ *(air) = 1.4 ;* γ *(gases) = 1.33.*

If a reheater is used between two turbines at a pressure 2.24 bar, calculate the following :

(i) the mass flow rate of air, and

(ii) the overall efficiency.

Neglect the mass of the fuel. **(P.U.)**

Solution. *Given :* Power developed = 5 MW ;

$p_1 = 1$ bar ; $T_1 = 30 + 273 = 303$ K ;

$r_p = \frac{p_3}{p_1} = 5$ or $p_3 = 5 \times 1 = 5$ bar ;

$p_2 = 2.24$ bar ;

$T_3 = T_5 = 550 + 273 = 823$ K ;

$\eta_{comp.} = 80\%$,

$\eta_{T_1} = \eta_{T_2} = 85\%$; $c_{pa} = 1$ kJ/kg K ;

$c_{pg} = 1.15$ kJ/kg K ; γ (air) $= 1.4$;

γ (gases) $= 1.33$.

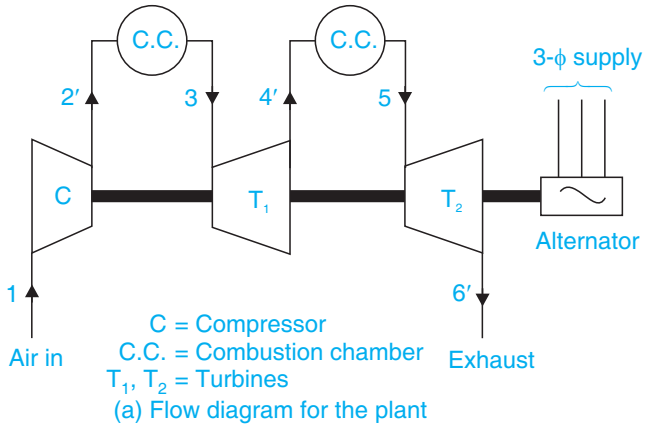
The schematic arrangement and its corresponding *T-s* diagram are shown in Fig. 5.63 (*a*) and (*b*) respectively.

Compressor :

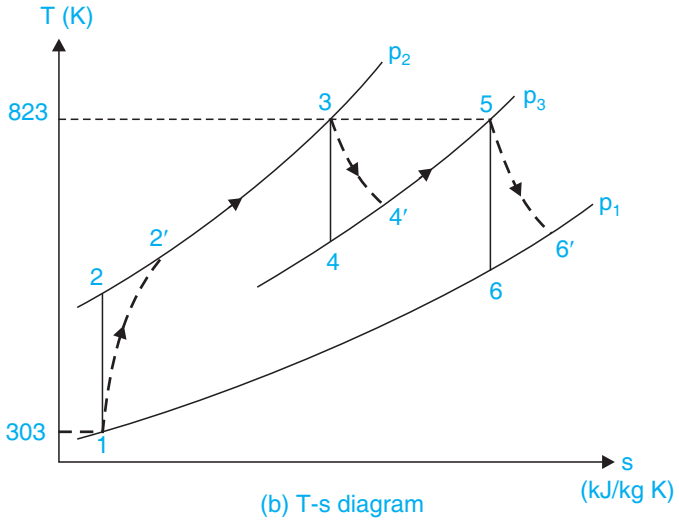
$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} = (5)^{\frac{1.4 - 1}{1.4}} = (5)^{0.2857} = 1.584$$

$$\therefore \quad T_2 = T_1 \times 1.584 = 303 \times 1.584 = 480 \text{ K}$$

$$\eta_{comp.} = 0.8 = \frac{T_2 - T_1}{T_{2'} - T_1} = \frac{480 - 303}{T_{2'} - 303}$$



(a) Flow diagram for the plant



(b) T-s diagram

Fig. 5.63

$$\therefore \quad T_{2'} = 303 + \frac{(480 - 303)}{0.8} = 524.2 \text{ K}$$

$$W_{comp.} = c_{pa}(T_{2'} - T_1) = 1.0(524.2 - 303)$$
$$= 221.2 \text{ kJ/kg}$$

Turbine, T_1 :

$$\frac{T_3}{T_4} = \left(\frac{p_2}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5}{2.24}\right)^{\frac{1.33-1}{1.33}}$$

$$= \left(\frac{5}{2.24}\right)^{0.2481} = 1.22$$

$$\therefore \quad T_4 = \frac{T_3}{1.22} = \frac{823}{1.22} = 674.6 \text{ K}$$

$$\eta_{T_1} = 0.85 = \frac{T_3 - T_{4'}}{T_3 - T_4} = \frac{823 - T_{4'}}{823 - 674.6}$$

$$\therefore \quad T_{4'} = 823 - 0.85(823 - 674.6) = 696.9 \text{ K}$$

Turbine, T_2 :

$$\frac{T_5}{T_6} = \left(\frac{p_3}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{2.24}{1}\right)^{\frac{1.33-1}{1.33}}$$
$$= (2.24)^{0.2481} = 1.22$$

$$\therefore \quad T_6 = \frac{T_5}{1.22} = \frac{823}{1.22} = 674.6 \text{ K}$$

$$\eta_{T_2} = 0.85 = \frac{T_5 - T_{6'}}{T_5 - T_6} = \frac{823 - T_{6'}}{823 - 674.6}$$

$$\therefore \quad T_{6'} = 823 - 0.85\,(823 - 674.6) = 696.9 \text{ K}$$

$$\therefore \quad (W_{\text{turbine}})_{\text{total}} = 2\, c_{pg}\,(T_3 - T_{4'}) \quad \text{as} \quad T_3 = T_5$$

and $T_{4'} = T_{6'}$

$$= 2 \times 1.15\,(823 - 696.9)$$
$$= 290 \text{ kJ/kg}$$

$$\therefore \quad W_{\text{net}} = (W_{\text{turbine}})_{\text{total}} - W_{\text{comp.}}$$
$$= 290 - 221.2 = 68.8 \text{ kJ/kg}$$

(*i*) The mass flow rate of air, $\dot{m}_a$:

Power developed $= \dot{m}_a \times W_{\text{net}}$

$$5 \times 10^3 = \dot{m}_a \times 68.8$$

$$\therefore \quad \dot{m}_a = \frac{5 \times 10^3}{68.8} = \mathbf{72.67\ kg/s.} \quad \textbf{(Ans.)}$$

(*ii*) Overall efficiency, η_{overall} :

Heat supplied, $Q_s = c_{pg}\,(T_3 - T_{2'}) + c_{pg}(T_5 - T_{4'})$
$= 1.15\,[(823 - 524.2)$
$+ (823 - 696.9)] = 488.6 \text{ kJ/kg}$

$$\therefore \quad \eta_{\text{overall}} = \frac{W_{\text{net}}}{\text{Heat supplied } (Q_s)}$$

$$= \frac{68.8}{488.6}$$

$$= 0.1408 \quad \text{or} \quad \mathbf{14.08\%.} \quad \textbf{(Ans.)}$$

Example 5.17. *The following data refer to a gas turbine plant in which the compression is carried out in one stage and expansion is carried out in two stages with reheating to the original temperature.*

Capacity of the gas turbine plant	*= 6 MW*
Temperature at which air is supplied	*= 20°C*
Suction and exhaust pressure	*= 1 bar*
Pressure ratio	*= 6*
Maximum temperature limit	*= 750°C*
Isentropic efficiency of compressor	*= 80 per cent*
Isentropic efficiency of each turbine	*= 84 per cent*
Effectiveness of heat exchanger	*= 0.72*
Calorific value of fuel	*= 18500 kJ/kg*

c_{pa} = 1 kJ/kg K ; c_{pg} = 1.15 kJ/kg K ;
γ (air) = 1.4, γ(gas) = 1.33.

Determine the following :

(i) A/F ratio entering in the first turbine, and

(ii) Thermal efficiency of the cycle,

(iii) Air supplied to the plant,

(iv) Fuel consumption of the plant per hour.

Solution. *Given :* Capacity of the plant = 6 MW ;

$T_1 = 20 + 273 = 293$ K ; $p_1 = 1$ bar ;

$r_p = \dfrac{p_3}{p_1} = 6$ or $p_3 = 6$ bar ;

$T_4 = T_5 = 750 + 273 = 1023$ K ;

$\eta_{comp.} = 80\%$, $\eta_{T_1} = \eta_{T_2} = 84\%$;

$\in = 0.72$, $C = 18500$ kJ/kg ;

$c_{pa} = 1$ kJ/kg K ; $c_{pg} = 1.15$ kJ/kg K ;

γ(air) = 1.4 ; γ(gas) = 1.33.

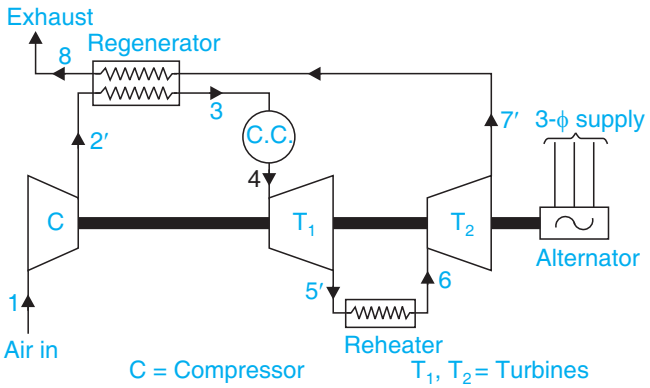
The schematic arrangement of the gas turbine plant and its corresponding *T-s* diagram are shown in Fig. 5.64 (*a*) and (*b*) respectively.

$$p_2 = \sqrt{p_3 \times p_1} = \sqrt{6 \times 1} = 2.45 \text{ bar}$$

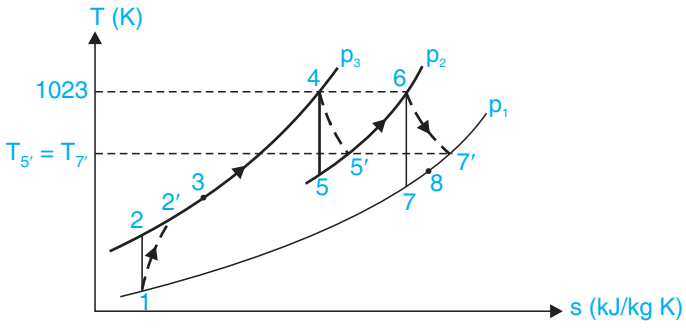
Compressor :

$$\frac{T_2}{T_1} = \left(\frac{p_3}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} = (6)^{\frac{1.4 - 1}{1.4}}$$

$$= (6)^{0.2857} = 1.668$$



(a) Schematic arrangement of the gas turbine plant



(b) T-s diagram

Fig. 5.64

$$\therefore \quad T_2 = T_1 \times 1.668 = 293 \times 1.668 = 488.7 \text{ K}$$

$$\eta_{comp.} = 0.8 = \frac{T_2 - T_1}{T_{2'} - T_1} = \frac{488.7 - 293}{T_{2'} - 293}$$

$$\therefore \quad T_{2'} = 293 + \frac{488.7 - 293}{0.8} = 537.6 \text{ K}$$

Turbine-1

$$\frac{T_4}{T_5} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma - 1}{\gamma}} = \left(\frac{6}{2.45}\right)^{\frac{1.33 - 1}{1.33}}$$

$$= (2.45)^{0.2481} = 1.249$$

$$\therefore \quad T_5 = \frac{T_4}{1.249} = \frac{1023}{1.249} = 819 \text{ K}$$

$$\eta_{T_1} = 0.84 = \frac{T_4 - T_{5'}}{T_4 - T_5} = \frac{1023 - T_{5'}}{1023 - 819}$$

$$\therefore \quad T_{5'} = 1023 - 0.84\,(1023 - 819) = 851.6 \text{ K}$$

$\eta_{T_1} = \eta_{T_2}$ (Given), $\therefore$ $T_{5'} = T_{7'} = 851.6$ K

Regenerator :

Effectiveness,

$$\in = 0.72 = \frac{T_3 - T_{2'}}{T_{7'} - T_{2'}} = \frac{T_3 - 537.6}{851.6 - 537.6}$$

$$\therefore \quad T_3 = 537.6 + 0.72\,(851.6 - 537.6)$$

$$= 763.7 \text{ K}$$

(*i*) A/F ratio entering in the first turbine :

Let m_{f_1} = Mass of fuel supplied per kg of air to the combustion chamber (and hence to the first turbine)

$$\therefore \quad (1 + m_{f_1})\, c_{pg}\, (T_4 - T_3) = m_{f_1} \times C$$

or $$(1 + m_{f_1}) \times 1.15\,(1023 - 763.7) = m_{f_1} \times 18500$$

or $$298.2\,(1 + m_{f_1}) = 18500\, m_{f_1}$$

$$\therefore \quad m_{f_1} = \frac{298.2}{(18500 - 298.2)}$$

$$= 0.01638 \text{ kg/kg of air}$$

$$\therefore \quad A/F \text{ ratio} = \frac{1}{0.01638} = \mathbf{61 : 1.} \quad \textbf{(Ans.)}$$

(*ii*) Thermal efficiency of the cycle, $\eta_{thermal}$:

Considering the flow with burning through the reheater, we have

$$(1 + m_{f_1} + m_{f_2})\, c_{pg}\, (T_6 - T_{5'}) = m_{f_2} \times C$$

where m_{f_2} is the fuel supplied in the reheater per kg of air entering into the compressor.

$$\therefore \quad (1 + 0.01638 + m_{f_2}) \times 1.15\,(1023 - 851.6)$$

$$= m_{f_2} \times 18500$$

or $$197.11(1.01638 + m_{f_2}) = 18500\, m_{f_2}$$

or $$200.34 + 197.11\, m_{f_2} = 18500\, m_{f_2}$$

$$\therefore \quad m_{f_2} = \frac{200.34}{(18500 - 197.11)}$$

$$= 0.0109 \text{ kg/kg of air}$$

$$\therefore \quad W_{comp.} = 1 \times c_{pa}(T_{2'} - T_1) = 1 \times 1 \times (537.6 - 293)$$
$$= 244.6 \text{ kJ/kg of air}$$

$$W_{\text{Turbine (total)}} = W_{T_1} + W_{T_2}$$
$$= (1 + m_{f_1})\, c_{pg}\, (T_4 - T_{5'}) + (1 + m_{f_1} + m_{f_2})\, c_{pg}\, (T_6 - T_{7'})$$
$$= (1 + 0.01638) \times 1.15(1023 - 851.6) + (1 + 0.01638 + 0.0109) \times 1.15(1023 - 851.6)$$
$$= 1.15(1023 - 851.6)\,[(1 + 0.01638) + (1 + 0.01638 + 0.0109)]$$
$$= 402.8 \text{ kJ/kg of air.}$$

$$W_{net} = W_{\text{turbine (total)}} - W_{comp.}$$
$$= 402.8 - 244.6 = 158.2 \text{ kJ/kg of air}$$

$$\therefore \quad \eta_{thermal} = \frac{W_{net}}{\text{Heat supplied } (Q_s)} = \frac{W_{net}}{(m_{f_1} + m_{f_2}) \times C}$$
$$= \frac{158.2}{(0.01638 + 0.0109) \times 18500}$$
$$= 0.3135 \quad \text{or} \quad \mathbf{31.35\%.} \quad \textbf{(Ans.)}$$

(*iii*) Air supplied to the plant, m_a :

$$m_a \times W_{net} = 6 \times 1000$$

$$\therefore \quad m_a = \frac{6000}{W_{net}} = \frac{6000}{158.2} = \mathbf{37.93 \text{ kg/s.}} \quad \textbf{(Ans.)}$$

(*iv*) Fuel consumption of the plant per hour :

Fuel consumption of the plant per hour

$$= m_a(m_{f_1} + m_{f_2}) \times 3600$$
$$= 37.93(0.01638 + 0.0109) \times 3600$$
$$= \mathbf{3725 \text{ kg/h.}} \quad \textbf{(Ans.)}$$

Example 5.18. *An open cycle constant pressure gas turbine power plant of 1500 kW capacity comprises a single stage compressor and two turbines with regenerator. One turbine is used to run the compressor and other one runs the generator. Separate combustion chamber is used for each turbine. Air coming out from the regenerator is divided into two streams, one goes to compressor turbine and other to power turbine. The pressure and temperature of air entering the compressor are 1 bar and 25°C. The maximum temperature in the compressor turbine is 750°C and in power turbine is 800°C. The maximum pressure in the stream is 5 bar. The exhaust pressure of both turbine is 1 bar and both exhausts pass through the regenerator. The temperature of exhaust entering the regenerator is 475°C.*

Use the following data :

Isentropic efficiency of compressor ($\eta_{comp.}$) *= 82 per cent*

Isentropic efficiency of compressor turbine (η_{T_1}) *= 84 per cent*

Isentropic efficiency of power turbine (η_{T_2}) *= 89 per cent*

Calorific value of fuel = 40500 kJ/kg

Combustion efficiency ($\eta_{comb.}$) *in both the combustion chambers = 94 per cent*

Mechanical efficiency ($\eta_{mech.}$) *for both the turbines = 89 per cent*

Effectiveness of regenerator ($\in$) *= 0.72*

$c_{pa} = 1.005$ *kJ/kg K* ; $c_{pg} = 1.1$ *kJ/kg K;*

γ*(for air)* $= 1.4$; γ*(for gases)* $= 1.35$

Neglecting pressure losses, heat losses and mass of fuel, determine :

(i) Plant efficiency,

(ii) Specific fuel consumption, and

(iii) Air fuel ratio.

Solution. *Given* : Capacity of the plant = 1500 kW ;

$p_1 = 1$ bar ; $T_1 = 25 + 273 = 298$ K ;

$T_4 = 750 + 273 = 1023$ K ;

$T_6 = 800 + 273 = 1073$ K ; $p_1 = 1$ bar ;

$p_2 = 5$ bar ;

$T_8 = 475 + 273 = 748$ K ; $\eta_{comp.} = 82\%$;

$\eta_{T_1} = 84\%$; $\eta_{T_2} = 89\%$;

$C = 40500$ kJ/kg ; $\eta_{comb.} = 94\%$;

$\eta_{mech} = 89\%$, $\in = 0.72$ $c_{pa} = 1.005$ kJ/kg K ;

$c_{pg} = 1.1$ kJ/kg K ; γ (for air) $= 1.4$;

γ (for gases) $= 1.35$.

The schematic arrangement of the plant and its corresponding *T-s* diagram are shown in Fig. 5.65 (*a*) and (*b*) respectively.

Compressor :

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} = \left(\frac{5}{1}\right)^{\frac{1.4 - 1}{1.4}} = (5)^{0.2857} = 1.584$$

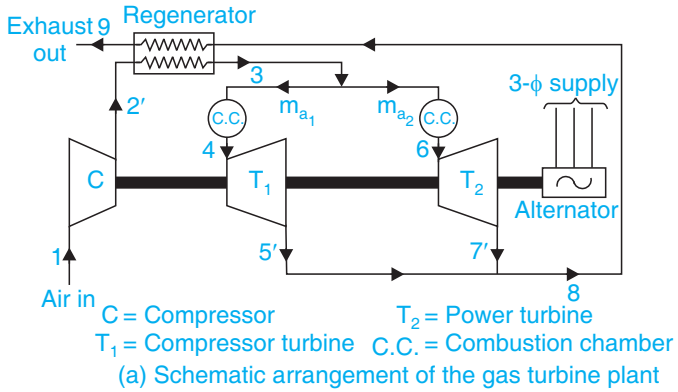
$$\therefore \quad T_2 = T_1 \times 1.584 = 298 \times 1.584 = 472 \text{ K}$$

$$\eta_{comp.} = 0.82 = \frac{T_2 - T_1}{T_{2'} - T_1} = \frac{472 - 298}{T_{2'} - 298}$$

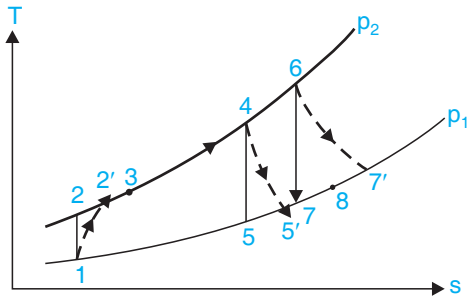
$$\therefore \quad T_{2'} = 298 + \frac{472 - 298}{0.82} = 510.2 \text{ K}$$

Compressor turbine :

$$\frac{T_4}{T_5} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} = (5)^{\frac{1.35 - 1}{1.35}}$$
$$= (5)^{0.2592} = 1.518$$



(a) Schematic arrangement of the gas turbine plant



(b) T-s diagram

Fig. 5.65

$$\therefore \quad T_5 = \frac{T_4}{1.518} = \frac{1023}{1.518} = 673.9 \text{ K}$$

$$\eta_{T_1} = 0.84 = \frac{T_4 - T_{5'}}{T_4 - T_5} = \frac{1023 - T_{5'}}{1023 - 673.9}$$

$$\therefore \quad T_{5'} = 1023 - 0.84(1023 - 673.9) = 729.7 \text{ K}$$

Power Turbine :

$$\frac{T_6}{T_7} = \left(\frac{p_2}{p_1}\right)^{\frac{1.35-1}{1.35}} = (5)^{0.2592} = 1.518$$

$$\therefore \quad T_7 = \frac{T_6}{1.518} = \frac{1073}{1.518} = 706.8 \text{ K}$$

$$\eta_{T_2} = 0.89 = \frac{T_6 - T_{7'}}{T_6 - T_7} = \frac{1073 - T_{7'}}{1073 - 706.8}$$

$$\therefore \quad T_{7'} = 1073 - 0.89(1073 - 706.8) = 747.1 \text{ K}$$

Let, m_{a_1} = Mass of air passing through the compressor turbine, and

m_{a_2} = Mass of air passing through the power turbine.

Then, power output of the power turbine is given by :

$$m_{a_2} \times c_{pg} (T_6 - T_{7'}) \times \eta_{\text{mech.}} \times \eta_{\text{gen.}} = 1500$$

or $$m_{a_2} \times 1.1\,(1073 - 747.1) \times 0.89 \times 1 = 1500$$

$$\therefore \quad m_{a_2} = 4.7 \text{ kg/s}$$

Power developed by the compressor turbine = Power absorbed by the compressor

$$\therefore \quad m_{a_1} \times c_{pg}(T_4 - T_5') \times \eta_{\text{mech.}} = (m_{a_1} + m_{a_2}) \times c_{pa}(T_2' - T_1)$$

or $$m_{a_1} \times 1.1(1023 - 729.7) \times 0.89 = (m_{a_1} + 4.7) \times 1.005(510.2 - 298)$$

$$287.1\, m_{a_1} = (m_{a_1} + 4.7) \times 213.26$$

$$\therefore \quad m_{a_1} = \frac{4.7 \times 213.26}{(287.1 - 213.26)} = 13.57 \text{ kg/s}$$

The exhaust gases of both turbines are mixed before entering into the regenerator. Therefore, the temperature of the gases entering into the regenerator is designated by the point 8 on the *T-s* diagram and it is given by:

$$m_{a_1} \times c_{pg} \times T_5' + m_{a_2} \times c_{pg} \times T_{7'} = (m_{a_1} + m_{a_2}) \times c_{pg} \times T_8$$

where, T_8 is the temperature after mixing.

$$\therefore \quad T_8 = \left(\frac{m_{a_1}}{m_{a_1} + m_{a_2}}\right) \times T_{5'} + \left(\frac{m_{a_2}}{m_{a_1} + m_{a_2}}\right) \times T_{7'}$$

$$= \left(\frac{13.57}{13.57 + 4.7}\right) \times 729.7 + \left(\frac{4.7}{13.57 + 4.7}\right) \times 747.1$$

$$= 541.98 + 192.19 = 734.2 \text{ K}$$

Regenerator :

Effectiveness, $$\in = 0.72 = \frac{m_a\, c_{pa}\, (T_3 - T_{2'})}{m_g\, c_{pg}\, (T_8 - T_{2'})}$$

or $$0.72 = \frac{c_{pa}\, (T_3 - T_{2'})}{c_{pg}\, (T_8 - T_{2'})}$$

($\because \quad m_a = m_g$, as fuel mass is neglected)

$$= \frac{1.005\,(T_3 - 510.2)}{1.1\,(748 - 510.2)}$$

or $$T_3 = 510.2 + \frac{0.72 \times 1.1\,(748 - 510.2)}{1.005} = 697.6 \text{ K}$$

Combustion chambers :

Total heat supplied in both combustion chambers

$$= c_{pg}\, m_{a_1} (T_4 - T_3) + c_{pg}\, m_{a_2} (T_6 - T_3)$$

$$= m_f \times C \times \eta_{\text{comb.}}$$

or $$1.1[13.57(1023 - 697.6) + 4.7(1073 - 697.6)] = m_f \times 40500 \times 0.94$$

$$1.1(4415.68 + 1764.38) = 38070 \times m_f$$

$$\therefore \quad m_f = 0.178 \text{ kg/s}$$

***(i)* Plant efficiency :**

$$\text{Plant efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{1500}{0.178 \times 40500}$$

$$= 0.208 \quad \text{or} \quad \mathbf{20.8\%}. \quad \textbf{(Ans.)}$$

(ii) Specific fuel consumption :

Specific fuel consumption

$$= \frac{0.178 \times 3600}{1500} = \mathbf{0.427\ kg/kWh.} \quad \textbf{(Ans.)}$$

(iii) Air-fuel (A/F) ratio :

$$\text{A/F ratio} = \frac{m_{a_1} + m_{a_2}}{m_f} = \frac{13.57 + 4.7}{0.178}$$

$$= \mathbf{102.64.} \quad \textbf{(Ans.)}$$

Example 5.19. *The air supplied to a gas turbine plant is 10 kg/s. The pressure ratio is 6 and pressure at the inlet of the compressor is 1 bar. The compressor is two-stage and provided with perfect intercooler. The inlet temperature is 300 K and maximum temperature is limited to 1073 K.*

Take the following data :

Isentropic efficiency of compressor each stage ($\eta_{comp.}$) = 80%

Isentropic efficiency of turbine ($\eta_{turbine}$) = 85%

A regenerator is included in plant whose effectiveness is 0.7. Neglecting the mass of fuel, determine the thermal efficiency of the plant.

Take c_p *for air = 1.005 kJ/kg K.* **(P.U.)**

Solution. *Given :* $\dot{m}_a = 10$ kg/s ;

$r_p = 6, p_1 = 1$ bar ;

$T_1 = 300$ K ; $T_6 = 1073$ K ;

$\eta_{comp.} = 80\%$; $\eta_{turbine} = 85\%$; $\in = 0.7$.

The schematic arrangement of the gas turbine plant and its corresponding *T-s* diagram are shown in Fig. 5.66(*a*) and (*b*) respectively. As the cooling is perfect,

$$p_2 = \sqrt{p_1 p_3} = \sqrt{1 \times 6} = 2.45 \text{ bar}$$

$$\left[\because\ r_p = 6 = \frac{p_3}{p_1} = \frac{p_3}{1} \text{ or } p_3 = 6 \text{ bar}\right]$$

Considering *isentropic compression in L.P. compressor*, we have :

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{2.45}{1}\right)^{\frac{1.4-1}{1.4}} = 1.29$$

$$\therefore\ T_2 = T_1 \times 1.29 = 300 \times 1.29 = 387 \text{ K}$$

Also, $\eta_{comp.(L.P.)} = 0.8 = \dfrac{T_2 - T_1}{T_2' - T_1} = \dfrac{387 - 300}{T_2' - 300}$

$$\therefore\quad T_{2'} = 300 + \frac{387 - 300}{0.8} = 408.7 \text{ K}$$

$$\therefore\quad W_{comp.(L.P.)} = 1 \times c_{pa}(T_2' - T_1) \text{ per kg of air}$$

$$= 1 \times 1.005(408.7 - 300)$$

$$= 109.2 \text{ kJ/kg}$$

Since *intercooling is perfect*, therefore,

$$W_{comp.(L.P.)} = W_{comp.\ (H.P.)}$$

$\therefore$ Total compressor work,

$$W_{comp.\ (total)} = 2 \times 109.2 = 218.4 \text{ kJ/kg}$$

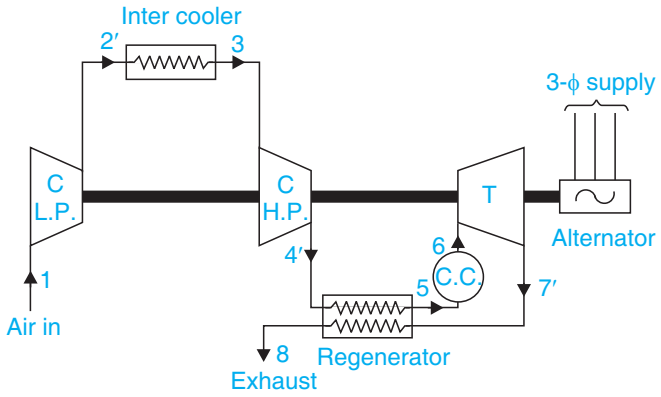
As $T_3 = T_1$

and $r_p = \dfrac{p_2}{p_1} = \dfrac{p_3}{p_2}$ (for perfect intercooling)

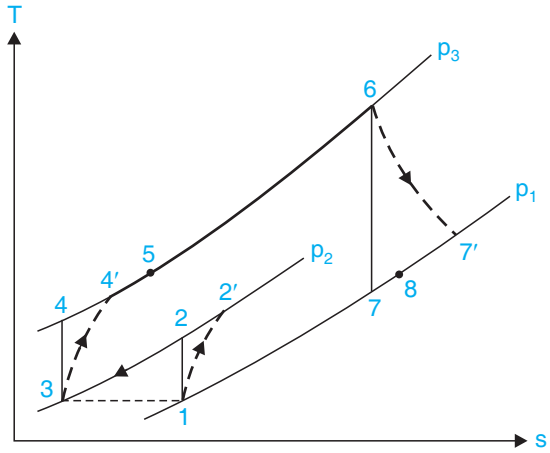
$\therefore\quad T_{4'} = T_{2'} = 408.7$ K

Considering *isentropic expansion in the turbine*, we have

$$\frac{T_6}{T_7} = \left(\frac{p_3}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = (6)^{\frac{1.4-1}{1.4}} = 1.668$$



(a) Schematic arrangement of the gas turbine plant



(b) T-s diagram

Fig. 5.66

$$\therefore\quad T_7 = \frac{T_6}{1.668} = \frac{1073}{1.668} = 643.3 \text{ K}$$

Also, $\eta_{turbine} = 0.85\ \dfrac{T_6 - T_{7'}}{T_6 - T_7} = \dfrac{1073 - T_{7'}}{1073 - 643.3}$

or $T_{7'} = 1073 - 0.85(1073 - 643.3)$

$= 707.7$ K

$$\therefore \quad W_{\text{turbine}} = c_{pa}(T_6 - T_{7'}) = 1.005(1073 - 707.7)$$
$$= 367.1 \text{ kJ/kg}$$

The effectiveness (ϵ) of *regenerator* is given by,

$$\epsilon = 0.7 = \frac{T_5 - T_{4'}}{T_{7'} - T_{4'}} = \frac{T_5 - 408.7}{707 - 408.7}$$

$$T_5 = 408.7 + 0.7(707 - 408.7) = 617.5 \text{ K}$$

Heat supplied in the combustion chamber,

$$Q_s = 1 \times c_{pa}(T_6 - T_5)$$
$$= 1 \times 1.005(1073 - 617.5)$$
$$= 457.77 \text{ kJ/kg}$$

$$W_{\text{net}} = W_{\text{turbine}} - W_{\text{comp.}}$$
$$= 367.1 - 218.4 = 148.7 \text{ kJ/kg}$$

$$\therefore \quad \eta_{\text{thermal}} = \frac{W_{\text{net}}}{Q_s} = \frac{148.7}{457.77}$$
$$= 0.3248 \quad \text{or} \quad \mathbf{32.48\%}. \quad \textbf{(Ans.)}$$

Example 5.20. *A gas turbine plant consists of one turbine as compressor drive and other to drive a generator. Each turbine has its own combustion chamber getting air directly from the compressor. Air enters the compressor at 1 bar 15°C and compressed with isentropic efficiency of 76 per cent. The gas inlet pressure and temperature in both the turbines are 5 bar and 680°C respectively. Take isentropic efficiency of both the turbines as 86 per cent. The mass flow rate of air entering compressor is 23 kg/s. The calorific value of the fuel is 42000 kJ/kg. Determine the, power output and thermal efficiency of the plant.*

Take, $c_{pa} = 1.005$ *kJ/kg K, and* $\gamma_{air} = 1.4$;
$c_{pg} = 1.128$ *kJ/kg K, and* $\gamma_{gas} = 1.34$

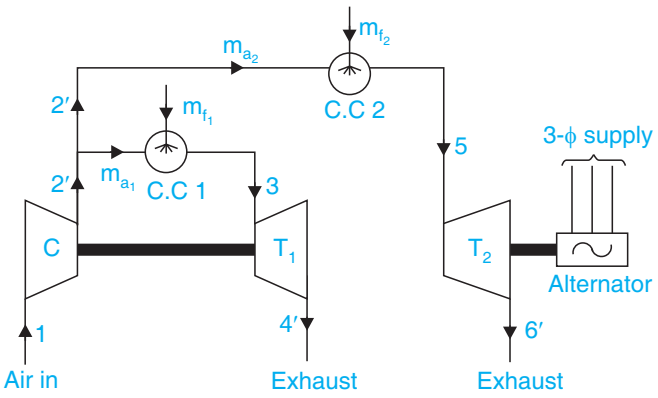
(P.U.)

Solution. *Given* : $p_1 = 1$ bar,
$T_1 = 15 + 273 = 288$ K ;
$p_2 = 5$ bar,
$T_3 = T_5 = 680 + 273 = 953$ K ;
$\eta_{\text{comp.}} = 76\%$; $\eta_{T_1} = \eta_{T_2} = 86\%$;
$m_a\ (= m_{a_1} + m_{a_2}) = 23$ kg/s ;
$C = 42000$ kJ/kg ;
$c_{pa} = 1.005$ kJ/kg K ;
$c_{pg} = 1.128$ kJ/kg K ;
$\gamma_{\text{air}} = 1.4$; $\gamma_{\text{gas}} = 1.34$.

The schematic arrangement of the plant and its corresponding T-s diagrams (separately for $C - T_1$ and $C - T_2$) are shown in Fig. 5.67 (a) and (b) respectively.

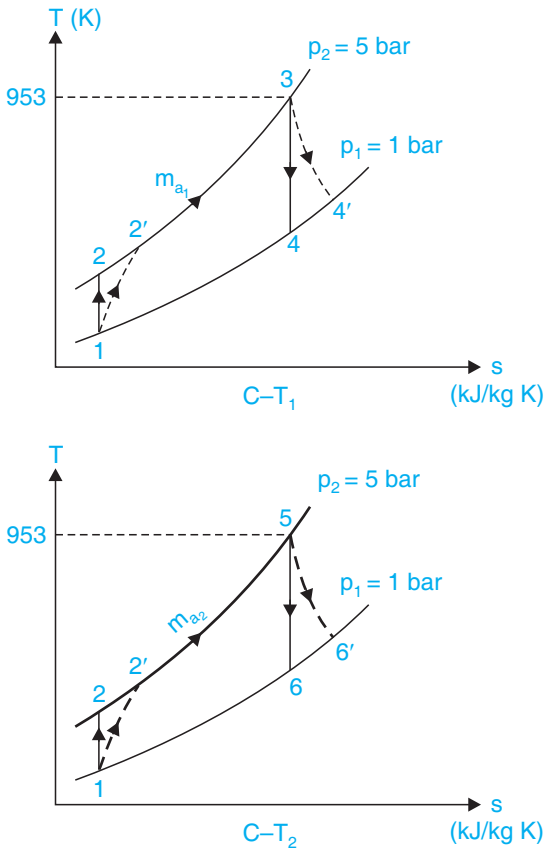
Compressor-Turbine-1 (C – T_1) :

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} = (5)^{\frac{1.4 - 1}{1.4}}$$
$$= (5)^{0.2857} = 1.584$$



C = Compressor
T_1, T_2 = Turbines
C.C 1, C.C 2 = Combustion chambers

(a) Schematic arrangement of the plant



(b) T-s diagrams

Fig. 5.67

$$\therefore \quad T_2 = T_1 \times 1.584 = 288 \times 1.584 = 456.2 \text{ K}$$

$$\eta_{\text{comp.}} = 0.76 = \frac{T_2 - T_1}{T_{2'} - T_1} = \frac{456.2 - 288}{T_{2'} - 288}$$

$$\therefore \quad T_{2'} = 288 + \frac{456.2 - 288}{0.76} = 509.3 \text{ K}$$

Let m_{f_1} = Fuel supplied in *C*. $C - 1$

Then, $m_{f_1} \times C = (m_{a_1} + m_{f_1}) \times c_{pg}(T_3 - T_{2'})$

or $$C = \left(\frac{m_{a_1}}{m_{f_1}} + 1\right) \times c_{pg}(T_3 - T_{2'})$$

or $$42000 = \left(\frac{m_{a_1}}{m_{f_1}} + 1\right) \times 1.128(953 - 509.3)$$

$$\therefore \quad \frac{m_{a_1}}{m_{f_1}} = \frac{42000}{1.128\,(953 - 509.3)} - 1 = 82.92$$

Also, $$\frac{T_3}{T_4} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} = (5)^{\frac{1.34 - 1}{1.34}} = (5)^{0.254} = 1.5$$

$$\therefore \quad T_4 = \frac{T_3}{1.5} = \frac{953}{1.5} = 635.3 \text{ K}$$

$$\eta_{T_1} = 0.86 = \frac{T_3 - T_{4'}}{T_3 - T_4} = \frac{953 - T_{4'}}{953 - 635.3}$$

$$\therefore \quad T_{4'} = 953 - 0.86(953 - 635.3) = 679.8 \text{ K}$$

Now, the work required to run the compressor must be *equal to* the work developed by T_1.

$$\therefore \quad m_a \times c_{pa}(T_{2'} - T_1) = (m_{a_1} + m_{f_1}) \times c_{pg}(T_3 - T_{4'})$$

$$= m_{f_1}\left(\frac{m_{a_1}}{m_{f_1}} + 1\right) \times c_{pg}(T_3 - T_{4'})$$

or $$23 \times 1.005(509.3 - 288) = m_{f_1}\,(82.92 + 1) \times 1.128(953 - 679.8)$$

or $$5115.35 = 25861.6\, m_{f_1}$$

$$\therefore \quad m_{f_1} = \frac{5115.35}{25861.6} = 0.198 \text{ kg/s}$$

$$\therefore \quad m_{a_1} = 82.92 \times 0.198 = 16.42 \text{ kg/s}$$

and $$m_{a_2} = m_a - m_{a_1} = 23 - 16.42 = 6.58 \text{ kg/s}$$

Compressor-turbine-2 (C – T_2) :

Work developed by the turbine T_2,

$$W_{T_2} = (m_{a_2} + m_{f_2}) \times c_{pg}(T_5 - T_{6'}) \qquad ...(i)$$

Considering the combustion chamber of turbine T_2, we can write

$$m_{f_2} \times C = (m_{a_2} + m_{f_2}) \times c_{pg}(T_5 - T_{2'})$$

or $$m_{f_2} \times 42000 = (6.58 + m_{f_2}) \times 1.128(953 - 509.3)$$

$$= 500.49(6.58 + m_{f_2})$$

$$= 3293.22 + 500.49\, m_{f_2}$$

$$\therefore \quad m_{f_2} = \frac{3293.22}{(42000 - 500.49)} = 0.079 \text{ kg/s}$$

$$\left(\text{or } \frac{m_{a_2}}{m_{f_2}} = \frac{6.58}{0.079} = 83.3\right)$$

Substituting the values in eqn. (*i*), we get

$$W_{T_2} = (6.58 + 0.079) \times 1.128(953 - 679.8)$$

($\because$ $T_{6'} = T_{4'}$ as per given conditions)

$$= \mathbf{2052.1\ kJ/s.} \quad \textbf{(Ans.)}$$

The capacity of turbine T_2 to run the compressor,

$$W_{T_1} = m_{a_1} \times c_{pa}(T_{2'} - T_1)$$

$$= 16.42 \times 1.005(509.3 - 288)$$

$$= 3651.9 \text{ kJ/s}$$

Total fuel consumed,

$$m_f = m_{f_1} + m_{f_2}$$

$$= 0.198 + 0.079 = 0.277 \text{ kg/s}$$

$\therefore$ Thermal efficiency of the plant,

$$\eta_{\text{thermal}} = \frac{W_{T_2}}{m_f \times C}$$

$$= \frac{2052.1}{0.277 \times 42000}$$

$$= 0.1764 \quad \text{or} \quad \mathbf{17.64\%.} \quad \textbf{(Ans.)}$$

Example 5.21. *A gas turbine plant consists of two-stage compressor with intercooler and it is driven by a separate turbine. The gases coming out from first turbine are passed to the power turbine after reheating to the temperature which is equal to the temperature at the inlet of the compressor turbine. The power turbine generates the electrical energy. A regenerator is used for heating the air before entering into the combustion chamber by using the exhaust gases coming out of power turbine.*

Use the following data :

Ambient air temperature and pressure
= *15°C, 1 bar*

Maximum cycle temperature
= *1000 K*

Air mass flow = *20 kg/s*

Isentropic efficiency of each compressor
= *80 per cent*

Insentropic efficiencies of turbines :
η_{T_1} = *87%* ; η_{T_2} = *80%*

Pressure drop in intercooler
= *0.07 bar*

Pressure drop in regenerator (H.E.)
= *0.1 bar in each side*

Effectiveness of heat exchanger
= *0.75*

Pressure drop in combustion chamber
= *0.15 bar*

Pressure drop in reheater
= *0.1 bar*

Mechanical efficiency for compressor-turbine
= *99%*

Combustion efficiency (in combustion chamber and reheater) $= 98\%$

Compression ratio of each stage of compressor $= 2 : 1$

Calorific value of fuel used $= 43500\ kJ/kg$

$c_{pa} = 1\ kJ/kg\ K$; $c_{pg} = 1.1\ kJ/kg\ K$,

$\gamma_{air} = 1.4$; $\gamma_{gas} = 1.33$.

Assuming perfect intercooling, determine :

(i) Net output of plant,

(ii) Specific fuel consumption of the plant, and

(iii) Overall efficiency of the plant. **(K.U.)**

Solution. *Given* : $T_1 = 15 + 273 = 288$ K ; $p_1 = 1$ bar ;

$T_6 = T_8 = 1000$ K ; $m_a = 20$ kg/s ;

$\eta_{C_1} = \eta_{C_2} = 80\%$; $\eta_{T_1} = 87\%$; $\eta_{T_2} = 80\%$;

$(\Delta p)_{\text{intercooler}} = 0.07$ bar ;

$(\Delta p)_{\text{regenerator}} = 0.1$ bar in each side ; $\in = 0.75$;

$(\Delta p)_{C.C.} = 0.15$ bar ; $(\Delta p)_{\text{reheater}} = 0.1$ bar ;

$\eta_{\text{mech}(T_1)} = 99\%$;

$\eta_{\text{comb. (C.C. and reheater)}} = 98\%$; $(r_p)_{C_1, C_2} = 2 : 1$;

$C = 43500$ kJ/kg ;

$c_{pa} = 1$ kJ/kg K ;

$c_{pg} = 1.1$ kJ/kg K ; $\gamma_{\text{air}} = 1.4$;

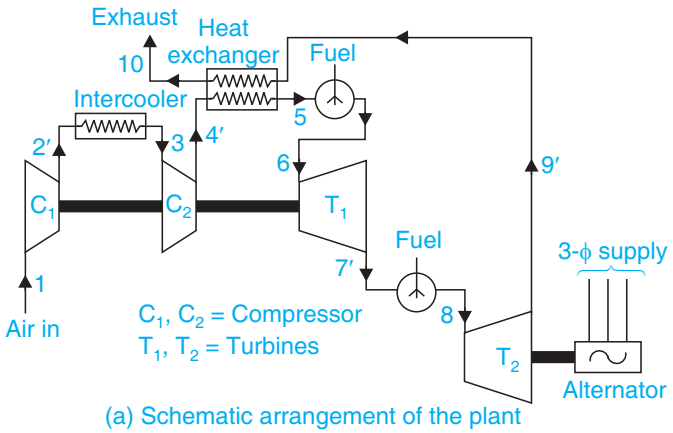
$\gamma_{\text{gas}} = 1.33$

The schematic arrangement of the gas turbine plant and its corresponding *T-s* diagram are shown in Fig. 5.68 (*a*) and (*b*) respectively.

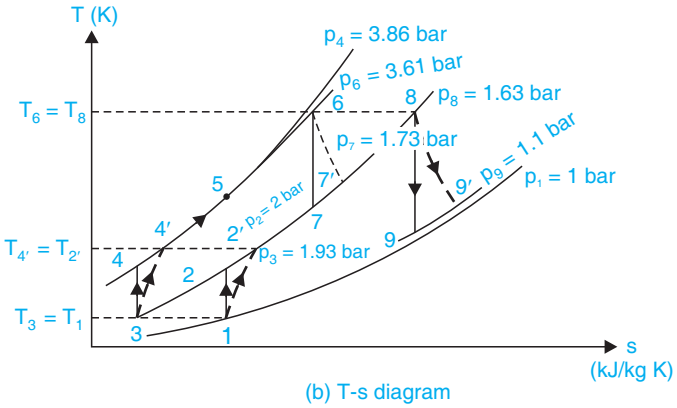
As for given data, we have :

$p_1 = 1$ bar, $\quad p_2 = 2$ bar as $\dfrac{p_2}{p_1} = 2$ (Given)

$p_3 = p_2 - (\Delta p)_{\text{intercooler}} = 2 - 0.07 = 1.93$ bar



(a) Schematic arrangement of the plant



(b) T-s diagram

Fig. 5.68

$p_4 = 2p_3 = 2 \times 1.93 = 3.86$ bar

$[\because (r_p)_{C_1, C_2} = 2 : 1]$

$p_6 = p_4 - (\Delta_p)_{\text{H.E. air side}} - (\Delta p)_{C.C}$

$= 3.86 - 0.1 - 0.15 = 3.61$ bar

p_7 is to be calculated

$p_8 = p_7 - (\Delta p)_{\text{reheater}}$

$p_9 = 1 + (\Delta p)_{\text{H.E. gas side}} = 1 + 0.1 = 1.1$ bar

Compressor C_1 :

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} = \left[(r_p)_{C_1}\right]^{\frac{\gamma - 1}{\gamma}} = (2)^{\frac{1.4 - 1}{1.4}}$$

$$= (2)^{0.2857} = 1.22$$

$$\therefore \quad T_2 = T_1 \times 1.22 = 288 \times 1.22 = 351.36 \text{ K}$$

$$\eta_{C_1} = 0.8 = \frac{T_2 - T_1}{T_{2'} - T_1} = \frac{351.36 - 288}{T_{2'} - 288}$$

$$\therefore \quad T_{2'} = 288 + \frac{351.36 - 288}{0.8} = 367.2 \text{ K}$$

Compressor C_2 :

Since the *intercooling is perfect* therefore,

$T_1 = T_3 = 288$ K, and

$T_{2'} = T_{4'} = 367.2$ K

$[\because \ (r_p)_{C_1} = (r_p)_{C_2} = 2 : 1]$

$\therefore$ The power required to run the compressors

$= m_a\, c_{pa}(T_{2'} - T_1) + m_a\, c_{pa}(T_{4'} - T_3)$

$= 2 \times m_a\, c_{pa}(T_{2'} - T_1)$

$[\because \quad T_1 = T_3 \quad \text{and} \quad T_{2'} = T_{4'}]$

$= 2 \times 20 \times 1(367.2 - 288) = 3168$ kW

Compressor turbine :

Power developed by the compressor turbine,

$$W_{T_1} = \frac{3168}{\eta_{\text{mech}}} = \frac{3168}{0.99} = 3200 \text{ kW}$$

∴ Work developed by the compressor turbine per kg of air

$$= \frac{3200}{20} = 160 \text{ kJ/kg}$$

The work developed by the compressor turbine per kg of air is given by

$$c_{pg}(T_6 - T_{7'}) = 160$$

$$\therefore \quad T_6 - T_{7'} = \frac{160}{1.1} = 145.45 \text{ K}$$

$$\frac{T_6}{T_7} = [(r_p)_{T_1}]^{\frac{\gamma - 1}{\gamma}}$$

$$\eta_{T_1} = \frac{T_6 - T_{7'}}{T_6 - T_7}$$

or $$T_6 - T_{7'} = \eta_{T_1}(T_6 - T_7)$$

or $$T_6 - T_{7'} = \eta_{T_1} \times T_6 \left(1 - \frac{T_7}{T_6}\right)$$

$$= \eta_{T_1} T_6 \left[1 - \frac{1}{\left\{(r_p)_{T_1}\right\}^{\frac{\gamma - 1}{\gamma}}}\right]$$

or $$T_6 - T_{7'} = 0.87 \times 1000 \left[1 - \frac{1}{\left\{(r_p)_{T_1}\right\}^{\frac{1.33 - 1}{1.33}}}\right]$$

or $$145.45 = 870 \left[1 - \frac{1}{\left\{(r_p)_{T_1}\right\}^{0.2481}}\right]$$

or $$0.167 = 1 - \frac{1}{\left\{(r_p)_{T_1}\right\}^{0.2481}}$$

$$\therefore \quad (r_p)_{T_1} = \left(\frac{1}{1 - 0.167}\right)^{\frac{1}{0.2481}} = 2.09$$

Also, $$(r_p)_{T_1} = 2.09 = \frac{p_6}{p_7}$$

$$\therefore \quad p_7 = \frac{p_6}{2.09} = \frac{3.61}{2.09} = 1.73 \text{ bar}$$

$$p_8 = p_7 - (\Delta p)_{\text{reheater}} = 1.73 - 0.1$$
$$= 1.63 \text{ bar}$$

$$(r_p)_{T_2} = \frac{p_8}{p_9} = \frac{1.63}{1.1} = 1.48$$

where $(r_p)_{T_1}$ and $(r_p)_{T_2}$ are the pressure ratios of the turbines T_1 and T_2.

Turbine T_2 :

$$\frac{T_8}{T_9} = \left(\frac{p_8}{p_9}\right)^{\frac{\gamma - 1}{\gamma}} = (1.48)^{\frac{1.33 - 1}{1.33}}$$
$$= (1.48)^{0.2481} = 1.1$$

$$\therefore \quad T_9 = \frac{T_8}{1.1} = \frac{1000}{1.1} = 909.1 \text{ K}$$

$$\eta_{T_2} = 0.8 = \frac{T_8 - T_{9'}}{T_8 - T_9} = \frac{1000 - T_{9'}}{1000 - 909.1}$$

$$\therefore \quad T_{9'} = 1000 - 0.8(1000 - 909.1) = 927.3 \text{ K}$$

(*i*) Net output of the plant :

The power output of the plant is only from turbine T_2.

∴ Net-output of the plant

$$= m_a \, c_{pa} \, (T_8 - T_{9'})$$
$$= 20 \times 1.0(1000 - 927.3)$$
$$= \mathbf{1454 \text{ kW.}} \quad \textbf{(Ans.)}$$

(*ii*) Specific fuel consumption of the plant :

The effectiveness of heat exchanger

$$\in = 0.75 = \frac{T_5 - T_{4'}}{T_{9'} - T_{4'}} = \frac{T_5 - 367.2}{927.3 - 367.2}$$

$$\therefore \quad T_5 = 367.2 + 0.75(927.3 - 367.2) = 787.3 \text{ K}$$

The total heat supplied in the plant per kg of air,

$$Q_s = c_{pg}(T_6 - T_5) + c_{pg}(T_8 - T_{7'})$$
$$= c_{pg}[(T_6 - T_{7'}) + (T_8 - T_5)]$$
$$= 1.1(145.45 + 1000 - 787.3) = 394 \text{ kJ/kg})$$

Assuming m_f is mass of fuel supplied per second in combustion chamber and reheater, then,

Heat developed = Heat-gained by air

$$m_f \times C \times \eta_{\text{comb.}} = 20 \times 394$$

or $$m_f \times 43500 \times 0.98 = 20 \times 394$$

$$\therefore \quad m_f = \frac{20 \times 394}{43500 \times 0.98} = 0.185 \text{ kg/s}$$
$$= 666 \text{ kg/h}$$

∴ Specific fuel consumption (s.f.c.)

$$= \frac{666}{1454} = \mathbf{0.458 \text{ kg/kWh.}} \quad \textbf{(Ans.)}$$

(*iii*) Overall efficiency of the plant, η_{overall} :

$$\eta_{\text{overall}} = \frac{\text{Output}}{\text{Input}}$$

$$= \frac{1454}{20 \times 394}$$

$$= 0.1845 \quad \text{or} \quad \mathbf{18.45\%.} \quad \textbf{(Ans.)}$$

HIGHLIGHTS

1. The major fields of application of gas turbines are :
   (*i*) Aviation (*ii*) Power generation
   (*iii*) Oil and gas industry (*iv*) Marine propulsion.
2. A gas turbine plant may be defined as one "in which the principal prime mover is of the turbine type and the working medium is a permanent gas".
3. A simple gas turbine plant consists of the following :
   (*i*) Turbine (*ii*) Compressor
   (*iii*) Combustor (*iv*) Auxiliaries.
   A modified plant may have in addition an *intercooler, a regenerator, a reheater* etc.
4. Methods for improvement of thermal efficiency of open cycle gas turbine plant are :
   (*i*) Intercooling (*ii*) Reheating
   (*iii*) Regeneration.
5. *Free-piston engine plants* are the conventional gas turbine plants with the difference that the air compressor and combustion chamber are replaced by a free piston engine.

THEORETICAL QUESTIONS

1. What are the major fields of application of gas turbine ?
2. State the limitations of gas turbines.
3. List the applications of gas turbine plants.
4. State the advantages and disadvantages of gas turbine power plants over diesel and thermal power plants.
5. What factors should be considered while selecting a site for a gas turbine power plant ?
6. Give the description of a simple gas turbine plant.
7. Explain with the help of a neat diagram the energy cycle for a simple-cycle gas turbine.
8. Define the following performance terms :
   Air ratio, Pressure ratio, Work ratio, Compressor efficiency, Engine efficiency, Machine efficiency, Combustion efficiency and Thermal efficiency.
9. How are gas turbine power plants classified ?
10. How are gas turbines classified ?
11. State the merits of gas turbines over I.C. engines and steam turbines. Discuss also the demerits over gas turbines.
12. Describe with neat sketches the working of a simple constant pressure open cycle gas turbine.
13. Discuss briefly the methods employed for improvement of thermal efficiency of open cycle gas turbine plant.
14. Describe with a neat diagram a closed cycle gas turbine. State also its merits and demerits.
15. Explain with a neat sketch the working of a constant volume combustion turbine.
16. Write a short note on fuels used for gas turbines.
17. What do you mean by "combination gas turbine cycles". Explain briefly combined gas turbine and steam power plants.
18. List the advantages of 'combined cycle'.
19. How is a gas turbine 'started' and 'shut down' ?
20. Explain with a neat sketch the layout of a gas turbine power plant.
21. Enumerate and explain briefly the components of a gas turbine power plant.
22. With the help of neat sketches give the working of a free-piston engine plant. State also the advantages and disadvantages of such an arrangement.

UNSOLVED EXAMPLES

1. In an air standard gas turbine engine, air at a temperature of 15°C and a pressure of 1.01 bar enters the compressor, where it is compressed through a pressure ratio of 5. Air enters the turbine at a temperature of 815°C and expands to original pressure of 1.01 bar. Determine the ratio of turbine work to compressor work and the thermal efficiency when the engine operates on ideal Brayton cycle.
   Take : $\gamma = 1.4$, $c_p = 1.005$ kJ/kg K. [**Ans.** 2.393 ; 37.03%]
2. In an open cycle constant pressure gas turbine air enters the compressor at 1 bar and 300 K. The pressure of air after the compression is 4 bar. The isentropic efficiencies of compressor and turbine are 78% and 85% respectively. The air-fuel ratio is 80 : 1. Calculate the power developed and thermal efficiency of the cycle if the flow rate of air is 2.5 kg/s.
   Take $c_p = 1.005$ kJ/kg K and $\gamma = 1.4$ for air and $c_{pg} = 1.147$ kJ/kg K and $\gamma = 1.33$ for gases.
   $R = 0.287$ kJ/kg K. Calorific value of fuel = 42000 kJ/kg.
   [**Ans.** 204.03 kW/kg of air ; 15.54%]
3. A gas turbine has a pressure ratio of 6/1 and a maximum cycle temperature of 600°C. The isentropic efficiencies of the compressor and turbine are 0.82 and 0.85 respectively. Calculate the power output in kilowatts of an electric generator geared to the turbine when the air enters the compressor at 15°C at the rate of 15 kg/s.
   Take : $c_p = 1.005$ kJ/kg K and $\gamma = 1.4$ for the compression process, and take $c_p = 1.11$ kJ/kg K and $\gamma = 1.333$ for the expansion process. [**Ans.** 920 kW]
4. Calculate the thermal efficiency and the work ratio of the plant in example 3(above), assuming that c_p for the combustion process is 1.11 kJ/kg K.
   [**Ans.** 15.8% ; 0.206]
5. The gas turbine has an overall pressure ratio of 5 : 1 and a maximum cycle temperature of 550°C. The turbine drives the compressor and an electric generator, the mechanical efficiency of the drive being 97%. The ambient temperature is 20°C and the isentropic efficiencies of the compressor and turbine are 0.8 and 0.83 respectively.

Calculate the power output in kilowatts for an air flow of 15 kg/s. Calculate also the thermal efficiency and the work ratio.

Neglect changes is kinetic energy, and the loss of pressure in combustion chamber. [**Ans.** 655 kW ; 12% ; 0.168]

6. Air is drawn in a gas turbine unit at 17°C and 101 bar and the pressure ratio is 8 : 1. The compressor is driven by the H.P. turbine and the L.P. turbine drives a separate power shaft. The isentropic efficiencies of the compressor, and the H.P. and L.P. turbines are 0.8, 0.85 and 0.83 respectively. Calculate the pressure and temperature of the gases entering the power turbine, the net power developed by the unit per kg/s of mass flow, the work ratio and the thermal efficiency of the unit. The maximum cycle temperature is 650°C.

For the compression process take

c_p = 1.005 kJ/kg K and γ = 1.4

For the combustion process and expansion process, take

c_p = 1.15 kJ/kg K and γ = 1.333

Neglect the mass of fuel.

[**Ans.** 1.65 bar, 393°C ; 74.5 kW, 0.201 ; 19.1%]

7. In a gas turbine plant, air is compressed through a pressure ratio of 6 : 1 from 15°C. It is then heated to the maximum permissible temperature of 750°C and expanded in two stages each of expansion ratio $\sqrt{6}$, the air being reheated between the stages to 750°C. An heat exchanger allows the heating of the compressed gases through 75 per cent of the maximum range possible. Calculate : (*i*) The cycle efficiency, (*ii*) The work ratio, (*iii*) The work per kg of air.

The isentropic efficiencies of the compressor and turbine are 0.8 and 0.85 respectively.

[**Ans.** (*i*) 32.75%; (*ii*) 0.3852; (*iii*) 152 kJ/kg]

8. At the design speed the following data apply to a gas turbine set employing the heat exchanger : Isentropic efficiency of compressor = 75%, isentropic efficiency of the turbine = 85%, mechanical transmission efficiency = 99%, combustion efficiency = 98%, mass flow = 22.7 kg/s, pressure ratio = 6 : 1, heat exchanger effectiveness = 75%, maximum cycle temperature = 1000 K.

The ambient air temperature and pressure are 15°C and 1.013 bar respectively. Calculate :

(*i*) The net power output,(*ii*) Specific fuel consumption, (*iii*) Thermal efficiency of the cycle.

Take the lower calorific value of fuel as 43125 kJ/kg and assume no pressure-loss in heat exchanger and combustion chamber.

[**Ans.** (*i*) 2019 kW; (*ii*) 0.4999 kg/kWh; (*iii*) 16.7%]

9. In a gas turbine plant air at 10°C and 1.01 bar is compressed through a pressure ratio of 4 : 1. In a heat exchanger and combustion chamber the air is heated to 700°C while its pressure drops 0.14 bar. After expansion through the turbine the air passes through a heat exchanger which cools the air through 75% of maximum range possible, while the pressure drops 0.14 bar, and the air is finally exhausted to atmosphere. The isentropic efficiency of the compressor is 0.80 and that of turbine 0.85. Calculate the efficiency of the plant. [**Ans.** 22.76%]

10. In a marine gas turbine unit a high-pressure stage turbine drives the compressor, and a low-pressure stage turbine drives the propeller through suitable gearing. The overall pressure ratio is 4 : 1, and the maximum temperature is 650°C. The isentropic efficiencies of the compressor, H.P. turbine, and L.P. turbine are 0.8, 0.83 and 0.85 respectively, and the mechanical efficiency of both shafts is 98%. Calculate the pressure between turbine stages when the air intake conditions are 1.01 bar and 25°C. Calculate also the thermal efficiency and the shaft power when the mass flow is 60 kg/s. Neglect kinetic energy changes, and pressure loss in combustion.

[**Ans.** 1.57 bar ; 14.9% ; 4560 kW]

11. In a gas turbine unit comprising L.P. and H.P. compressors, air is taken at 1.01 bar 27°C. Compression in L.P. stage is upto 3.03 bar followed by intercooling to 30°C. The pressure of air after H.P. compressor is 58.7 bar. Loss in pressure during intercooling is 0.13 bar. Air from H.P. compressor is transferred to heat exchanger of effectiveness 0.60 where it is heated by gases from L.P. turbine. The temperature of gases supplied to H.P. turbine is 750°C. The gases expand in H.P. turbine to 3.25 bar and are then reheated to 700°C before expanding in L.P. turbine. The loss of pressure in reheated is 0.1 bar. If isentropic efficiency of compression in both stages is 0.80 and isentropic efficiency of expansion in turbine is 0.85, calculate : (*i*) Overall efficiency, (*ii*) Work ratio, (*iii*) Mass flow rate when the gas power generated is 6500 kW. Neglect the mass of fuel.

Take, for air : c_p = 1.005 kJ/kg K, γ = 1.4

for gases : c_{pg} = 1.15 kJ/hr K, γ = 1.3.

[**Ans.** (*i*) 16.17% ; (*ii*) 0.2215 ; (*iii*) 69.33 kg of air/s]

12. In a gas turbine installation, air is taken in L.P. compressor at 15°C, 1.1 bar and after compression it is passed through intercooler where its temperature is reduced to 22°C. The cooled air is further compressed in H.P. unit and then passed in the combustion chamber where its temperature is increased to 677°C by burning the fuel. The combustion products expand in H.P. turbine which runs the compressor and further expansion is continued in the L.P. turbine which runs the alternator. The gases coming out from L.P. turbine are used for heating the incoming air from H.P. compressor and then exhausted to atmosphere.

Taking the following data determine :

(*i*) Power output (*ii*) Specific fuel consumption (*iii*) Thermal efficiency :

Pressure ratio of each compressor = 2, isentropic efficiency of each compressor stage = 85%, isentropic efficiency of each turbine stage = 85%, effectiveness of heat exchanger = 0.75, air flow = 15 kg/sec., calorific value of fuel = 45000 kJ/kg, c_p(for gas) = 1 kJ/kg K, c_p (for gas) = 1.15 kJ/kg K, γ (for air) = 1.4, γ (for gas) = 1.33.

Neglect the mechanical, pressure and heat losses of the system and fuel mass also.

[**Ans.** (*i*) 1849.2 kW ; (*ii*) 0.241 kg/kWh ; (*iii*) 33.17%]

COMPETITIVE EXAMINATIONS QUESTIONS

1. (*a*) With the help of a block-diagram, explain the working principles of a closed cycle gas turbine plant.
(*b*) Explain three important refinements by which the efficiency of a simple gas turbine plant can be improved considerably.
(*c*) What are the various fuels that are usually used for running gas turbines ?

2. (*a*) What are the advantages of a gas turbine plant over diesel and steam power plants of the same capacity ?
(*b*) What are the different components of a gas turbine plant ?
Explain them with the help of neat sketches.

3. (*a*) Draw a neat diagram of a regenerative gas turbine plant having intercooling and reheater. Explain the working on the *p-v* diagram.
(*b*) (*i*) Under what conditions the gas turbine plants have maximum utility ?
(*ii*) What are the disadvantages of gas turbine plants?
(*iii*) Why are gas turbine plants not so common in India ?

4. (*a*) What are the different fuels that are used for gas turbine power plants ? What are the most suitable fuels for gas turbine plants in a country like India ? Explain.
(*b*) Explain with the help of *T-s* chart and line diagram the working of a gas turbine plant. How can the efficiency of the plant be improved ?

5. (*a*) Describe with diagram the working of a closed cycle gas turbine plant.
(*b*) Describe methods of improving output and performance of gas turbine plants.

6. (*a*) State the advantages and disadvantages of gas turbine power plants.
(*b*) The following data refer to an open-cycle gas turbine plant. The compressor, turbine and electric generator are mounted on the same shaft :

Compressor pressure ratio	= 4 : 1
Isentropic efficiency of compressor	= 85%
Isentropic efficiency of the turbine	= 85%
Effectiveness of the heat exchanger	= 76%
Pressure loss in the combustion chamber	= 0.05 kgf/cm^2
Combustion efficiency	= 90%
Mechanical efficiency	= 95%
C.V. of fuel used	= 9,000 kcal/kg
Rate of air flow	= 20 kg/sec

Ambient pressure and temperature = kgf/cm^2 and 30°C
The maximum temperature of the cycle = 1000 K
$c_{p\ \text{air}}$ = .24, $c_{p\ \text{gas}}$ = 0.25, γ for air = γ for gas = 1.4.
Calculate : (*i*) Power output at the generator ; (*ii*) Overall efficiency of the plant ; (*iii*) Specific fuel consumption.

7. (*a*) Make a schematic diagram of a gas turbine power plant employing a regenerator, a reheater and an intercooler. Draw *T-s* diagram showing the above arrangement.
(*b*) The isentropic efficiency of a compressor in a simple gas turbine plant is 80% and that of the turbine unit is 85%. The air enters at 290 K and the maximum temperature in the cycle is 800°C, while the pressure rises from 1.25 kgf/cm^2 to 5.0 kgf/cm^2. Draw the cycle on *T-s* diagram and calculate the efficiency of the plant and the work ratio. Take γ = 1.4 and c_p = 0.24.

8. Calculate the η of an open cycle internal combustion turbine fitted with a heat exchanger of 75% effectiveness. The pressure ratio is 4 : 1 and compression is carried out in two stages of equal pressure ratio with intercooling back to initial temperature of 15°C. The maximum temperature is 650°C. The turbine isentropic η is 88% and each compressor isentropic η is 85%.
For air γ = 1.4 and c_p = 0.24.

9. (*a*) Discuss in brief the methods adopted for improving the thermal efficiency of simple gas turbine plant.
(*b*) A simple gas turbine plant draws in air at 1 kgf/cm^2 and 15°C and compresses it through a pressure ratio of 5 : 1, the isentropic efficiency of compression being 85%. The air passes to the combustion chamber and after combustion, gases enter the turbine at a temperature of 540°C and expand to 1 kgf/cm^2, the turbine efficiency being 80%.
Calculate the flow of air and gases for a net horse-power of 2,200 assuming that the loss of pressure through the combustion system is 0.07 kgf/cm^2. Take c_p = 0.25 for air and combustion gas and γ = 1.40. Neglect the addition of mass flow due to fuel.

10. (*a*) What do you understand by combination gas turbine plants ? What are their salient features ? Discuss briefly the popular systems.
(*b*) Describe briefly the working of different type of relays which are commonly used in power plants.

11. (*a*) What are the different methods used to improve output and performance of gas turbine plants ? Discuss.
(*b*) "Diesel power plants are used as stand by units in a grid system". Discuss.

12. Write short notes on the following :
(*a*) Solar power plants ;
(*b*) Switchgears ;
(*c*) Closed cycle gas turbine plant.

13. (*a*) Discuss in brief the availability of nuclear fuel in India.
(*b*) Distinguish between (*i*) fission and fusion, and (*ii*) fast neutrons and thermal neutrons.
(*c*) In a nuclear reactor, explain the functions of :
(*i*) Moderator ; (*ii*) Coolant ;
(*iii*) Control rod ; (*iv*) Reflector.

14. (*a*) Discuss the future of nuclear power plants for power generation in India. Enumerate the advantages and disadvantages of nuclear power plants as compared to conventional power plants.
(*b*) Describe, with the help of a neat sketch, the working of a pressurised water reactor plant. What are its advantages and disadvantages ?

15. (*a*) Discuss the factors to be kept in mind for selecting the site of a nuclear power plant.

(*b*) What is the function of moderator in a nuclear power plant ? What are the desirable properties of a good moderator ? Compare different moderators used in practice.

16. (*a*) Draw a neat diagram of nuclear reactor and explain the function of its various components.

(*b*) Explain with a neat sketch the principle of working of magneto-hydrodynamic system of power generation. State the difficulties encountered in its design.

17. (*a*) What do you understand by a close cycle gas turbine power plant ? List out its advantages over open cycle plant. What difficulties are there in development of close cycle plants ?

(*b*) Following observations were made during a test on an open cycle constant pressure gas turbine plant :

Inlet temperature	= 27°C
Maximum temperature in the cycle	= 800°C
Pressure ratio	= 6
Isentropic efficiency of compressor	= 85%
Isentropic efficiency of turbine	= 90%
Combustion efficiency	= 95%
Mass flow of air	= 100 kg/sec
Specific heat of air	= 0.24
Specific heat of gases	= 0.26
Specific heat ratio for air and gases	= 1.4
Calorific value of fuel	= 10,500 kcal/kg

Find : (*i*) Thermal efficiency of the plant ; (*ii*) Power developed ; (*iii*) Air fuel ratio ; (*iv*) Specific fuel consumption.

18. (*a*) Describe the functions of the major components used in gas turbine plant.

(*b*) What are the factors to be considered in designing steam piping in thermal plant ? What are the materials used for (*i*) steam piping, and (*ii*) its thermal insulation ?

19. (*a*) What are the advantages of gas turbine plant over other thermal power plants ?

(*b*) Describe briefly the working of closed cycle gas turbine plant with the help of *T*-*s* diagram.

(*c*) In a closed cycle gas turbine the following data were applied :

Working substance is air with $c_p = 0.24$ and $\gamma = 1.4$

Ambient temperature	= 27°C
Maximum temperature	= 823°C
Pressure at compressor inlet	= 1 kgf/cm^2
Pressure ratio	= 4
Compressor efficiency	= 80%
Gas turbine efficiency	= 85%

Determine the thermal efficiency of gas turbine.

20. In a 5 MW gas turbine generating set, HP turbine is used to drive the compressor unit and LP turbine, mounted on separate shaft, drives the alternator. After two-stage compression having overall pressure ratio of 9 with perfect intercooling, the compressed air is supplied to the combustion chamber *via* a regenerator which receives the exhaust from the LP turbine. The temperature of the gases at entry to the HP turbine is 727°C and the gases are reheated to 727°C again before entering the LP turbine. Draw the schematic diagram of the plant and *T*-*s* diagram. Considering open cycle, calculate (*i*) overall thermal efficiency of the plant, and (*ii*) the mass flow rate of air in kg/sec.

Assume the following :

Air inlet pressure and temperature 1 kg/cm^2 and 27°C respectively

Isentropic efficiency of compressor in each stage	= 0.8
Isentropic efficiency of expansion in each unit	= 0.85
Mechanical efficiency of both the turbines	= 0.98
Thermal ratio of the regenerator	= 0.75
Combustion efficiency	= 0.97

$c_{p\,\text{air}} = 0.24$; $c_{p\,\text{gas}} = 0.25$; $\gamma_{\text{air}} = 1.4$; $\gamma_{\text{gas}} = 1.33$.

Neglect mass of fuel and consider the specific heat values to be constant over the pressure and temperature range.

Hydro-Electric Power Plant

6

6.1. Introduction. 6.2. Application of hydro-electric plants. 6.3. Advantages and disadvantages of hydro-electric plants. 6.4. Selection of site for a hydro-electric plant. 6.5. Essential features/elements of hydro-electric power plant—Catchment area—Reservoir—Dam—Spillways—Conduits—Surge tanks—Prime movers—Draft tubes—Powerhouse and equipment. **6.6. Classification of hydro-electric power plants**—High head power plants—Medium head power plants—Low head power plants—Base load plants—Peak load plants—Run-of-river plants without pondage—Run-of-river plant with pondage—Storage type plants—Pumped storage plants—Mini and microhydel plants. **6.7. Hydraulic turbines**—Classification of hydraulic turbines—Description of various types of turbine—Specific speed of a turbine—Efficiencies of a turbine—Cavitation—Performance of hydraulic turbine—Governing of hydraulic turbines—Selection of turbines. **6.8. Plant layout. 6.9. Hydro-plant auxiliaries. 6.10. Cost of hydro-plant. 6.11. Average life of hydro-plant components. 6.12. Hydro-plant controls. 6.13. Electrical and mechanical equipment in a hydro-plant. 6.14. Combined hydro and steam power plants. 6.15. Comparison of hydro-power station with thermal power stations. 6.16. Underground hydro-plants. 6.17. Automatic and remote control of hydro-station. 6.18. Safety measures in hydro-electric power plants. 6.19. Preventive maintenance of hydro-plant. 6.20. Calculation of available hydro-power. 6.21. Cost of hydro-power. 6.22. Hydrology**—Introduction—The hydrologic cycle—Measurement of run-off—Hydrograph—Flow duration curve—Mass curve. **6.23. Hydro-power development in India**—*Worked Examples—Highlights—Theoretical Questions—Unsolved Examples—Competitive Examinations Questions.*

6.1. INTRODUCTION

In hydro-electric plants energy of water is utilised to move the turbines which in turn run the electric generators. The energy of water utilised for power generation may be kinetic or potential. The *kinetic energy* of water is its energy in motion and is a function of mass and velocity, while the *potential energy* is a function of the difference in level/head of water between two points. In either case continuous availability of a water is a basic necessity ; to ensure this, water collected in natural lakes and reservoirs at high altitudes may be utilised or water may be artificially stored by constructing dams across flowing streams. The ideal site is one in which a good system of natural lakes with substantial catchment area, exists at a high altitude. *Rainfall is the primary source of water* and depends upon such factors as temperature, humidity, cloudiness, wind etc. The usefulness of rainfall for power purposes further depends upon several complex factors which include its intensity, time distribution, topography of land etc. However it has been observed that only a small part of the rainfall can actually be utilised for power generation. A significant part is accounted for by *direct evaporation,* while another similar quantity *seeps* into the soil and forms the underground storage. Some water is also absorbed by vegetation. Thus, only a part of water falling as rain actually flows over the ground surface as direct run off and forms the streams which can be utilised for hydro-schemes.

First hydro-electric station was probably started in America in 1882 and thereafter development took place very rapidly. In India the first major hydro-electric development of 4.5 MW capacity named as Sivasamudram Scheme in Mysore was commissioned in 1902. In 1914 a hydro-power plant named Khopoli project of 50 MW capacity was commissioned in Maharashtra. The hydro-power capacity, upto 1947, was nearly 500 MW.

Hydro (water) power is a conventional renewable source of energy which is clean, free from pollution and generally has a good environmental effect. However the following factors are major obstacles in the utilisation of hydro-power resources :

(*i*) Large investments

(*ii*) Long gestation period

(*iii*) Increased cost of power transmission.

Next to thermal power, hydro-power is important in regard to power generation. The hydro-electric power plants provide 30 per cent of the total power of the world. The total hydro-potential of the world is about 5000 GW. In some countries (like Norway) almost total power generation is hydrobased.

6.2. APPLICATION OF HYDRO-ELECTRIC PLANTS

Earlier hydro-electric plants have been used as exclusive source of power, but the trend is towards use of hydropower in an *inter connected system with thermal stations*. As a self-contained and independent power source, a hydro-plant is most effective with adequate storage capacity otherwise the maximum load capacity of the station has to be based on minimum flow of stream and there is a great wastage of water over the dam for greater part of the year. This increases the per unit cost of installation. By inter-connecting hydro-power with steam, a great deal of saving in cost can be effected due to :

(*i*) reduction in necessary reserve capacity,

(*ii*) diversity in construction programmes,

(*iii*) higher utilisation factors on hydroplants, and

(*iv*) higher capacity factors on efficient steam plants.

In an inter connected system the base load is supplied by hydropower when the maximum flow demand is less than the stream flow while steam supplies the peak. When stream flow is lower than the maximum demand the hydroplant supplies the peak load and steam plant the base load.

6.3. ADVANTAGES AND DISADVANTAGES OF HYDRO-ELECTRIC PLANTS

Advantages of hydro-electric plant :

1. No fuel charges.
2. An hydro-electric plant is highly reliable.
3. Maintenance and operation charges are very low.
4. Running cost of the plant is low.
5. The plant has no stand by losses.
6. The plant efficiency does not change with age.
7. It takes a few minutes to run and synchronise the plant.
8. Less supervising staff is required.
9. No fuel transportation problem.
10. No ash problem and atmosphere is not polluted since no smoke is produced in the plant.
11. In addition to power generation these plants are also used for flood control and irrigation purposes.
12. Such a plant has comparatively a long life (100–125 years as against 20–45 years of a thermal plant).
13. The number of operations required is considerably small compared with thermal power plants.
14. The machines used in hydro-electric plants are more robust and generally run at low speeds at 300 to 400 r.p.m. where the machines used in thermal plants run at a speed 3000 to 4000 r.p.m. Therefore, there are no specialised mechanical problems or special alloys required for construction.
15. The cost of land is not a major problem since the hydro-electric stations are situated away from the developed areas.

Disadvantages :

1. The initial cost of the plant is very high.
2. It takes considerable long time for the erection of such plants.
3. Such plants are usually located in hilly areas far away from the load centre and as such they require long transmission lines to deliver power, subsequently the cost of transmission lines and losses in them will be more.
4. Power generation by the hydro-electric plant is only dependent on the quantity of water available which in turn depends on the natural phenomenon of rain. So if the rainfall is in time and proper and the required amount of can be collected, the plant will function satisfactorily otherwise not.

6.4. SELECTION OF SITE FOR A HYDRO-ELECTRIC PLANT

The following factors should be considered while selecting the site for a hydro-electric plant :

1. Availability of water
2. Water storage
3. Water head
4. Accessibility of the site
5. Distance from the load centre
6. Type of the land of the site.

1. Availability of water : The most important aspect of hydro-electric plant is the availability of water at the site since all other designs are based on it. Therefore the run-off data at the proposed site must be available before hand. It may not be possible to have run-off data at the proposed site but data concerning the rainfall over the large catchment area is always available. Estimate should be made about the average quantity of water available throughout the year and also about maximum and minimum quantity of water available during the year. These details are necessary to :

(*i*) decide the capacity of the hydro-electric plant,

(*ii*) setting up of peak load plant such as steam, diesel or gas turbine plant and to,

(*iii*) provide adequate spillways or gate relief during the flood period.

2. Water storage : Since there is a wide variation in rainfall during the year, therefore, it is always necessary to store the water for continuous generation of power. The storage capacity can be calculated with the help of mass curve. Maximum storage should justify the expenditure on the project.

The two types of storages in use are :

(*i*) The storage is so constructed that it can make water available for power generation of one year only. In this case storage becomes full in the beginning of the year and becomes empty at the end of each year.

(*ii*) The storage is so constructed that water is available in sufficient quantity even during the worst dry periods.

3. Water head : In order to generate a requisite quantity of power it is necessary that a large quantity of water at a *sufficient head* should be available. An increase in effective head, for a given output, reduces the quantity of water required to be supplied to the turbines.

4. Accessibility of the site : The site where hydro-electric plant is to be constructed should be easily accessible. This is important if the electric power generated is to be utilised at or near the plant site. The site selected should have transportation facilities of rail and road.

5. Distance from the load centre : It is of paramount importance that the power plant should be set up *near the load centre ;* this will *reduce the cost of erection and maintenance of transmission line*.

6. Type of the land of the site : The land to be selected for the site should be cheap and rocky. The ideal site will be one where the dam will have largest catchment area to store water at high head and will be economical in construction.

The necessary requirements of the foundation rocks for a masonry dam are as follows :

(*i*) The rock should be strong enough to withstand the stresses transmitted from the dam structure as well as the thrust of the water when the reservoir is full.

(*ii*) The rock in the foundation of the dam should be reasonably impervious.

(*iii*) The rock should remain stable under all conditions.

6.5. ESSENTIAL FEATURES/ELEMENTS OF HYDRO-ELECTRIC POWER PLANT

The following are the *essential elements of hydro-electric power plant* :

1. Catchment area
2. Reservoir
3. Dam
4. Spillways
5. Conduits
6. Surge tanks
7. Prime movers
8. Draft tubes
9. Powerhouse and equipment.

Fig. 6.1 shows the flow sheet of hydro-electric power plant.

The description of various elements of hydro-electric plants is as follows :

6.5.1. Catchment Area

The whole area behind the dam draining into a stream or river across which the dam has been built at a suitable place, is called *catchment area*.

6.5.2. Reservoir

The water reservoir is the primary requirement of hydro-electric plant. A reservoir is employed to store water which is further utilised to generate power by running the hydraulic turbines.

A reservoir may be of the following two types :

1. Natural
2. Artificial

A *natural reservoir* is a lake in high mountains.

An artificial reservoir is built by erecting a dam across the river.

Water held in upstream reservoir is called *storage* whereas water behind the dam at the plant is called *pondage*.

6.5.3. Dam

A dam is a barrier to confine or raise water for storage or diversion to create a hydraulic head. An hydro-electric dam diverts the flow from the river to the turbines and usually increases the head. A reservoir dam stores water by raising its level.

Dams are built of *concrete* or *stone masonry, earth* or *rock fill,* or *timber*. Masonry dams may be the solid-gravity, buttress or arch type. A *barrage* is a diversion dam, especially at a tidal power project. A *weir* is a low overflow dam across a stream for measuring flow or maintain water level, as at a lake outlet. A *dike* is an embankment to confine water ; a *levee* is a dike near the bank of a river to keep low land from being overflowed.

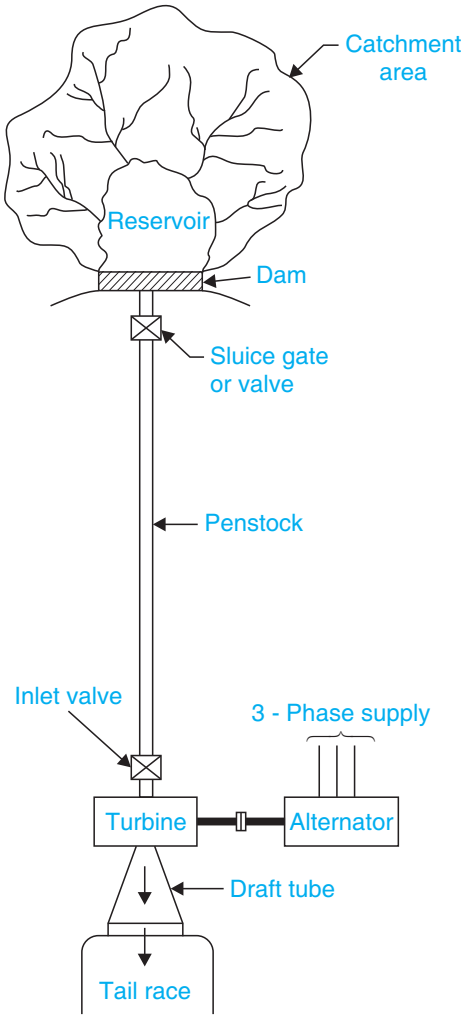


Fig. 6.1. Flow sheet of hydro-electric power plant.

6.5.3.1. Types of dams

The different types of dams are as follows :

A. Fill dams

1. Earth dams
2. Rock-fill dams.

B. Masonry dams

1. Solid gravity dams
2. Buttress dams
3. Arch dams.

C. Timber dams

Selection of site for dams

The following points should be taken into consideration while selecting the site for a dam.

1. For achieving economy the water storage should be largest for the minimum possible height and length. Naturally site should be located in a narrow valley.

2. For safe and cheap construction good foundation should be available at moderate depth.

3. Good and suitable basin should be available.

4. Material for construction should be available at a dam site or near by. As huge quantities of construction materials are required for construction of the dam, the distance at which the material is available affects the total cost of the project.

5. For passing the surplus water, after the reservoir has been filled upto its maximum capacity, a spillway is to be provided. There should be good and suitable site available for spillway construction. It may be in dam itself or near the dam on the periphery of the basin.

6. The value of the property and the land likely to be submerged by the proposed dam should be sufficiently low in comparison with the benefits expected from the project.

7. The site of the dam should be easily accessible in all the seasons. It should be feasible to connect the site with good lines of communication.

8. There should be a good catchment on the upstream side of the site, that is the catchment should contribute good and sufficient water to the basin. The catchment area should not be easily erodable otherwise excessive silt will come in the reservoir basin.

9. There should be suitable site available for providing living accommodation to the labourers and engineering staff. It is very essential to see that the climate of the site is healthy.

10. Overall cost of construction and maintenance of the dam should be taken into consideration.

Selection of type of a dam

The selection of a type of dam is affected by the following topographical and geological factors :

1. Nature of foundation

Sound rock formation in the foundation	Any type of dam can be adopted
Poor rock and earth foundation	Earth dam

2. Nature of valley

Narrow valleys (with good rock abutments)	Arch dam
If george with rocky bed available	Solid gravity dam
If valley is wide and foundation is weak	Buttress dam
For any width of valley with good foundations	Steel dam
For any width of valley with any foundation and low height of water to be stored	Timber dam

For wide valley with gentle side slopes	Earth dam or rock fill dam.

3. Permeability of foundation material

When uplift pressure exerted on the base of the dam is excessive	Arch dam
When the foundations are pervious	Earth dam

In addition to these factors the following points should also be given consideration.

(*i*) Suitable site for locating spillways sometimes affects the selection of the type of a dam.

(*ii*) The availability of construction material may sometimes dictate the choice.

It may be mentioned that in general the most permanent and safe dam will be found to be most economical one.

Description of dams

A. *Fill dams :*

1. Earth dams. For small projects, in particular, dam constructed of earth fill or embankment are commonly used. Because of the great volume of material required, it is imperative that the fill be obtainable in the vicinity of dam site.

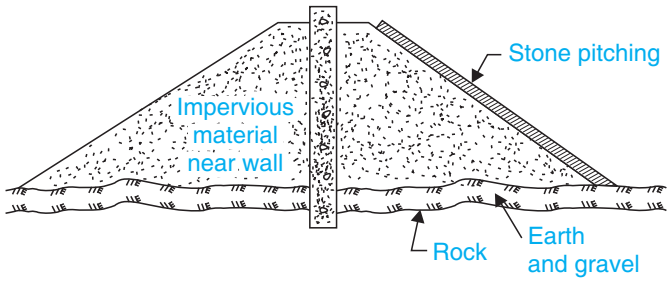


Fig. 6.2. Earth dam.

The earth dams have the following **advantages** :

(*i*) It is usually cheaper than a masonry dam.

(*ii*) It is suitable for relatively previous foundation.

(*iii*) It blends best with the natural surroundings.

(*iv*) It is the most permanent type of construction if protected from corrosion.

Disadvantages of the earth dam are :

(*i*) It has greater seepage losses than most other types of dams.

(*ii*) Since this type of dam is not suitable for a spillway structure, therefore it requires a supplementary spillway.

(*iii*) It is subject to possible destruction or serious damage from erosion by water either over-topping the dam or seeping through it.

Following are the *causes of failure* of earth dams :

1. Overtopping caused by insufficient spillway capacity.
2. Seepage along conduits through the dam.
3. Piping through the dam or its foundation.

2. Rock-fill dams. A rock-fill dam consists of loose rock of all sizes and has a trapezoidal shape with a wide base, with a watertight section to reduce seepage. It is *used in mountaneous locations* where rock rather than earth is available. A rock-fill dam may be destroyed if overtopped to any great extent, and so it needs a supplementary spillway of adequate capacity.

B. *Masonry dams :*

1. Solid gravity dams. This type of dam is more massive and bulky than the other types since it depends on its weight for stability. Because of its weight it requires a sound rock foundation. It may be used as a spillway section for a dam of another type on sand or gravel foundations if the stresses are limited and a suitable cut-off is provided. On a rock foundation the base of a solid gravity dam which is 0.7 of the head usually results in a satisfactory and economical section for either a bulkhead or spillway section. On an earth foundation the base generally equals the head.

2. Buttress dam. A buttress dam has an inclined upstream face, so that water pressure creates a large downward force which provides stability against overturning or sliding. The forces on the upstream face are transmitted to a row of buttresses or piers. This type of dam requires only about *one-third* the concrete needed for a solid gravity dam, but extra cost of reinforcing steel and framework and the skilled labour needed for the thinner sections may largely offset the saving in concrete. The relatively thin sections of concrete in a buttress dam are susceptible to damage from frost and temperature and may require protection or precautionary measures.

Fig. 6.3 and Fig. 6.4 shows typical buttress dams.

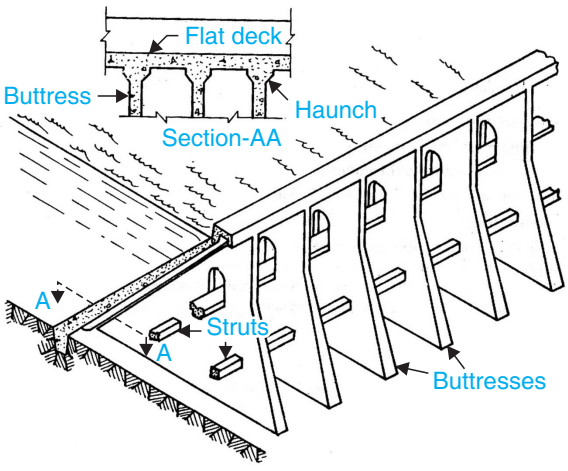


Fig. 6.3. Slab-and-buttress type.

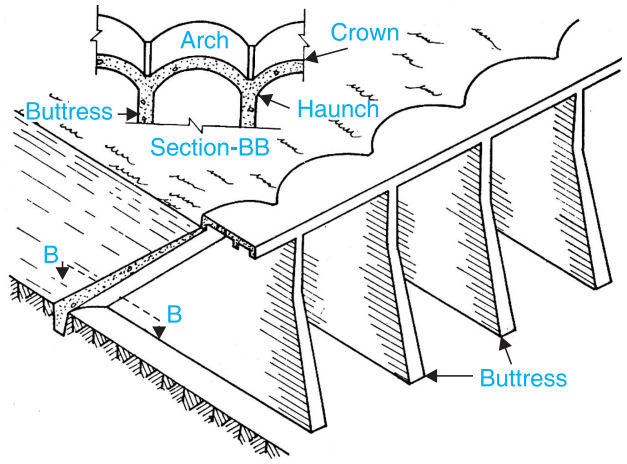


Fig. 6.4. Multiple-arch type.

3. Arch dam. Refer to Fig. 6.5. This type of dam resists the water force by being braced against the canyon sides because of its curved shape. Few sites are suitable for the this type of dam, which requires a fairly narrow valley with steep slopes of solid rock to support the outward thrust of the structure. An arch dam is not ordinarily used for a spillway as the downstream face is too steep for the over- flowing water except for low discharges. It is generally necessary to provide a separate spillway for an arch dam, either a tunnel or conduit type, a side-channel wasteway at the end of the dam, or a spillway in another location.

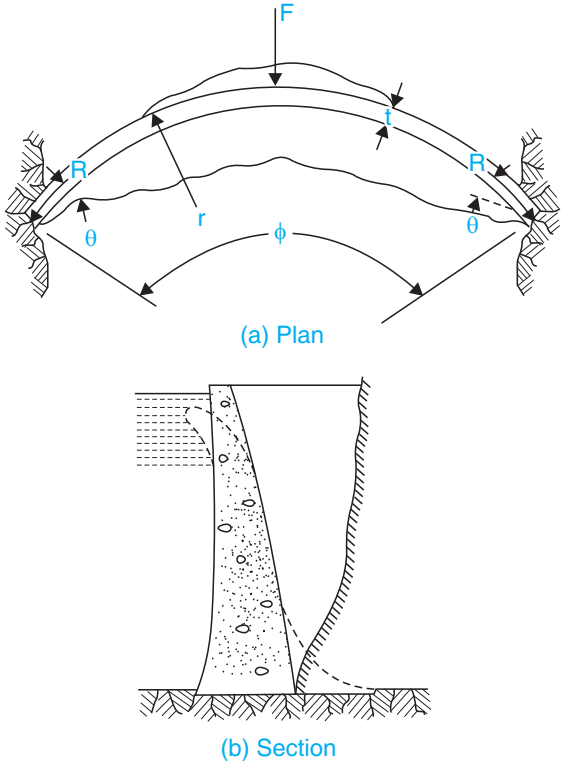


Fig. 6.5. Typical arch dam : (*a*) Plan (*b*) Section.

C. *Timber dams :*

When wood is plentiful and more durable materials are not accessible timber is sometimes used for low dams upto 12 m. In the early days, timber could be had for the cutting, but most of the original timber dams have been superseded by masonry or fill dams. Now-a-days wooden dams are uncommon.

6.5.4. Spillways

When the water enters the reservoir basin, the level of water in basin rises. This rise is arranged to be of temporary nature because excess accumulation of water endangers the stability of dam structure. To relieve reservoir of this excess water contribution, a structure is provided in the body of a dam or near the dam or on the periphery of a basin. This *safeguarding structure is called a spillway*.

A spillway should fulfil9 the following requirements:

1. It should provide structural stability to the dam under all conditions of floods.
2. It should be able to pass the designed flood without raising reservoir level above H.F.L. (high flood level).
3. It should have an efficient operation.
4. It should have an economical section.

Types of spillways

Following are some types of spillways :

(*i*) Overfall spillway or solid gravity spillway
(*ii*) Chute or trough spillway
(*iii*) Side channel spillway
(*iv*) Saddle spillway
(*v*) Emergency spillway
(*vi*) Shaft or glory hole spillway
(*vii*) Siphon spillway.

In the types from (*i*) to (*v*) *water spills and flows over the body of the spillway whereas* in the types (*vi*) and (*vii*) *water spills over the crest and then flows through the body of the spillway*.

The *selection* of type of spillway is generally based *on the type of the dam and the quantity of flood water to be discharged below* ; it also depends on the *site conditions*.

6.5.4.1. Overfall spillway or Solid gravity spillway

Refer to Fig. 6.6. This type of spillway is provided in case of concrete and masonry dams. It is situated in the body of the dam, generally in the centre. As it is provided in the dam itself the length of dam should be sufficient to accommodate the designed spillway crest.

This spillway consists of an *ogee crest* and a *bucket*. Water spills and flows over the crest in the form of a rolling sheet of water. The bucket provided at the lower end of the spillway *changes the direction of the fast moving water*. In this process the excess energy of fast moving water is *destroyed*. The portion between the front vertical face and

the lower nappe of sheet of water is filled with concrete to conform the profile of the spillway to the lower nappe. This type of construction practically avoids the development of *negative pressures*. The section is always designed for maximum head of water over the crest of spillway.

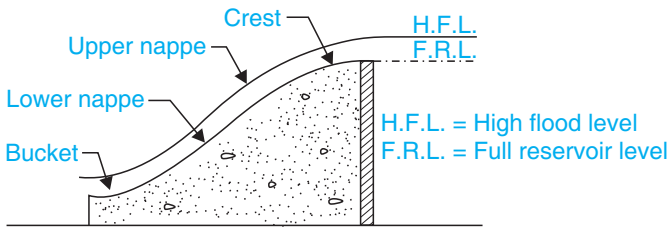


Fig. 6.6. Overfall spillway.

6.5.4.2. Chute or Trough spillway

This type of spillway is most suited under the situation when the *valley is too narrow* to accommodate the solid gravity spillway in the body of the dam or when the non-rigid type of dam is adopted. It is called chute spillway because after crossing over the crest of the spillway the water flow *shoots down a channel or a trough* to meet the river channel downstream of the dam.

In this type the crest of the spillway is at right angles to the centre line of the trough or the chute. The crest is isolated from the dam axis. The trough is taken straight from the crest to the river and it is generally lined with concrete.

6.5.4.3. Side channel spillway

A side channel spillway is employed when the *valley is too narrow in case of a solid gravity dams and when non-rigid dams are adopted*. In non-rigid dams it is undesirable to pass the flood water over the dam. When there is no room for the provision of chute spillway this type is adopted as it requires comparatively limited space. Thus the situations where chute and side channel spillways are required are mostly the same. *The side channel spillway differs from the chute spillway in the sense that after crossing over the spillway crest, water flows parallel to the crest length in former, whereas the flow is normal to the crest in the latter* (Fig. 6.7).

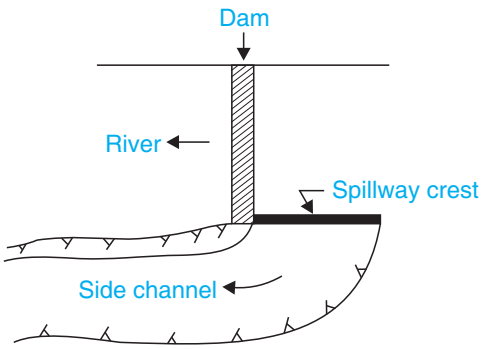


Fig. 6.7. Side channel spillway.

To maintain satisfactory flow conditions a sufficient longitudinal slope is given to the side channel.

6.5.4.4. Saddle spillway

A saddle spillway may be constructed when conditions are not favourable for any of the types mentioned above. There may be some natural depression or saddle on the periphery of the reservoir basin away from the dam as shown in Fig. 6.8. The depression may be used as a spillway. It is essential that *the bottom of the depression should be at full reservoir level*. For ideal conditions there should be good rock formation at the site of a spillway.

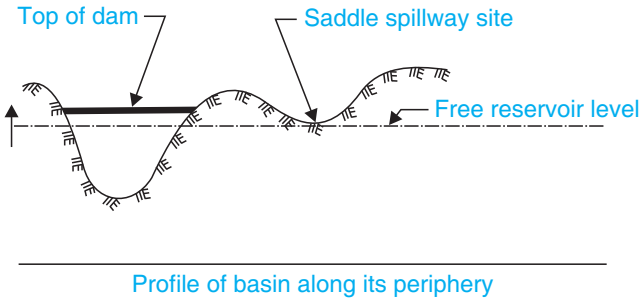


Fig. 6.8. Saddle spillway.

6.5.4.5. Emergency spillway

As the name suggests this type of spillway is very rarely put into action. Naturally it is not necessary to protect the structure, its foundation or its discharge channel from serious damage.

An emergency spillway comes into action when the occurring flood discharge *exceeds* the designed flood discharge.

6.5.4.6. Shaft or Glory hole spillway

The shape of shaft spillway is just like a funnel. The lower end of the funnel is turned at right angles and then taken out below the dam horizontally. Water spills over the crest, which is circular, and then enters the vertical shaft and is taken out below the dam through a horizontal tunnel. Sometimes the flow is guided by means of radial piers on the crest of the spillway. It avoids creation of spiral flow in the shaft. The piers may be used to support a bridge around the crest. The bridge may be used to connect the spillway to the dam.

6.5.4.7. Siphon spillway

A siphon spillway, as the name suggests, is designed on the *principle of a siphon*.

Fig. 6.9 shows a saddle siphon spillway. The crest is fixed at full reservoir level (F.R.L.). When the water level in the reservoir rises above F.R.L. water starts spilling over the crest. The step or a joggle deflects the sheet of water

and consequently the lower end is sealed. As the lower end is sealed the air gets entrapped in the lower limb. This air is driven out by incoming water completely. This process of evacuating and filling the lower limb by water is known as *priming*. Once the siphon is primed water starts flowing out till the level of the water in the reservoir falls below the level of the upper limb. Usually the lower end of the upper limb is kept below full reservoir level. It prevents blocking of the entrance due to the floating matter such as ice etc. Naturally if the water is emptied till the lower end of the upper limb emerges out the useful live storage is lost. To break the siphon action at proper time, that is when the water level falls to F.R.L., an air vent is provided on the crown as shown in Fig. 6.9. Thus when the water level falls to F.R.L. air enters in the lower limb through air vent and siphonic action is broken or stopped.

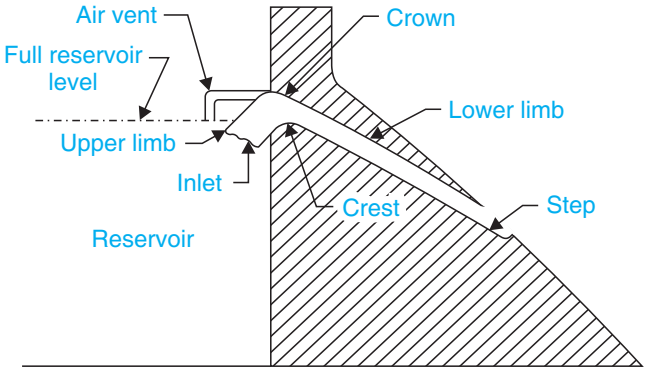


Fig. 6.9. Saddle siphon spillway.

6.5.5. Conduits

A headrace is a channel which leads water to a turbine and a tailrace is a channel which conducts water from the wheels. The conduit may be open or close.

Open conduits	..... Canals and flumes
Close conduits	..... Tunnels, pipelines and penstocks

Canal. A canal is an open waterway excavated in natural ground. It has to follow the contour of the ground, with perhaps a slight gradient corresponding to the head loss.

Flume. A flume is an open channel erected on the surface of supported above ground on a trestle. A flume might be used with a canal to cross a ravine or where the slope of the ground is greater than the hydraulic gradient.

Tunnel. It is a closed channel excavated through a natural obstruction such as a ridge of higher land between the dam and the powerhouse. A tunnel across a bend in the river might be cheaper than a conduit that goes around. Tunnels are also commonly used in diverting water from one drainage area to another, where the divide between watersheds is higher than the reservoir.

Pipeline. A pipeline is a closed conduit usually supported on or above the surface of the land. When a pipeline is laid on the hydraulic gradient, it is called a *flow line*.

Penstock. It is a closed conduit for supplying *water under pressure* to a turbine.

Advantages and limitations of different types of conduits :

Open channels are generally the *least expensive*, but the cost of a flume increases with the height of the trestle.

Where the land is fairly level at head water elevation between the dam and powerhouse sites, a *canal* would be feasible, but not many sites fit this requirement.

Tunnels are generally the *most costly type* of conduit for a given length but are justified if their use results in considerable saving in distance. While ordinarily tailraces are open channels, tunnels are used for the discharge from an underground hydro-station.

Penstocks are used where the *slope is too great for a canal*, especially for the final stretch of the diversion system where the land pitches steeply to the powerhouse. Surge tanks or other measures are necessary to prevent damage in closed conduits due to abnormal pressures.

Fig. 6.10 shows the combination of tunnel, flume, and penstocks at a high-head development. The tunnel

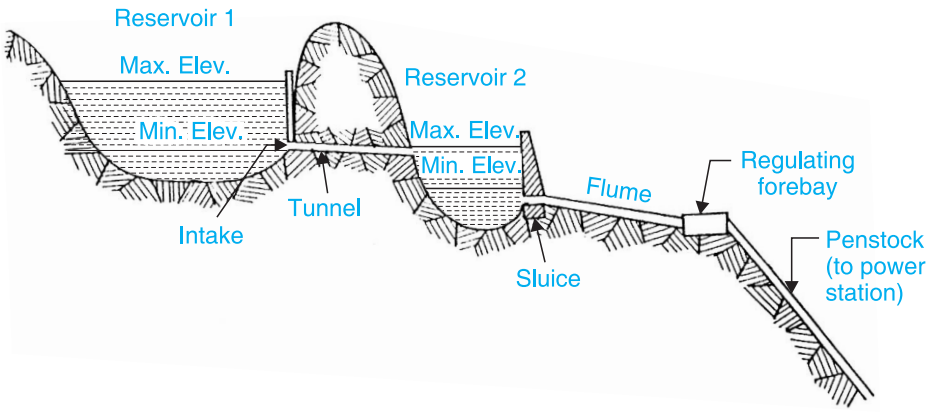


Fig. 6.10. Combination of tunnel, flume and penstocks at a high-head development.

intake regulates the flow between the reservoirs, while the sluice gates at the entrance to the flume control the discharge to that needed by the turbines. The regulating forebay has a small storage capacity to care for minor flow fluctuations. It has an automatic spillway to discharge overflow when turbines shut down suddenly.

Penstocks :

(*i*) *How to calculate penstock thickness ?*

The thickness of steel penstock which depends on the water head hoop/circumferential stress allowed in the material can be calculated by using the following relation:

$$t = \frac{pd}{2f\,\eta}$$

where t = Thickness of the penstock,

p = Pressure due to water including water hammer = wH, w and H being specific weight of water and head of water respectively,

d = Diameter (internal) of the penstock,

f = Permissible hoop/circumferential stress, and

η = Joint efficiency.

(*ii*) *Number of penstocks to be used :*

To supply water to a number of turbines penstocks needed may be decided from the *following alternatives* :

1. To provide *one penstock for each turbine* separately. In such a case water is supplied independently to each turbine from a separate penstock.

2. To use a *single penstock* for the entire plant. In this case the penstock should have as *many branches* as the number of hydraulic turbines.

3. To provide *multiple penstocks* but each penstock should supply water to atleast two hydraulic turbines.

While selecting the number of penstocks to be used for supplying water to the turbines, the following points need be considered :

(*a*) Operational safety. As far as possible a single penstock should not be used for supplying to different turbines for generating power because any damage to this penstock would mean shut down of the entire set of turbines.

(*b*) Economy. From view point of economy, if the length of penstock required is short then one penstock each may be provided to the turbines, however for longer penstocks a single penstock or as few penstocks as possible may be used.

(*c*) Transportation facilities. The penstock size should be so selected that it is easily transported from one place to another.

(*iii*) *Penstock materials and their suitability :*

— *Reinforced concrete penstocks* are suitable upto 18 m head as greater pressures cause rapid deterioration of concrete exposed to frost action.

— *Wood-stave penstocks* are used for heads upto about 75 m and consist of treated timbers laid side by side to form a cylinder held together by the steel hoops. The size and spacing of the hoops on a wood-stave pipe and the reinforcing steel in concrete increase with the head.

— *Steel penstocks* can be designed for any head, with the thickness varying with the pressure and diameter. The minimum thickness of steel plate is used for heads upto 45 m ; for lower heads it may be more economical to use wood or concrete pipe rather than steel.

The strength of a penstock can be expressed as the horse power it can carry. Since the size of a pipe depends on the flow, the product of head and flow determines both maximum stresses and power.

— *High pressure penstocks* are fabricated in 6 to 8 m lengths for mountaneous regions where transportation is difficult. The manholes give access to the interior of the penstocks for inspection and maintenance. *Welded joints are preferable to riveted ones because of the higher friction losses in the latter. Steel penstocks* are usually given protective coatings in the shop and after erection.

— Penstocks are generally supported by *concrete piers* or *cadles,* although they may be laid on or in the ground. A bridge or trestle is used to carry a penstock across a narrow defile. *Anchors* on steep grades support the weight of the fill penstock and also take the thrusts from water pressure acting at angles in the pipe. It may be cheaper to bury small pipes, while penstocks are sometimes covered to protect them from rock or snow slides, prevent freezing, or eliminate expansion joints. *Buried penstocks* are subject to corrosion, which can be eliminated or at least greatly reduced by *cathodic protection* which prevents electrolysis from attacking the metal. *Exposed penstocks last longer and are more accessible for inspection and maintenance.*

6.5.6. Surge Tanks

*A **surge tank** is a small reservoir or tank in which the water level rises or falls to reduce the pressure swings so that they are not transmitted in full to a closed circuit*. In general a surge tank serves the following purposes :

1. To reduce the distance between the free water surface and turbine thereby reducing the water-hammer effect (the *water hammer* is defined as the change in pressure rapidly above or below normal pressure caused by sudden changes in the rate of water flow through the pipe according to the demand of prime mover) on penstock and also protect upstream tunnel from high pressure rises.

2. To serve as a *supply tank* to the turbine when the water in the pipe is accelerating during increased load conditions and as a *storage tank* when the water is decelerating during reduced load conditions.

Types of surge tanks

The different types of surge tanks in use are :

1. Simple surge tank
2. Inclined surge tank
3. The expansion chamber and gallery type surge tank
4. Restricted orifice surge tank
5. Differential surge tank.

1. Simple surge tank. A simple surge tank is a vertical stand pipe connected to the penstock as shown in Fig. 6.11. In the surge tank if the overflow is allowed, the rise in pressure can be eliminated but *overflow surge tank is seldom satisfactory and usually uneconomical*. Surge tanks are built high enough so that water cannot overflow even with a full load change on the turbine. It is always desirable to place the surge tank on grond surface, above the penstock line, at the point where the latter drops rapidly to the power house as shown in Fig. 6.11. Under the circumstances when suitable site for its location is not available the height of the tank should be increased with the help of a support.

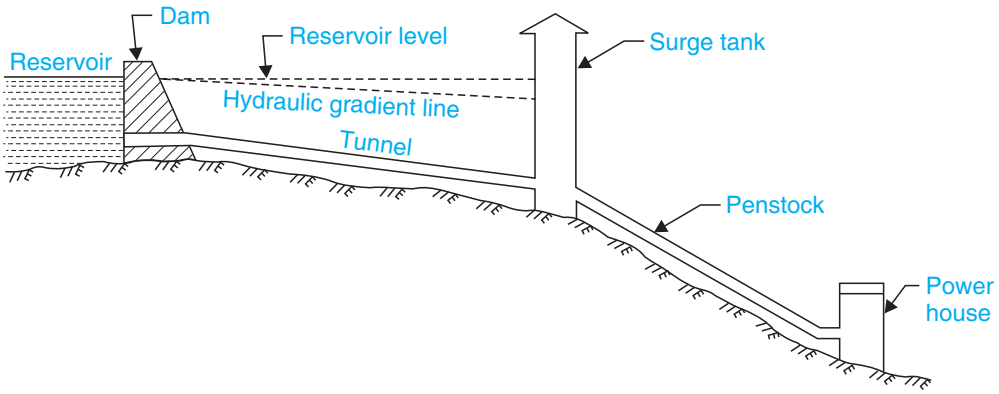


Fig. 6.11. Surge tank on ground level.

2. Inclined surge tank. When a surge tank is inclined (Fig. 6.12) to the horizontal its effective water surface increases and therefore, lesser height surge tank is required of the same diameter if it is inclined or lesser diameter tank is required for the same height. But this type of surge tank is *more costlier than ordinary type as construction is* difficult and is rarely used unless the topographical conditions are in favour.

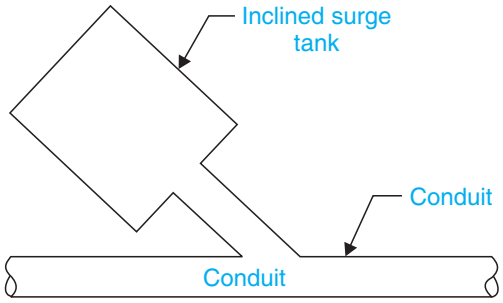


Fig. 6.12. Inclined surge tank.

3. Expansion chamber surge tank. Refer to Fig. 6.13. This type of a surge tank has an expansion tank at top and expansion gallery at the bottom ; these expansions *limit the extreme surges*. The 'upper expansion chamber' must be *above the maximum reservoir level* and 'bottom gallery' must be *below the lowest steady running level in the surge tank*. Besides this the intermediate shaft should have a stable minimum diameter.

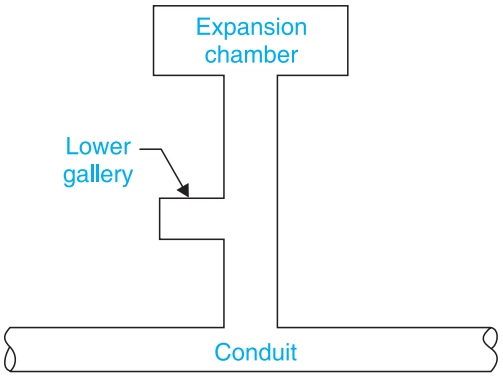


Fig. 6.13. The expansion chamber surge tank.

4. Restricted orifice surge tank. Refer to Fig. 6.14. It is also called *throttled surge tank*. The main object of providing a throttle or restricted orifice is *to create an appreciable friction loss when the water is flowing to or from the tank*. When the load on the turbine is reduced, the surplus water passes through the throttle and a retarding head equal to the loss due to throttle is built up in the conduit. The size of the throttle can be designed for

any designed retarding head. *The size of the throttle adopted is usually such as the initial retarding head is equal to the rise of water surface in the tank when the full load is rejected by the turbine* (a case when there is closure of the gate valve).

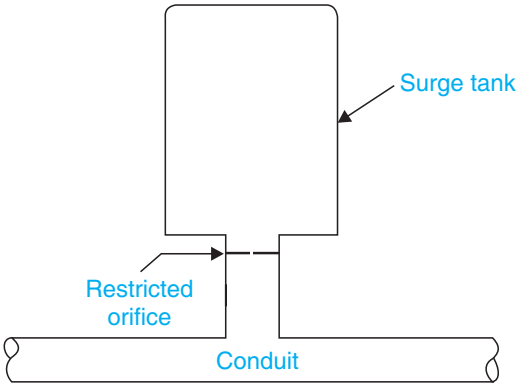


Fig. 6.14. Restricted orifice surge tank.

Advantage. Storage function of the tank can be separated from accelerating and retarding functions.

Disadvantage. Considerable portion of water hammer pressure is transmitted directly into the low pressure conduit.

In comparison to other types of surge tanks these are *less popular.*

5. Differential surge tank. Refer to Fig. 6.15. A differential surge tank has a riser with a small hole at its lower end through which water enters in it. The function of the surge tank depends upon the area of hole.

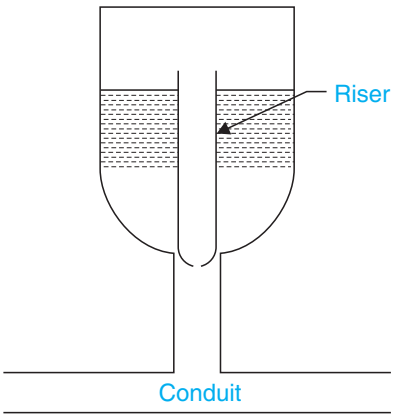


Fig. 6.15. Differential surge tank.

6.5.7. Prime Movers

In an hydraulic power plant the prime mover converts the energy of water into mechanical energy and further into electrical energy. These machines are classified on the basis of the action of water on moving blades. As per action of water on the prime mover, they are classified as :

1. Impulse turbine. Here the *pressure energy of water is converted into kinetic energy* when passed through the nozzle and forms the high velocity jet of water. The formed water jet is used for driving the wheel.

2. Reaction turbine. In this case the water pressure combined with the velocity works on the runner. The power in this turbine is developed from the *combined action of pressure and velocity of water* that completely fills the runner and water passage.

For more details on hydraulic turbines refer to Arte 6.7.

6.5.8. Draft Tubes

The draft tube serves the following two purposes :

1. *It allows the turbine to be set above tail-water level, without loss of head, to facilitate inspection and maintenance*.

2. *It regains, by diffuser action, the major portion of the kinetic energy delivered to it from the runner.*

At rated load the velocity at the upstream end of the tube for modern units ranges from 7 to 9 m/s, representing from 2.7 to 4.8 m head. As the specific speed (it is the speed of a geometrically similar turbine running under a unit head and producing unit power) is increased and the head reduced, it becomes increasingly important to have an efficient draft tube. Good practice limits the velocity at the discharge end of the tube to 1.5 to 2.1 m/s, representing less than 0.3 m velocity head loss.

Types of draft tubes. The following two types of draft tubes are commonly used :

(*i*) The straight conical or concentric tube

(*ii*) The elbow type.

Properly designed, the two types are about equally efficient, over 85%.

(*i*) Conical type. The conical type is generally used on low-powered units for all specific speeds and, frequently, on large high-head units. The side angle of flare ranges from 4 to 6°, the length from 3 to 4 times the diameter and the discharge area from four to five times the throat area. Fig. 6.16 shows a straight conical draft tube.

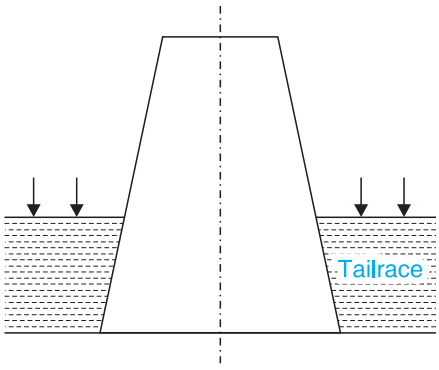


Fig. 6.16. Straight conical draft tube

(*ii*) **Elbow type.** The elbow type of tube is now used with most turbine installation. With this type the vertical portion begins with a conical section which gradually flattens in the elbow section and then discharges horizontally through substantially regular sections to the tailrace. Most of the regain of energy takes place in the vertical portion, very little in the elbow section, which is shaped to deliver the water to the horizontal portion so that the regain may be efficiently completed. Fig. 6.17 shows an elbow type draft tube. One or two vertical piers are placed in the horizontal portion of the tube, for structural and hydraulic reasons.

Small conical tubes are sometimes made entirely of steel plate. Most tubes are made of concrete with a steel-plate lining extending from the upper end to a point where the velocity has been sufficiently reduced (say 5 m/s) to prevent erosion of the concrete. Sometimes the liner is carried around the elbow. Pier noses are also lined where necessary to prevent erosion for structural reasons.

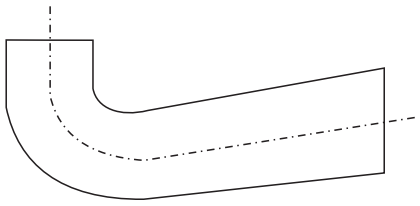


Fig. 6.17. Elbow type draft tube.

6.5.9. Powerhouse and Equipment

A powerhouse should have a stable structure and its layout should be such that adequate space is provided around the equipment (such as turbines, generators, valves, pumps, governors etc.), so that the dismantling and repairing may be easily carried out.

A powerhouse, mostly, comprises of the following sub-divisons :

1. **The substructure.** This part of the powerhouse extends from top of generator to the soil or rock and houses most of the generating equipment. In case of Francis and Kaplan turbines the substructure not only accommodates various equipment but draft tube as well.

2. **Intermediate structure.** It is that part of the structure which extends from the top of the draft tube to top of generator foundation.

3. **The superstructure.** This part of the structure, lies above the generator level. It houses mostly the cranes which handle the heavy equipment in the substructures.

Following important equipment may be provided in a power house

(*i*) Hydraulic turbines
(*ii*) Electric generators
(*iii*) Governors
(*iv*) Gate valves
(*v*) Relief valves
(*vi*) Water circulating pumps
(*vii*) Flow measuring equipment
(*viii*) Air duct
(*ix*) Water circulating pumps
(*x*) Switch board equipment and instruments
(*xi*) Oil circuit breakers
(*xii*) Reactors
(*xiii*) Low tension and high tension bar
(*xiv*) Storage batteries
(*xv*) Cranes.

Besides the above important equipment shops and offices are also provided in the power house.

6.6. CLASSIFICATION OF HYDRO-ELECTRIC POWER PLANTS

Hydro-electric power stations may be classified as follows:

A. According to availability of head

1. High head power plants
2. Medium head power plants
3. Low head power plants

B. According to the nature of load

1. Base load plants
2. Peak load plants

C. Accordingly to the quantity of water available

1. Run-of-river plant without pondage
2. Run-of-river plant with pondage
3. Storage type plants
4. Pump storage plants
5. Mini and microhydel plants

A. *According to availability of head*

The following figures give a rough idea of the heads under which the various types of plants work :

(*i*) High head power plants	100 m and above
(*ii*) Medium head power plants	30 to 500 m
(*iii*) Low head power plants	25 to 80 m.

Note. It may be noted that figures given above overlap each other. Therefore it is difficult to classify the plants directly on the basis of head alone. The basis, therefore, technically adopted is the *specific speed* of the turbine used for a particular plant.

6.6.1. High Head Power Plants

These types of plants work under heads 100 m and above. Water is usually stored up in lakes on high mountains during the rainy season or during the reason when the snow melts. The rate of flow should be such that water can last throughout the year.

Fig. 6.18 shows high head power plant layout. Surplus water discharged by the spillway cannot endanger the stability of the main dam by erosion because they are separated. The tunnel through the mountain has a surge chamber excavated near the exit. Flow is controlled by head gates at the tunnel intake, butterfly valves at the top of the penstocks, and gate valves at the turbines. This type of site might also be suitable for an underground station.

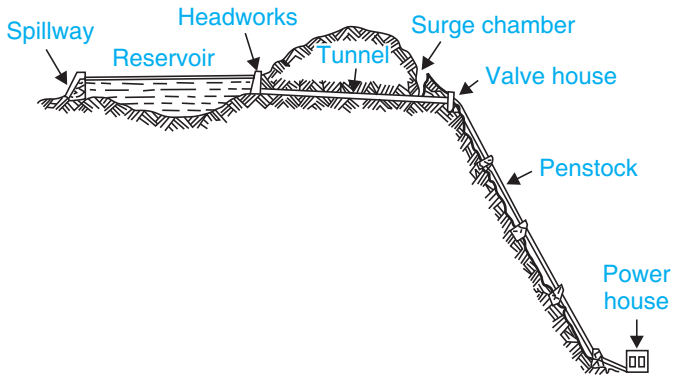


Fig. 6.18. High head power plant layout. The main dam, spillway, and powerhouse stand at widely separated locations. Water flows from the reservoir through a tunnel and penstock to the turbines.

The *Pelton wheel* is the common prime mover used in high *head power plants*.

6.6.2. Medium Head Power Plants

Refer to Fig. 6.19. When the operating head of water lies between 30 to 100 metres, the power plant is known as medium head power plant. This type of plant commonly uses *Francis turbines*. The forebay provided at the beginning of the penstock serves as water reservoir. In such plants, the water is generally carried in open canals from main reservoir to the forebay and then to the powerhouse through the penstock. The forebay itself works as a surge tank in this plant.

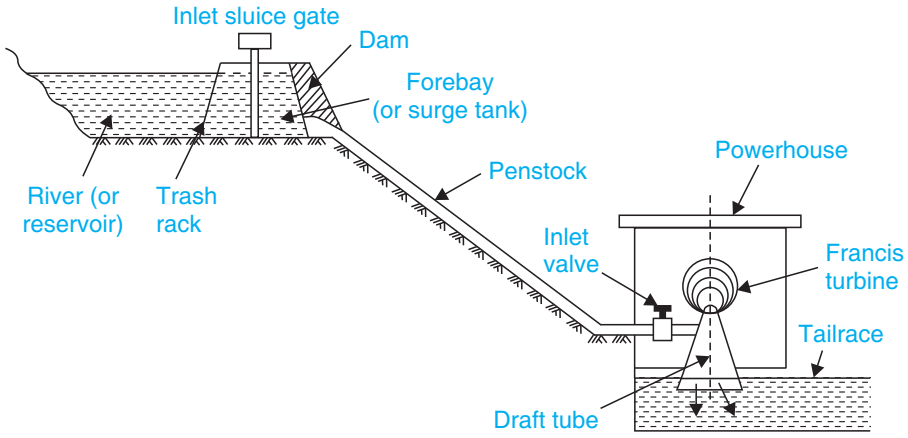


Fig. 6.19. Medium head power plant layout.

6.6.3. Low Head Power Plants

Refer to Fig. 6.20. These plants usually consist of a dam across a river. A sideway stream diverges from the river at the dam. Over this stream the power house is constructed. Later this channel joins the river further downstream. This type of plant uses vertical shaft Francis turbine or Kaplan turbine.

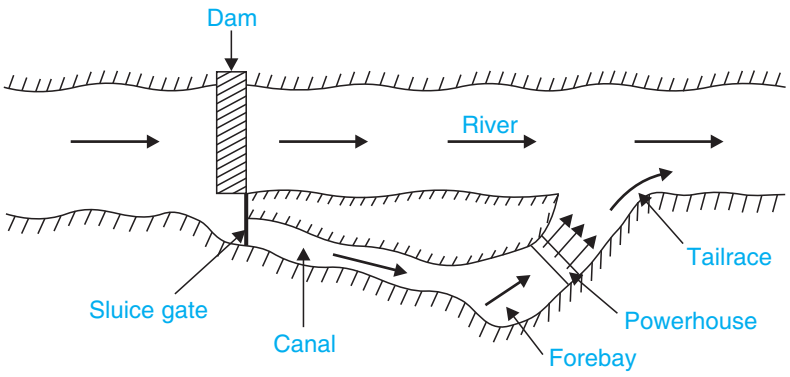


Fig. 6.20. Low head power plant layout.

B. *According to the nature of load*

6.6.4. Base Load Plants

The plants which cater for the base load of the system are called *base load plants*. These plants are required to *supply a constant power when connected to the grid*. Thus they *run without stop* and are often remote-controlled with which *least staff* is *required for such plants*. Run-of-river plants without pondage may sometimes work as baseload plant, but the firm capacity in such cases, will be muchless.

6.6.5. Peak Load Plants

The plants which can supply the power during peak loads are known as *peak load plants*. Some of such plants supply the power during average load but also supply peak load as and when it is there ; whereas other peak load plants are required to work during peak load hours only. The run-of-river plants may be made for the peak load by providing pondage.

C. *According to the quantity of water available*

6.6.6. Run-of-River Plants Without Pondage

A run-of-river plant without pondage, as the name indicates, does not store water and uses the water as it comes. There is *no control on flow of water* so that during high floods or low loads water is wasted while during low run-off the plant capacity is considerably reduced. *Due to non-uniformity of supply and lack of assistance from a firm capacity the utility of these plants is much less* than those of other types. The head on which these plants work *varies considerably*. Such a plant can be made a great deal more useful by providing sufficient storage at the plant to take care of the hourly fluctuations in load. This lends some *firm capacity* to the plant. During good flow conditions these plants may cater to base load of the system, when flow reduces they may supply the peak demands. *Head water elevation for plant fluctuates with the flow conditions*. These plants without storage may sometimes be made to supply the base load, but the firm capacity depends on the minimum flow of river. The run-of-river plant may be made for load service with pondage, though storage is usually seasonal.

6.6.7. Run-of-River Plant with Pondage

Pondage usually refers to the collection of water behind a dam at the plant and increases the stream capacity for a short period, say a week. *Storage* means collection of water in up stream reservoirs and this increases the capacity of the stream over an extended period of several months. Storage plants may work satisfactorily as base load and peak load plants.

This type of plant, as compared to that without pondage, is *more reliable* and its generating capacity *is less dependent on the flow rates of water available*.

6.6.8. Storage Type Plants

A storage type plant is one with a reservoir of sufficiently large size to permit carry-over storage from the wet reason to the dry reason, and thus to supply firm flow substantially more than the minimum natural flow. This plant can be used as base load plant as well as peak load plant as water is available with control as required. The majority of hydro-electric plants are of this type.

6.6.9. Pumped Storage Plants

Refer to Fig. 6.21.

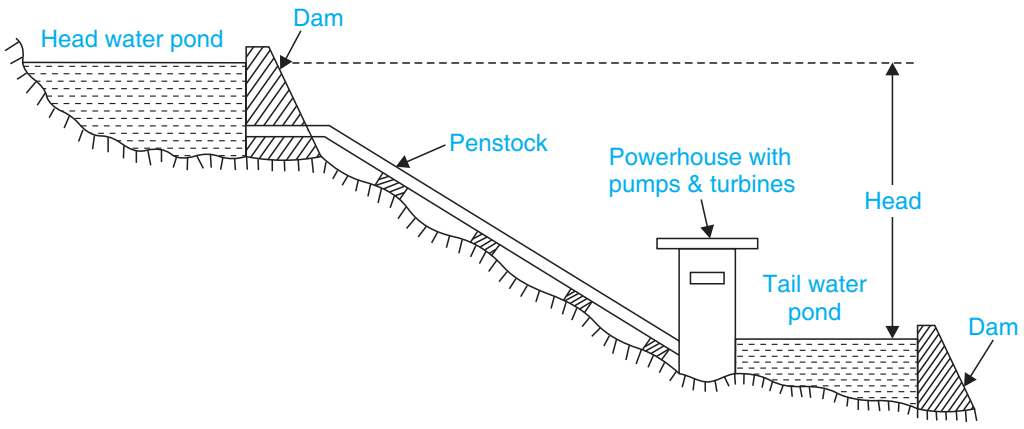


Fig. 6.21. Pumped storage plant.

Pumped storage plants are employed at the places where the quantity of water available for power generation is *inadequate*. Here the water passing through the turbines is stored in *'tail race pond'*. During low load periods this water is pumped back to the head reservoir using the extra energy available. This water can be again used for generating power during peak load periods. Pumping of water may be done seasonally or daily depending upon the conditions of the site and the nature of the load on the plant.

Such plants are *usually interconnected* with steam or diesel engine plants so that off peak capacity of interconnecting stations is used in pumping water and the same is used during peak load periods. Of course, the energy available from the quantity of water pumped by the plant is *less* than the energy input during pumped operation. Again while using pumped water the *power available is reduced* on account of losses occurring in prime movers.

Advantages. The pump storage plants entail the following *advantages* :

1. There is substantial increase in peak load capacity of the plant at comparatively low capital cost.
2. Due to load comparable to rated load on the plant, the operating efficiency of the plant is high.
3. There is an improvement in the load factor of the plant.
4. The energy available during peak load periods is higher than that of during off peak periods so that inspite of losses incurred in pumping there is *over-all gain*.
5. Load on the hydro-electric plant remains uniform.
6. The hydro-electric plant becomes partly independent of the stream flow conditions.

Under pump storage projects almost 70 per cent power used in pumping the water can be recovered. In this field the use of "*Reversible Turbine Pump*" units is also worth noting. These units can be used as turbine while generating power and as pump while pumping water to storage. The generator in this case works as motor during reverse operation. The efficiency in such case is high and almost the same in both the operations. With the use of reversible turbine pump sets, additional capital investment on pump and its motor can be saved and the scheme can be worked more economically.

6.6.10. Mini and Microhydel Plants

In order to meet with the present energy crisis partly, a solution is to develop *mini* (5 to 20 m head) and *micro* (less than 5 m head) hydel potential in our country. The low head hydro-potential is scattered in this country and estimated potential from such sites could be as much as 20,000 MW.

By proper planning and implementation, it is possible to commission a small hydro-generating set up of 5 MW with a period of one and half year against the period of a decade or two for large capacity power plants. Several such sets upto 1000 kW each have been already installed in Himachal Pradesh, U.P., Arunachal Pradesh, West Bengal and Bhutan.

To reduce the cost of microhydel stations than that of the cost of conventional installation the following considerations are kept in view :

1. The civil engineering work needs to be kept to a *minimum* and designed to fit in with already existing structures *e.g.,* irrigation, channels, locks, small dams etc.
2. The machines need to be manufactured in a small range of sizes of simplified design, allowing the use of unified tools and aimed at reducing the cost of manufacture.
3. These installations must be automatically controlled to reduce attending personnel.
4. The equipment must be simple and robust, with easy accessibility to essential parts for maintenance.
5. The units must be light and adequately subassembled for ease of handling and transport and to keep down erection and dismantling costs.

Microhydel plants (micro-stations) *make use of standardised bulb sets with unit output ranging from 100 to 1000 kW working under heads between 1.5 to 10 metres.*

6.7. HYDRAULIC TURBINES

*A **hydraulic turbine** converts the potential energy of water into mechanical energy which in turn is utilised to run an electric generator to get electric energy.*

6.7.1. Classification of Hydraulic Turbines

The hydraulic turbines are classified as follows :

(*i*) According to the head and quantity of water available.

(*ii*) According to the name of the originator.

(*iii*) According to the action of water on the moving blades.

(*iv*) According to the direction of flow of water in the runner.

(*v*) According to the disposition of the turbine shaft.

(*vi*) According to the specific speed N_s.

1. According to the head and quantity of water available :

(*i*) *Impulse turbine*—requires *high head* and *small quantity of flow*.

(*ii*) *Reaction turbine*—requires *low head* and *high rate of flow*.

Actually there are two types of reaction turbines, one for medium head and medium flow and the other for low head and large flow.

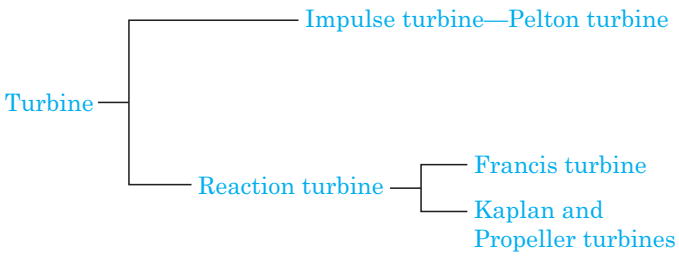
2. According to the name of the originator :

(*i*) *Pelton turbine*—named after Lester Allen Pelton of California (USA). It is an impulse type of turbine and is used for *high head* and *low discharge*.

(*ii*) *Francis turbine*—named after James Bichens Francis. It is a reaction type of turbine for *medium high to medium low heads* and *medium small to medium large quantities of water*.

(*iii*) *Kaplan turbine*—named after Dr. Victor Kaplan. It is a *reaction type of turbine for low heads and large quantities of flow*.

3. According to action of water on the moving blades :



4. According to direction of flow of water in the runner :

(*i*) Tangential flow turbine (Pelton turbine)

(*ii*) Radial flow turbine (no more used)

(*iii*) Axial flow turbine (Kaplan turbine)

(*iv*) Mixed (radial and axial) flow turbine (Francis turbine)

In *tangential flow* turbine of Pelton type the water strikes the runner tangential to the path of rotation.

In *axial flow* turbine water flows parallel to the axis of the turbine shaft. Kaplan turbine is an axial flow turbine. In Kaplan turbine the runner blades are *adjustable and can be rotated* about pivots fixed to the boss of the runner. If the runner blades of the axial flow turbines are *fixed*, these are called "*Propeller turbines*".

In *mixed flow* turbines the water enters the blades radially and comes out axially, parallel to the turbine shaft. Modern Francis turbines have mixed flow runners.

5. According to the disposition of the turbine shaft : Turbine shaft may be either vertical or horizontal. In modern turbine practice, Pelton turbines usually have horizontal shafts whereas the rest, especially the large units, have vertical shafts.

6. According to specific speed : The *specific speed* of a turbine is defined as the speed of a geometrically similar turbine that would develop *one brake horse power* under the *head of one metre*. All geometrically similar turbines (irrespective of their sizes) will have the same specific speed when operating under the same conditions of head and flow.

$$\text{Specific speed,} \quad N_s = \frac{N\sqrt{P_t}}{H^{5/4}}$$

where, N = The normal working speed in r.p.m.,

P_t = Power output of the turbine, and

H = The net or effective head in metres.

The specific speeds for the various types of runners are given below :

Type of turbine	Type of runner	Specific speed (N_s)
Pelton	Slow	10 to 20
	Normal	20 to 28
	Fast	28 to 35
Francis	Slow	60 to 120
	Normal	120 to 180
	Fast	180 to 300
Kaplan	—	300 to 1000

Turbines with low specific speeds work under a high head and low discharge condition, while high specific speed turbines work under low head and high discharge conditions.

6.7.2. Description of Various Types of Turbines

6.7.2.1. Impulse turbines

Pelton wheel, among the various impulse turbines that have been designed and utilized, is by far the important. The Pelton wheel or Pelton turbine is a *tangential flow impulse turbine*. It consists of a rotor, at the periphery of which are mounted equally spaced double-hemispherical or double-ellipsoidal buckets. Water is transferred from a high head source through penstock pipes. A branch pipe from each penstock pipe ends in a nozzle, through which the water flows out as a high speed jet. A needle or spear moving inside the nozzle controls the water flow through the nozzle and at the same time, provides a smooth flow with negligible energy loss. All the available *potential energy is thus converted into kinetic energy* before the jet strikes the buckets. The pressure all over the wheel is *constant and equal to atmosphere, so that energy transfer occurs due to purely impulse action*.

Fig. 6.22 shows a schematic diagram of a Pelton wheel, while Fig. 6.23 shows two views of its bucket.

The jet emerging from the nozzle hits the splitter symmetrically and is equally distributed into the two halves of hemispherical bucket as shown. *The bucket centre-line cannot be made exactly like a mathematical cusp, partly because of manufacturing difficulties and partly because the jet striking the cusp invariably carries particles of sand and other abrasive materials which tend to wear it down*. The inlet angle of the jet is therefore between 1° and 3°, but it is always assumed to be zero in all calculations. Theoretically, if the bucket were exactly hemispherical, it would deflect the jet through 180°. Then, the relative velocity of the jet leaving the bucket, C_{r_2}, would be opposite in direction to the relative velocity of the entering jet C_{r_1}. This cannot be achieved in practice since the jet leaving the bucket would then strike the *back of the succeeding bucket to cause splashing and interference so that the overall*

turbine efficiency would fall to low values. Hence, in practice, the angular deflection of the jet in the bucket is limited to about 165° or 170°, and the *bucket is therefore, slightly smaller than a hemisphere in size*.

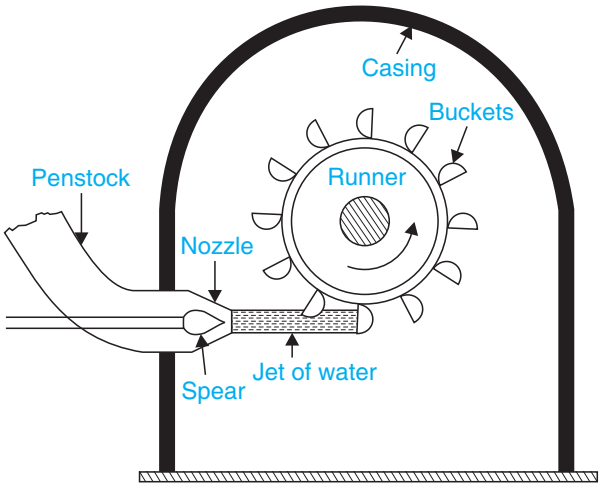
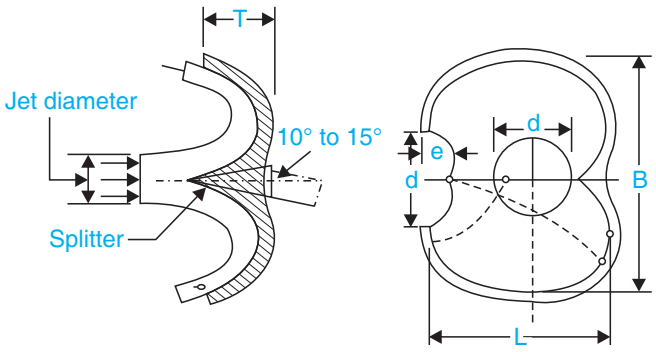


Fig. 6.22. Pelton wheel.



$\frac{L}{d}$ = 2.5 – 2.8,

$\frac{D}{d}$ = 14 – 16,

$\frac{T}{d}$ = 0.95, Notch (width) = 1.1d + 5 mm

Fig. 6.23. The bucket dimensions.

Fig. 6.24 shows a section through horizontal-impulse turbine.

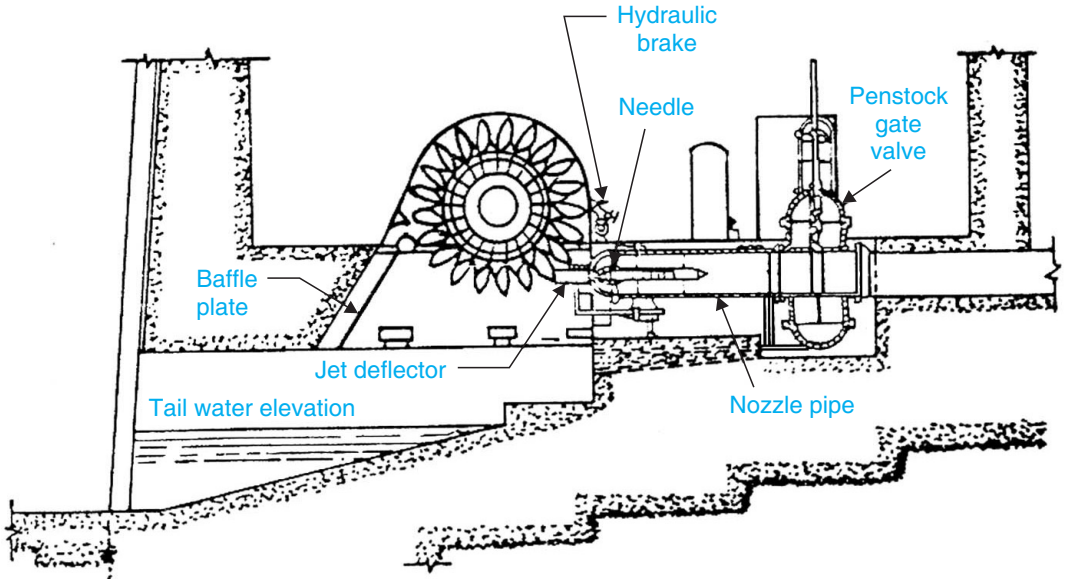


Fig. 6.24. Section through horizontal-impulse turbine.

Velocity triangles

Refer to Fig. 6.25.

Let, C_{bl} = Peripheral (or circumferential) velocity of runner. It will be same at inlet and outlet of the runners at the mean pitch diameter (*i.e.*, $C_{bl_1} = C_{bl_2} = C_{bl}$),

C_1 = Absolute velocity of water jet at inlet,

C_{r_1} = Jet velocity relative to vane/bucket at inlet,

α = Angle between the direction of the jet and direction of motion of the vane/bucket (also called *guide angle*),

θ = Angle made by the relative velocity (C_{r_1}) with the direction of motion at inlet (also called *vane angle at inlet*),

C_{w_1} and C_{f_1} = The components of the velocity of the jet C_1, in the direction of motion and perpendicular to the direction of motion of the vane respectively.

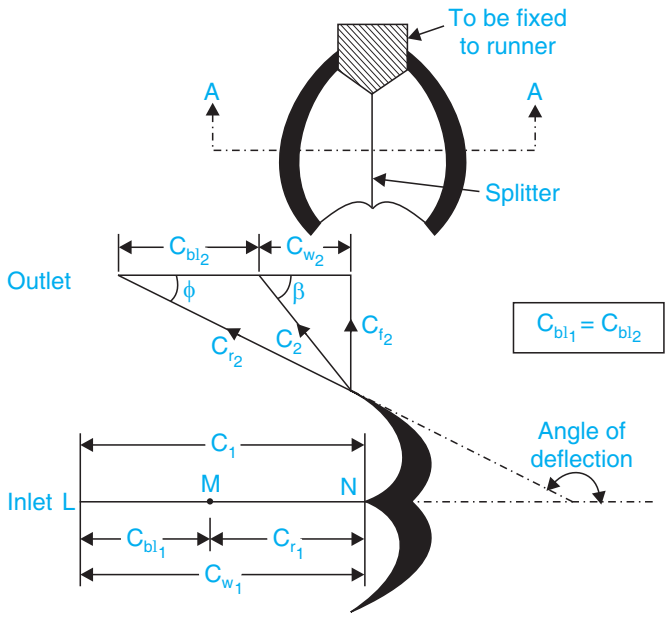


Fig. 6.25. Velocity triangles.

C_{w_1} is also known as *velocity of whirl* at inlet

C_{f_1} is also known as *velocity of flow* at inlet

C_2 = Velocity of jet, leaving the vane or velocity of jet at outlet of the vane.

C_{r_2} = Relative velocity of the jet with respect to the vane at outlet.

ϕ = Angle made by the relative velocity C_{r_2}, with the direction of motion of vane at outlet and also called *vane angle at outlet*.

β = Angle made by the velocity C_2 with the direction of motion of the vane at outlet.

C_{w_2} and C_{f_2} = Components of the velocity C_2, in the direction of motion of vane and perpendicular to the direction of motion of vane at outlet.

C_{w_2} is also called the *velocity of whirl at outlet*

C_{f_2} is also called *velocity of flow at outlet*.

Inlet. The velocity triangle at *inlet* will be a straight line where

$$C_{r_1} = C_1 - C_{bl_1} = C_1 - C_{bl}$$

$$C_{w_1} = C_1, \alpha = 0$$

and $\theta = 0$

Outlet. From the velocity triangle at outlet, we have

$$C_{r_2} = C_{r_1} \text{ (assuming no friction)}$$

and
$$C_{w_2} = C_{r_2} \cos \phi - C_{bl_2}$$
$$= C_{r_2} \cos \phi - C_{bl}$$

The force exerted by the jet of water in the direction of motion is given as

$$F = \rho a C_1 (C_{w_1} + C_{w_2}) \quad ...(6.1)$$

[ρ and a are mass density and area of jet ($a = \pi/4\ d^2$) respectively]

Now the work done by the jet on the runner per second

$$= F \times C_{bl}$$
$$= \rho a C_1 (C_{w_1} + C_{w_2}) \times C_{bl} \quad ...(6.2)$$

Work done/sec per unit weight of water striking

$$= \frac{\rho a C_1 (C_{w_1} + C_{w_2}) \times C_{bl}}{\text{Weight of water striking}}$$

$$= \frac{\rho a C_1 (C_{w_1} + C_{w_2}) \times C_{bl}}{\rho a C_1 \times g}$$

$$= \frac{1}{g}(C_{w_1} + C_{w_2}) \times C_{bl} \quad ...(6.3)$$

The energy supplied to the jet at inlet is in the form of kinetic energy and is equal to $\frac{1}{2} mC^2$.

∴ Kinetic energy (K.E.) of jet per second

$$= \frac{1}{2} (\rho a C_1) \times C_1^2$$

∴ Hydraulic efficiency,

$$\eta_h = \frac{\text{Work done per second}}{\text{K.E. of jet per second}}$$

$$= \frac{\rho a C_1 (C_{w_1} + C_{w_2}) \times C_{bl}}{\frac{1}{2} (\rho a C_1) \times C_1^2}$$

$$= \frac{2(C_{w_1} + C_{w_2}) \times C_{bl}}{C_1^2} \quad ...(6.4)$$

Now, $C_{w_1} = C_1$, C_{r_1}

$$= C_1 - C_{bl_1} = (C_1 - C_{bl})$$

∴ $C_{r_2} (= C_{r_1}) = C_1 - C_{bl}$

and
$$C_{w_2} = C_{r_2} \cos \phi - C_{bl_2}$$
$$= C_{r_2} \cos \phi - C_{bl}$$
$$= (C_1 - C_{bl}) \cos \phi - C_{bl}$$

Substituting the value of C_{w_1} and C_{w_2} in eqn. (6.4), we get:

$$\eta_h = \frac{2[C_1 + (C_1 - C_{bl}) \cos \phi - C_{bl}] \times C_{bl}}{C_1^2}$$

$$= \frac{2[(C_1 - C_{bl}) + (C_1 - C_{bl})\cos\phi] \times C_{bl}}{C_1^2}$$

$$= \frac{2(C_1 - C_{bl})(1 + \cos\phi) C_{bl}}{C_1^2} \quad ...(6.5)$$

The efficiency will be maximum for a given value of C_1 when

$$\frac{d}{dC_{bl}}(\eta_h) = 0$$

or $$\frac{d}{dC_{bl}}\left[\frac{2\,C_{bl}\,(C_1 - C_{bl})\,(1 + \cos\phi)}{C_1^2}\right] = 0$$

$$\frac{(1 + \cos\phi)}{C_1^2} \cdot \frac{d}{dC_{bl}}(2C_{bl}\,C_1 - 2C_{bl}^2) = 0$$

or $$\frac{d}{dC_{bl}}(2C_{bl}\,C_1 - 2C_{bl}^2) = 0$$

$$\left(\because \quad \frac{1 + \cos\phi}{C_1^2} \neq 0\right)$$

$$2C_1 - 4C_{bl} = 0$$

$$C_{bl} = \frac{C_1}{2} \quad ...(6.6)$$

The above equation states that *hydraulic efficiency of a Pelton wheel is maximum when the velocity of the wheel is half the velocity of the jet of water at inlet*. The maximum efficiency can be obtained by substituting the value of $C_{bl} = \frac{C_1}{2}$ in eqn. (6.5).

$$\therefore \quad \text{Max. } \eta_h = \frac{2\left[C_1 - \frac{C_1}{2}\right](1 + \cos\phi) \times \frac{C_1}{2}}{C_1^2}$$

$$= \frac{2 \times \frac{C_1}{2}(1 + \cos\phi)\frac{C_1}{2}}{C_1^2}$$

$$= \left(\frac{1 + \cos\phi}{2}\right) \quad ...(6.7)$$

Important relations for Pelton wheel :

1. The velocity of the jet at inlet is given by

$$C_1 = C_v\sqrt{2gH}$$

where C_v = Coefficient of velocity = 0.98 or 0.99 and H = Net head on turbine.

2. The velocity of wheel (C_{bl}) is given by

$$C_{bl} = \phi\sqrt{2gH}$$

where ϕ = Speed ratio. It varies from 0.43 to 0.48.

3. The angle of deflection of the jet through buckets is taken as 165° if no angle of deflection is given.

4. The mean diameter or the pitch diameter D of the Pelton wheel is given by

$$C_{bl} = \frac{\pi DN}{60}$$

or $$D = \frac{60C_{bl}}{\pi N}$$

5. Jet ratio (M) = $\frac{D}{d}$ (= 12 for most cases) ...(6.8)

[D = Pitch diameter of the Pelton wheel
d = Diameter of the jet]

6. Number of *buckets* on a runner

$$= 15 + \frac{D}{2d} = 15 + 0.5M \quad ...(6.9)$$

7. *Number of jets* is obtained by dividing the total rate of flow through the turbine by the rate of flow of water through a single jet.

6.7.2.2. Reaction turbines

In reaction turbines, the *runner utilizes both potential and kinetic energies*. As the water flows through the stationary parts of the turbine, whole of its pressure energy is not transferred to kinetic energy and when the water flows through the moving parts, there is a change both in the pressure and in the direction and velocity of flow of water. As the water gives up its energy to the runner, both its pressure and absolute velocity get reduced. The water which acts on the runner blades is under *a pressure above atmospheric and the runner passages are always completely filled with water*.

Francis turbines

Refer to Fig. 6.26 (*a*), (*b*). The modern Francis water turbine is an *inward mixed flow reaction turbine i.e.* the water under pressure, *enters the runner from the guide vanes towards the centre in radial direction and discharges out of the runner axially*. The Francis turbine operates under *medium heads* and also requires *medium quantity* of water. It is employed in the medium head power plants. This type of turbine covers a wide range of heads. Water is brought down to the turbine and directed to a number of stationary orifices fixed all around the circumference of the runner. These stationary orifices are commonly termed as *guide vanes or wicket gates.*

The head acting on the turbine is partly transformed into kinetic energy and the rest remains as pressure head. There is a difference of pressure between the guide vanes and the runner which is called the *reaction pressure* and is responsible for the motion of the runner. That is why a Francis turbine is also known as *reaction turbine*.

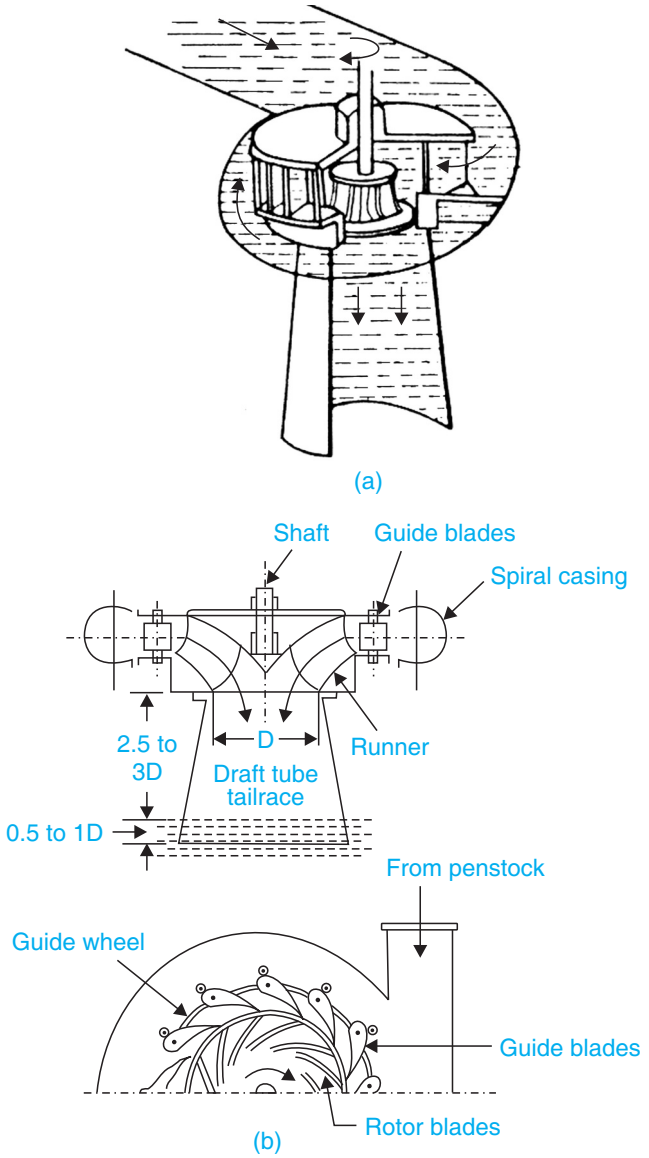


Fig. 6.26. Schematic diagram of a Francis turbine.

In Francis turbine the pressure at the inlet is more than that at the outlet. This means that the water in the turbine must flow in a closed conduit. Unlike the Pelton type, where the water strikes only a few of the runner buckets at a time, in the Francis turbine the *runner is always full of water. The moment of the runner is affected by the change of both the potential and the kinetic energies of water*. After doing its work the water is discharged to the tail race through a closed tube of gradually enlarging section. This tube is known as *draft tube*. It does not allow water to fall freely to tail race level as in the Pelton turbine. The free end of the draft tube is submerged deep in the tail water making, thus, the entire water passage, right from the head race upto the tail race, totally enclosed.

The inlet and outlet triangles are shown in the Fig. 6.27.

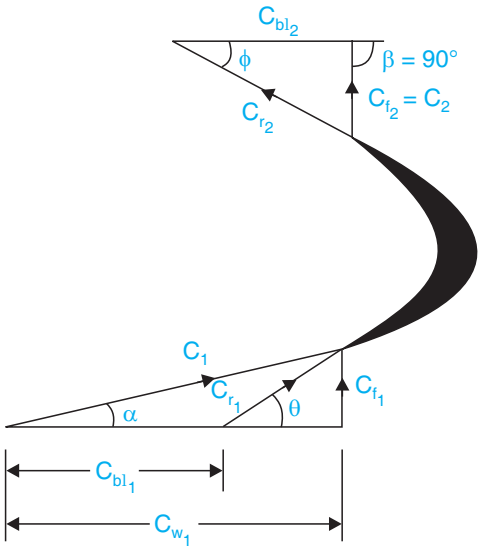


Fig. 6.27. The inlet and outlet triangles.

As in case of Francis turbine, the discharge is axial at outlet, the velocity of whirl at outlet (*i.e.*, C_{w_2}) will be zero. Hence the work done by water on the runner per second will be

$$= \rho Q(C_{w_1}\, C_{bl_1})$$

And work done per second per unit weight of water

$$= \frac{1}{g}[C_{w_1}\, C_{bl_1}]$$

Hydraulic efficiency will be given by,

$$\eta_h = \frac{C_{w_1}\, C_{bl_1}}{gH} \qquad ...(6.10)$$

Important relations for Francis turbine :

1. The ratio of width of the wheel to its diameter varies from 0.10 to 0.40.
2. Flow ratio $= \frac{C_{f_1}}{\sqrt{2gH}}$ and varies from 0.15 to 0.30.
3. The speed ratio $= \frac{C_{bl_1}}{\sqrt{2gH}}$ and varies from 0.6 to 0.9.

Fig. 6.28 shows a plate-steel spiral-case setting of vertical Francis turbine, welded casing.

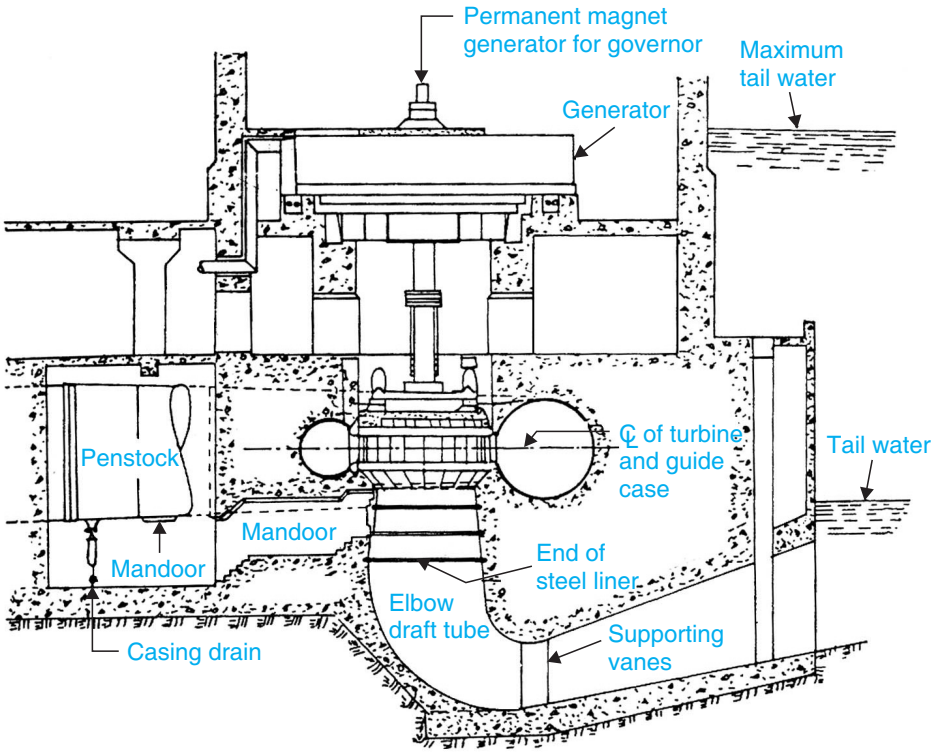


Fig. 6.28. Plate-steel spiral-case setting of vertical Francis turbine, welded casing.

Propeller and Kaplan turbines

The need to utilize low heads where large volumes of water are available makes it essential to provide a large flow area and to run the machine at very low speeds. The propeller turbine is a reaction turbine used for heads between 4 m and 80 m, and has a specific speed ranging from 300 to 1000. It is purely *axial-flow* device providing the largest possible flow area that will utilize a large volume of water and still obtain flow velocities which are not too large.

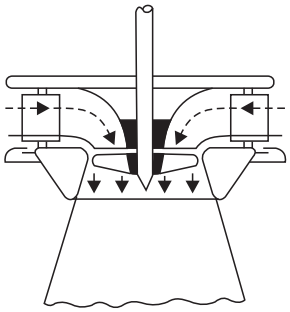
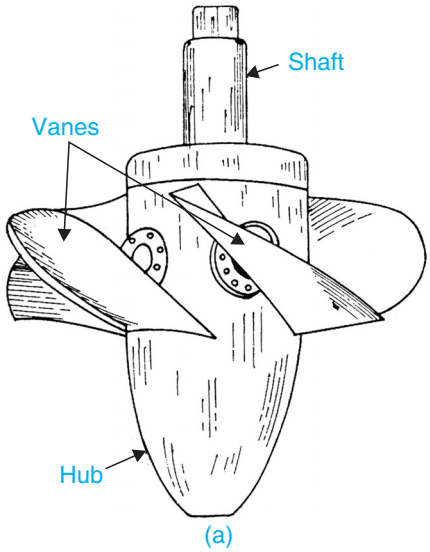


Fig. 6.29. Propeller turbine.

The propeller turbine (Fig. 6.29) consists of an axial-flow runner with four to six or at most ten blades of air-foil shape. The spiral casing and guide blades are similar to those in Francis turbines. In the **propeller turbine** as in Francis turbine the runner blades are *fixed* and *non-adjustable*. However in a *Kaplan turbine* (Fig. 6.30), which is modification of propeller turbine the runner blades are *adjustable and can be rotated about pivots fixed to the boss of the runner. The blades are adjusted automatically by servo-mechanism so that at all loads the flow enters them without shock.*

Kaplan turbines have taken the place of Francis turbines for certain medium head installations. Kaplan turbines with shoping guide vanes to reduce the overall dimensions are being used.



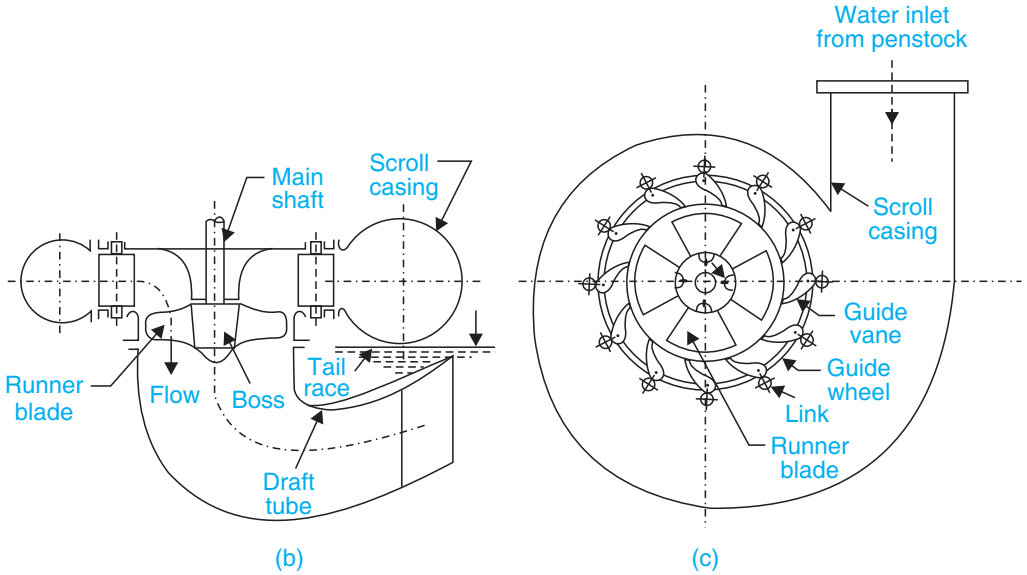


Fig. 6.30. Schematic diagram of a Kaplan turbine.

Fig. 6.31 shows a cross-section of typical low head concrete spiral-case setting, with Kaplan turbine.

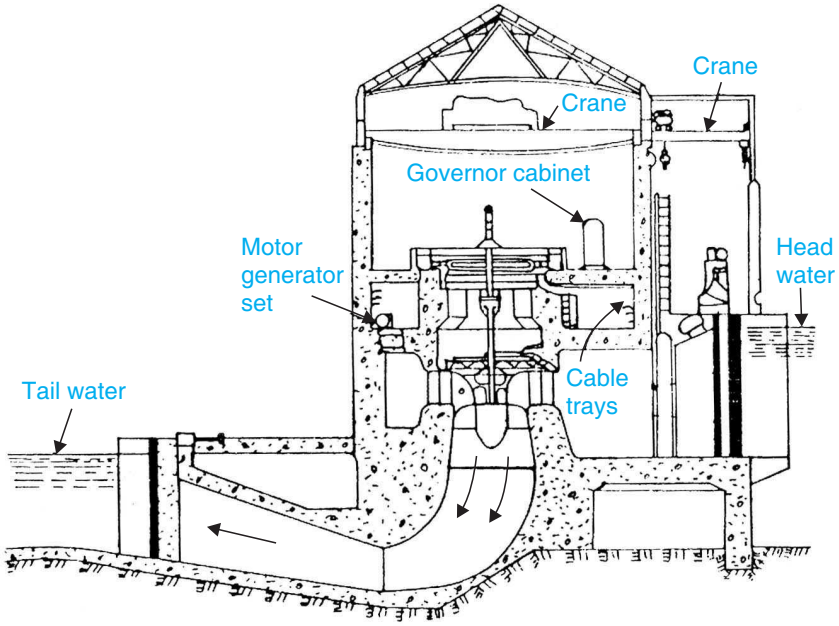


Fig. 6.31. Cross-section of typical low head concrete spiral-case setting, with Kaplan turbine.

Important Kaplan Turbine Installations in India

S. No.	Scheme/Project	Location (State)	Source of water
1.	Bhakra-Nangal project	Gangwal and Kota (Punjab)	Nangal hydel
2.	Hirakud dam project	Hirakud (Odisha)	Mahanadi river
3.	Nizam Sagar project	Nizam sagar (Andhra Pradesh)	Nanjira river
4.	Radhanagri hydroelectric scheme	Kolhapur (Maharashtra)	Bhagvati river
5.	Tungbhadra hydroelectric scheme	Tungbhadra (Karnataka)	Tungbhadra river

Differences between Francis Turbine and Kaplan Turbine

S.No.	Aspect	Francis turbine	Kaplan turbine
1.	*Type of turbine*	Radially inward or mixed flow	Partially axial flow
2.	*Disposition of shaft*	Horizontal or vertical	Only vertical
3.	*Adjustability of runner vanes*	Runner vanes are *not* adjustable	Runner vanes are adjustable
4.	*Number of vanes*	Large, 16 to 24 blades	Small 3 to 8 blades
5.	*Resistance to be overcome*	Large, (owing to large number of vanes and greater area of contact with water)	Less (owing to fewer number of vanes and less wetted area)
6.	*Head*	Medium (60 m to 250 m)	Low (upto 30 m)
7.	*Flow rate*	Medium	Large
8.	*Specific speed*	50–250	250–850
9.	*Type of governor*	Ordinary	Heavy duty

Working proportions : The expressions for work done, efficiency and power developed by axial flow propeller and Kaplan turbines are identical to those of a Francis turbine, and the working proportions are obtained in an identical fashion. However, the following *deviations need to be noted carefully*.

1. In case of a propeller/Kaplan turbine, the ratio n is taken as $\frac{D_b}{D_0}\left(\text{and not } \frac{B}{D}\right)$,

where, D_0 = Outside diameter of the runner, and

D_b = Diameter of boss (or hub).

Discharge Q = Area of flow × Velocity of flow

$$= \frac{\pi}{4}(D_0^2 - D_b^2) \times V_f$$

$$= \frac{\pi}{4}(D_0^2 - D_b^2) \times K_f \sqrt{2gH}$$

(where K_f = flow ratio)

or
$$Q = \frac{\pi}{4} D_0^2 (1 - n^2) \times K_f \sqrt{2gH} \qquad ...(6.9)$$

$$\left(\because \quad n = \frac{D_b}{D_0}\,;\, D_b = nD_0\right)$$

The value of n ranges from 0.35 to 0.60.

The value of $K_f \simeq 0.70$.

2. The peripheral velocity u of the runner vanes depends upon the radius of the point under consideration and thus the blade angles vary from the rim to the boss and the vanes are *warped* ; this is necessary to *ensure shock free entry and exit*.

3. The *velocity of flow remains constant throughout*.

Fig. 6.32 shows the comparison of efficiencies of propeller (fixed blades) and Kaplan turbines.

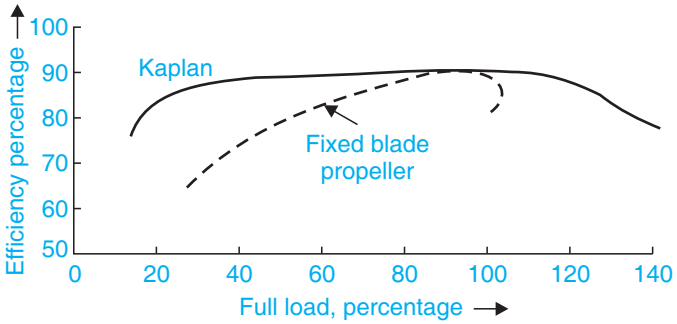


Fig. 6.32. Comparison of efficiencies of propeller (fixed blades) and Kaplan turbines.

Tubular (or Bulb) turbines

Kaplan turbine when employed for very low head has to be installed below the tail race level, thus requiring a *deep excavation.* Further for Kaplan turbine installation there are a number of bends at inlet casing and the draft tube of elbow type through which the water flows describing '*Z*' path giving rise to *continuous losses at the bends.* Whenever the turbine is repaired or dismantled, the generator has to be removed first. The cost of turbine and that of civil engineering works using conventional Kaplan turbine with deep excavation is very high. The efficiency of such plants working under low head is less due to excessive losses at the bends. Therefore, efforts have been made to *reduce the overall cost* and *improve the efficiency of the power plant* keeping these two things in view.

In 1937 Arno Fischer developed in Germany a modified axial flow turbine which is known as *tubular turbine.* The turbo-generator set using tubular turbine has an outer casing having the shape of a bulb. Such a set is now termed as *bulb set* and the turbine used for the set is called a *bulb turbine.* The bulb unit is a water tight assembly of turbine and generator with horizontal axis,

submerged in a stream of water. The economical harnessing of fairly low heads on major rivers is now possible with high-output bulb turbines.

Fig. 6.33 shows a power station (87300 kW) under a head of 10 m, provided with six 14550 kW bulb sets running at 125 r.p.m.

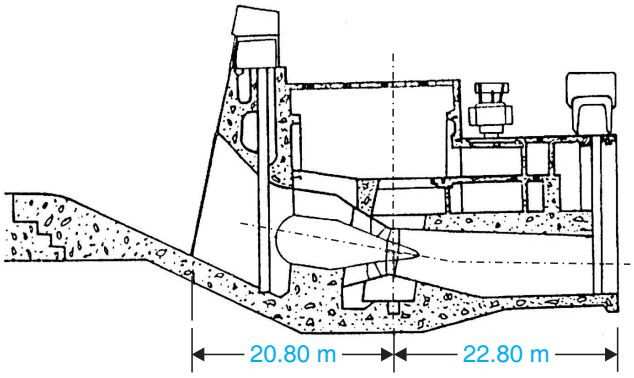


Fig. 6.33. Power station—using bulb turbines.

Runaway speed

'Runaway speed' is the maximum speed, governor being disengaged, at which a turbine would run when there is no external load but operating under design head and discharge. All the rotating parts including the rotor of alternator should be designed for the centrifugal stresses caused by this maximum speed.

The practical values of run away speeds for various turbines with respect to their *rated speed N* are as follows :

Pelton wheel	... 1.8 to 1.9 N
Francis turbine (mixed flow)	... 2.0 to 2.2 N
Kaplan turbine (axial flow)	... 2.5 to 3.0 N

Draft tube

In the case of mixed and axial flow turbines only a part of available energy is converted into velocity energy at the inlet to the runner ; the rest is in the form of pressure energy. This residual pressure is converted into velocity in the runner, as a consequence of which the outlet velocity increases. With the increase in the value of specific speed N_s, the exit velocity energy $\frac{V_2^2}{2g}$ increases compared with H (the available energy).

In the *Pelton Wheel* all the available energy is converted into velocity energy before it strikes the wheel. As such it works under *atmospheric conditions* and the wheel *has to be placed above the maximum tail water level*. The loss of energy due to exit velocity varies from 1 to 4%.

In the case of *mixed and axial flow turbines* a large portion of the energy is associated with the water as it leaves the runner. This exit energy varies from 4 to 25% for mixed flow turbines and from 20 to 50% of the total head for axial flow turbines. As this energy cannot be used in the runner, therefore, it becomes necessary to find a way out to extract this energy. *An expanding pressure conduit hermetically fixed at runner outlet and having the other end below the minimum tail water level helps to convert the velocity head into pressure or potential head. This expanding device is called* **draft tube.** Draft tube is an *integral part* of mixed and axial flow turbines. Because of the draft tube *it is possible to have the pressure at runner outlet much below the atmospheric pressure*.

The draft tube serves the following two *purposes* :

1. *It allows the turbine to be set above tail-water level, without loss of head, to facilitate inspection and maintenance.*
2. *It regains, by diffuse action, the major portion of the kinetic energy delivered to it from the runner.*

At rated load, the velocity at the upstream end of the tube for modern units ranges from 7 to 9 m/s, representing from 2.7 to 4.8 m head. As the specific speed (it is the speed of a geometrically similar turbine running under a unit head and producing unit power) is increased and the head reduced, it becomes increasingly important to have an efficient draft tube. Good practice limits the velocity at the discharge end of the tube from 1.5 to 2.1 m/s, representing less than 0.3 m velocity head loss.

Draft tube theory : Consider a turbine fitted with a draft tube (conical) as shown in Fig. 6.34.

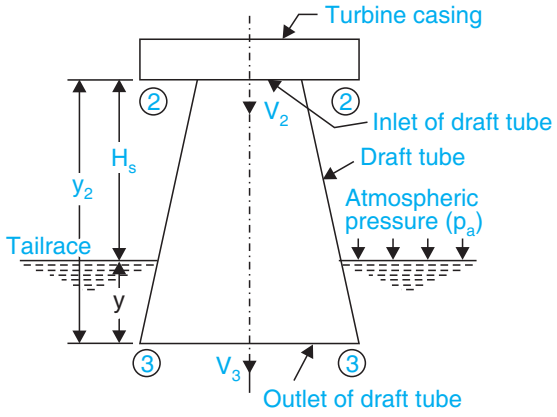


Fig. 6.34. Draft tube theory.

Let y = Distance of the bottom of draft tube from tail race, and p_a = atmospheric pressure at the surface of tailrace.

Applying Bernoulli's equation to the section 2-2 (representing the runner exit or inlet of the draft tube) and the section 3-3 (representing the draft tube exit) ; assuming section 3-3 as the datum line, we have:

$$\frac{p_2}{w} + \frac{V_2^2}{2g} + y_2 = \frac{p_3}{w} + \frac{V_3^2}{2g} + 0 + h_f \qquad ...(i)$$

where, h_f = Loss of energy between sections 2-2 and 3-3.

Rewriting the above expression (i) for $\frac{p_2}{w}$, we obtain:

$$\frac{p_2}{w} = \frac{p_3}{w} - y_2 - \left(\frac{V_2^2 - V_3^2}{2g} - h_f\right) \quad ...(ii)$$

Substituting $\frac{p_3}{w} = \frac{p_a}{w} + y$ in expression (ii), we get:

$$\frac{p_2}{w} = \frac{p_a}{w} + (y - y_2) - \left(\frac{V_2^2 - V_3^2}{2g} - h_f\right)$$

The term $(y_2 - y)$ which represents the vertical distance between the runner exit and the tail water level is called the **suction head of draft tube** and is denoted by H_s. Correspondingly the factor $\frac{V_2^2 - V_3^2}{2g}$ is called the **dynamic head.**

$$\therefore \quad \frac{p_2}{w} = \frac{p_a}{w} - H_s - \left(\frac{V_2^2 - V_3^2}{2g} - h_f\right) \quad ...[6.10\ (a)]$$

In eqn. [6.10 (a)], $\frac{p_2}{w}$ is *less than atmospheric pressure*.

The **efficiency of a draft tube** (η_d) is defined as the *ratio of net gain in pressure head to the velocity head at entrance of draft tube.* Thus

$$\eta_d = \frac{\text{Net gain in pressure head}}{\text{Velocity head at entrance of draft tube}}$$

$$= \frac{\left(\frac{V_2^2 - V_3^2}{2g} - h_f\right)}{\frac{V_2^2}{2g}} \quad ...(6.11)$$

where, V_2 = Velocity of water at section 2-2 (inlet of draft tube).

V_3 = Velocity of water at section 3-3 (outlet of draft tube).

$$h_f = \frac{V_2^2 - V_3^2}{2g} - \eta_d \times \frac{V_2^2}{2g} \quad ...[6.11\ (a)]$$

Types of draft tubes :

The following two types of draft tubes are commonly used :

1. The straight conical or concentric tube ;
2. The elbow type.

Properly designed, the two types are about equally efficient, *over 85 per cent*.

1. Conical type. The conical type draft tube is *generally* used on *low-powered units for all specific speeds, frequently, on large-head units*. The side angle of flare ranges from 4 to 6°, the length from 3 to 4 times the diameter and the discharge area from four to five times the throat area. Fig. 6.35 shows a straight *conical* draft tube.

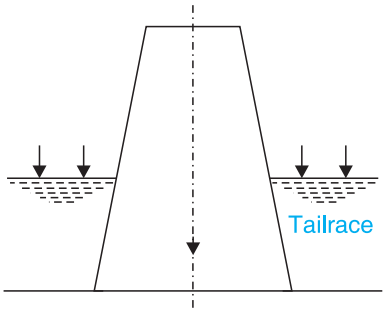


Fig. 6.35. Straight conical draft tube.

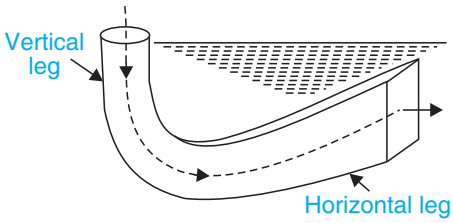


Fig. 6.36. Elbow type draft tube.

2. Elbow type. The elbow type of tube is used with *most* turbine installations. This type of draft tube is designed to turn the water from the *vertical to the horizontal direction with a minimum depth of excavation and at the same time having a high efficiency*. The transition from a circular section in the vertical leg to a rectangular section in the horizontal leg takes place in the bend. The horizontal portion of the draft tube is generally *inclined upwards to lead the water gradually to the level of the tail race and to prevent entry of air from the exit end.* The *exit* end of the draft tube *must be totally immersed in water*. Fig. 6.36 shows an elbow type draft tube. One or two vertical piers are placed in the horizontal portion of the tube, for structural and hydraulic reasons.

Moody spreading draft tube. Fig. 6.37 shows a *Moody's spreading draft tube*. It is provided with a *solid central core* of conical shape which *reduces whirling action of discharge water*. The efficiency of such a draft tube is about 85%. It is suited particularly for *helical flows* which occur when the water leaves the runner with a whirl component.

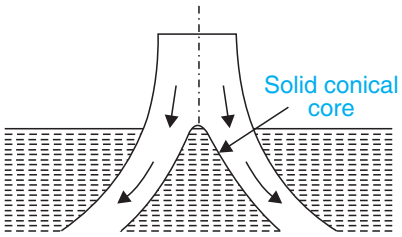


Fig. 6.37. Moody's spreading draft tube or 'Hydrocone'.

Comparison of hydraulic turbines :

A. Francis turbine versus Pelton wheel

The Francis turbine claims the following *advantages* over Pelton wheel :

1. In Francis turbine the variation in the operating head can be more easily controlled.
2. In Francis turbine the ratio of maximum and minimum operating head can be even two.
3. The operating head can be utilized even when the variation in the tail water level is relatively large when compared to the total head.
4. The mechanical efficiency of Pelton decreases faster with wear than Francis.
5. The size of the runner, generator and power house required is small and economical if the Francis turbine is used instead of Pelton wheel for same power generation.

Drawbacks of Francis turbine

As compared with Pelton wheel, the Francis turbine has the following drawbacks :

1. Water which is not clean can cause very rapid wear in high head Francis turbine.
2. The overhaul and inspection is much more difficult comparatively.
3. Cavitation is an ever-present danger.
4. The water hammer effect is more trouble some with Francis turbine.
5. If Francis turbine is run below 50% head for a long period it will not only lose its efficiency but also the cavitation danger will become more serious.

B. Kaplan verses Francis turbine

Kaplan turbine claims the following *advantages* over Francis turbine :

1. For the same power developed Kaplan turbine is more compact in construction and smaller in size.
2. Part-load efficiency is considerably high.
3. Low frictional losses (because of small number of blades used).

6.7.3. Specific Speed of a Turbine

The ***specific speed*** of a turbine is defined *as the speed of a turbine which is identical in shape, geometrical dimensions, blade angles, gate opening etc., with the actual turbine but of such a size that it will develop unit horse power when working under unit head.*

The specific speed may be *derived* as follows :

The overall efficiency (η_o) of any turbine is given by

$$\eta_o = \frac{\text{Power available at the shaft of the turbine}}{\text{Power supplied at the inlet of the turbine}}$$

$$= \frac{P}{w \times Q \times H} \quad \ldots(i)$$

where, P = Shaft power (S.P.),

Q = Discharge through turbine,

H = Head under which turbine is working,

w = Weight density of water.

From eqn. (i),

$$P = \eta_o \times w \times Q \times H$$

$$\propto Q \times H \text{ (as } \eta_o \text{ and } w \text{ are constants)} \quad \ldots(ii)$$

Let, D = Diameter of actual turbine,

N = Speed of actual turbine,

C_{bl} = Tangential velocity of the turbine,

N_s = Specific speed of the turbine, and

C = Absolute velocity of water.

The relation between C, C_{bl} and H is as given below:

$$C_{bl} \propto C, \text{ where } C \propto \sqrt{H}$$

$$\propto \sqrt{H} \quad \ldots(iii)$$

But the tangential velocity C_{bl} is given by:

$$C_{bl} = \frac{\pi DN}{60} \propto DN \quad \ldots(iv)$$

$\therefore$ From eqns. (iii) and (iv), we have:

$$\sqrt{H} \propto DN \quad \text{or} \quad D \propto \frac{\sqrt{H}}{N} \quad \ldots(v)$$

The discharge (Q) through the turbine is given by:

$$Q = \text{Area} \times \text{velocity}$$

But $\text{Area} \propto B \times D$ (where B = width)

$$\propto D^2 \quad (\because B \propto D)$$

$$\therefore \quad Q \propto D^2 \sqrt{H} \propto \left(\frac{\sqrt{H}}{N}\right)^2 \sqrt{H}$$

$$\left[\because \text{From eqn. } (v), \quad D \propto \frac{\sqrt{H}}{N}\right]$$

$$\propto \frac{H}{N^2}\sqrt{H} \propto \frac{H^{3/2}}{N^2}$$

Substituting the value of Q in eqn. (ii), we get:

$$P \propto \frac{H^{3/2}}{N^2} \times H \propto \frac{H^{5/2}}{N^2}$$

$$\therefore \quad P = K\frac{H^{5/2}}{N^2}$$

where, K = constant of proportionality.

If P = 1 kW, H = 1 m, the speed N = specific speeds N_s. Substituting these values in the above equation, we get:

$$1 = \frac{K \times 1^{5/2}}{N_s^{\,2}} \quad \text{or} \quad N_s^{\,2} = K$$

$$\therefore \quad P = N_s^2 \frac{H^{5/2}}{N^2} \quad \text{or} \quad N_s^2 = \frac{N^2 P}{H^{5/2}}$$

$$\therefore \quad N_s = \sqrt{\frac{N^2 P}{H^{5/2}}} = \frac{N\sqrt{P}}{H^{5/4}}$$

i.e., Specific speed, $N_s = \dfrac{N\sqrt{P}}{H^{5/4}}$ ...(6.12)

(where P is in kW and H in metres)

[N_s (S.I. Units) = 0.86 N_s (metric)]

Specific speed plays an important role for *selecting the type of the turbine.* Also the *performance of a turbine can be predicted* by knowing the specific speed of the turbine.

To compare the characteristics of machines of different types, it is necessary to know a characteristic of an imaginary machine identical in shape. The imaginary turbine is called a *specific turbine.* The specific speed provides a means of comparing the speed of all types of hydraulic turbines on the basis of head and horse power capacity.

If a runner of *high specific speed* is used for a given head horse power output, the *overall cost* of installation is *lower*. The selection of *too* high specific speed reaction runner would reduce the size of the runner to such an extent that the discharge velocity of water into the throat of draft tube would be excessive. This is objectionable because a *vacuum* may be created in the extreme case.

The runner of *too high* specific speed with available head *increases the cost of turbine* on account of high mechanical strength required. The runner of *too low* specific speed with low available head *increases the cost of generator* due to the low turbine speed.

An increase in specific speed of turbine is accompanied by lower maximum efficiency and greater depth of excavation of the draft tube. In choosing a high specific speed turbine, an increase in cost of excavation of foundation and draft tube should be considered in addition to the efficiency. The weighted efficiency over the operating range of turbine is more important in the selection of a turbine instead of maximum efficiency.

Table 6.1 gives the specific speeds for various turbines.

Table 6.1. Specific speeds

Type of turbine		*Specific speed (N_s)*	
		M.K.S. Units	*S.I. Units*
Impulse (Pelton)	Slow	4–10	3.5–8.5
	Normal	10–25	8.5–21.5
	Fast	25–60	21.5–51.5
Radial and mixed flow (Francis and Deriaz)	Slow	60–150	51.5–130
	Normal	150–250	130–215
	Fast	250–400	215–345
Axial flow (Kaplan)	Slow	300–450	255–385
	Normal	450–700	385–600
	Fast	700–1000	600–860

Unit Quantities :

Let us consider a *single unit.* When the head on the unit is changed/varied then the speed of an ungoverned turbine changes. The velocities at various points do not change direction but their magnitudes vary in proportion to the *square root of the head.*

At a given point in the turbine under a head H, let

V = Absolute velocity,

V_r = Relative velocity,

u = Peripheral velocity, and

V', V_r', u' = Corresponding values at a different head H', then as velocity is proportional to $\sqrt{H}$, we have

$$\frac{u}{u'} = \frac{V_r}{V_r'} = \frac{V}{V'} = \frac{\sqrt{H}}{\sqrt{H'}} \qquad ...(6.13)$$

If the discharges are Q and Q', then

$$\frac{Q}{Q'} = \frac{V}{V'} = \frac{N}{N'} = \frac{\sqrt{H}}{\sqrt{H'}} \qquad ...(6.14)$$

If the power outputs are P and P', then

$$\frac{P}{P'} = \frac{QH}{Q'H'} = \frac{\sqrt{H}}{\sqrt{H'}} \times \frac{H}{H'} = \left(\frac{H}{H'}\right)^{3/2} \qquad ...(6.15)$$

$$\left(\because \quad \frac{Q}{Q'} = \frac{\sqrt{H}}{\sqrt{H'}}\right)$$

The hydraulic efficiency of the turbine under these two heads may be considered to be nearly same, as the velocity triangles at these heads are similar at a point.

If the various quantities are *reduced to a theoretical one metre head* the comparison of performance data and computations of experimental values on a single unit are *considerably simplified,*

Then $$N_u = \frac{N}{\sqrt{H}} \qquad ...(6.16)$$

$$Q_u = \frac{Q}{\sqrt{H}} \qquad ...(6.17)$$

$$P_u = \frac{P}{H^{3/2}} \qquad ...(6.18)$$

The above quantities are called **unit quantities** of a turbine. *Unit speed is the hypothetical speed of the turbine operating under one metre head.* Similarly other proportionality constants in eqns. (6.17) and (6.18) are defined.

For presenting the performance of geometrically similar turbines independent of the actual head, discharge and power output the ***unit characteristics*** prove quite helpful. **Geometrically similar turbines will have the same unit characteristics under similar operating conditions.** Thus with the help of a model the performance of a prototype can be predicted within certain limits.

If a turbine is working under different heads the behaviour of the turbine can be easily known from the values of the *unit quantities* as follows :

Let H_1, H_2 = Heads under which a turbine works,
N_1, N_2 = Corresponding speeds,
Q_1, Q_2 = Corresponding discharges, and
P_1, P_2 = Corresponding power developed.

Then using eqns. (6.16), (6.17), (6.18), respectively, we obtain

$$N_u = \frac{N_1}{\sqrt{H_1}} = \frac{N_2}{\sqrt{H_2}} \qquad ...(6.19)$$

$$Q_u = \frac{Q_1}{\sqrt{H_1}} = \frac{Q_2}{\sqrt{H_2}} \qquad ...(6.20)$$

$$P_u = \frac{P_1}{H_1^{3/2}} = \frac{P_2}{H_2^{3/2}} \qquad ...(6.21)$$

Model Relationship :

(*i*) Head co-efficient, C_H :

The tangential velocity of the runner,

$$u = K_u\sqrt{2gH} = \frac{\pi DN}{60}$$

or $$N = \frac{60\,K_u\sqrt{2gH}}{\pi D} \quad \text{or} \quad N \propto \frac{\sqrt{H}}{D}$$

$$\therefore \quad ND \propto \sqrt{H}$$

or $$\frac{H}{N^2D^2} = \text{constant} \qquad ...(6.22)$$

The parameter $\frac{H}{N^2D^2}$ is called **head co-efficient, C_H.**

(*ii*) Capacity or flow co-efficient, C_Q :

Discharge through the turbine,

$$Q = \text{Area} \times \text{Velocity} = A \times V_f$$

But $$A \propto D^2$$

and $$V_f = K_f\sqrt{2gH} \propto \sqrt{H}$$

$$\therefore \quad Q \propto D^2\sqrt{H}$$

Substituting the value of Q in eqn. (6.22), we obtain

$$Q \propto D^2 \times ND \propto ND^3$$

or $$\frac{Q}{ND^3} = \text{constant} \qquad ...(6.23)$$

The parameter, $\frac{Q}{ND^3}$ is called the **capacity or flow co-efficient, C_Q.**

(*iii*) Power co-efficient C_p :

The shaft power available from a turbine,

$$P = \eta_o \times wQH \propto Q.H.$$

But $$Q \propto ND^3$$

and $$H \propto N^2D^2$$

$$\therefore \quad P \propto ND^3 \times N^2D^2 \propto N^3D^5$$

or $$\frac{P}{N^3D^5} = \text{constant} \qquad ...(6.24)$$

The parameter $\frac{P}{N^3D^5}$ is called the **power co-efficient, C_P.**

With the use of above relations it is possible to present the behaviour of a prototype from the test runs made on a geometrically similar model ; the model is presumed to have the same values of speed ratio K_u, flow ratio K_f and specific speed N_s. A group of geometrically similar machines are said to belong to a homologous series. All machines of such a series have the same value of C_H, C_Q or C_P or their combinations.

6.7.4. Efficiencies of a Turbine

The important efficiencies of a turbine are as under:

1. Hydraulic efficiency, η_h
2. Mechanical efficiency, η_m
3. Volumetric efficiency, η_v
4. Overall efficiency, η_o.

1. Hydraulic efficiency, (η_h). It is defined as the *ratio of power developed by the runner of a turbine to the power supplied by the water at the inlet of the turbine.*

$$\eta_h = \frac{\text{Power developed by runner}}{\text{Power developed at inlet}} \qquad ...(6.25)$$

2. Mechanical efficiency (η_m). It is defined as the *ratio of power available at the shaft of the turbine* (known as S.H.P. or B.H.P.) *to the power developed by the runner*.

$$\eta_m = \frac{\text{Power available at the shaft of the turbine}}{\text{Power developed by the runner}} \quad ...(6.26)$$

3. Volumetric efficiency (η_v). *The ratio of the volume of the water actually striking the runner to the volume of water supplied to the turbine is called volumetric efficiency*.

$$\eta_v = \frac{\text{Volume of water actually striking the runner}}{\text{Volume of water supplied to the turbine}} \quad ...(6.27)$$

4. Overall efficiency (η_o). It is defined as the *ratio of power available at the shaft of the turbine to the power supplied by the water at the inlet of the turbine*.

$$\eta_o = \frac{\text{Power available at the shaft of the turbine}}{\text{Power supplied at the inlet of the turbine}} = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{wQH}$$

If η_g is the efficiency of a generator, then power output of a hydro-unit (turbine + hydro generators)

$= (wQH) \times \eta_o \times \eta_g$.

6.7.5. Cavitation

It is known that when velocity of flow increases, the pressure falls. In liquids, the pressure cannot fall below vapour pressure which depends upon the temperature and height above mean sea level of the site. *In any turbine part if the pressure drops below the evaporation pressure, the liquid boils and a large number of small bubbles of vapour are formed*. These bubbles mainly formed *on account of low pressure* are carried by the stream to higher pressure zones where the vapours condense and the *bubbles suddenly collapse*, as the vapours are condensed to liquid again. This results in the *formation of a cavity* and the surrounding liquid rushes to fill it. The streams of liquid coming from all directions collide at the centre of cavity giving rise to a *very high local pressure* whose magnitude may be as high as 7000 atmospheres. Formation of cavity and high pressure are repeated many thousand times a second. This causes *pitting on the metallic surface of runner blades or draft tube*. The material then *fails by fatigue*, added perhaps by corrosion. During this process some parts like runner blades may be torn away completely.

'Cavitation' may thus be defined as the "*phenomenon which manifests itself in the pitting of the metallic surfaces of turbine parts because of formation of cavities*".

During 'cavitation' the cavities may be formed on the solid surface or near to it. In case it does not form on solid surface, the *pressure generated in the cavity is propagated by the pressure waves* similar to ones occurring in water hammer. The intense pressure is accompanied by a *considerable vibration and noise*.

Cavitation factor. Prof. Dietrich Thoma of Munich (Germany) suggested a cavitation factor σ (sigma) to *determine the zone* where turbine can work *without being affected from cavitation*. The *critical* value of cavitation factor (σ_c) is given by

$$\sigma_c = \frac{(H_a - H_v) - h}{H} \quad ...(6.28)$$

where, H_a = Atmospheric pressure head in metre of water,

H_v = Vapour pressure in metre of water corresponding to the water temperature,

H = Working head of turbine (difference between head race and tailrace level in metres), and

h = Height of turbine outlet above tailrace level in metres.

The values of critical factor depends upon the specific speed of the turbine (Refer to Table 6.2).

Methods to avoid cavitation :

The following methods may be used to *avoid cavitation* :

1. Runner/turbine may be *kept under water*. But it is not advisable as the inspection and repair of the turbine is difficult. The other method to avoid cavitation zone without keeping the runner under water is *to use the runner of low specific speed*.
2. The *cavitation free runner* may be designed to fulfil the given conditions with extensive research.
3. It is possible to reduce the cavitation effect by *selecting materials* which can *resist better the cavitation effect*. The cast steel is better than cast iron and stainless steel or alloy steel is still better than cast steel.
4. The cavitation effect can be reduced by *polishing* the surfaces. That is why the cast steel runners and blades are coated with stainless steel.
5. The 'cavitation' may be avoided by *selecting a runner of proper specific speed for given head*.

Table 6.2. Cavitation factors

Francis		Kaplan	
N_s	σ_c	N_s	σ_c
50	0.04	300 to 450	0.35 to 0.40
100	0.05	450 to 550	0.40 to 0.45
150	0.07	550 to 600	0.46 to 0.6
200	0.1	650 to 700	0.85
250	0.14	700 to 800	1.05
300	0.2	–	–
350	0.27	–	–

6.7.6. Performance of Hydraulic Turbines

In dimensional analysis we may arrive at the following relations :

Head co-efficient or parameter, $\frac{gH}{N^2D^2}$

Capacity or discharge parameter,

$$\frac{Q}{ND^3} \quad \text{or} \quad \frac{Q}{D^2\sqrt{H}}$$

Power co-efficient,

$$\frac{P}{\rho N^3 D^5} \quad \text{or} \quad \frac{P}{\rho D^2 H^{3/2}}$$

Efficiency of operation, η.

The laws of performance are stated as follows from the fact that each of these parameters should remain constant for the same machine or a family of similar machines :

		For the same machine	*For a similar machine*
Discharge Q	$\propto$	N	D^3
Head H	$\propto$	N^2	D^2
Power P	$\propto$	N^3	D^5

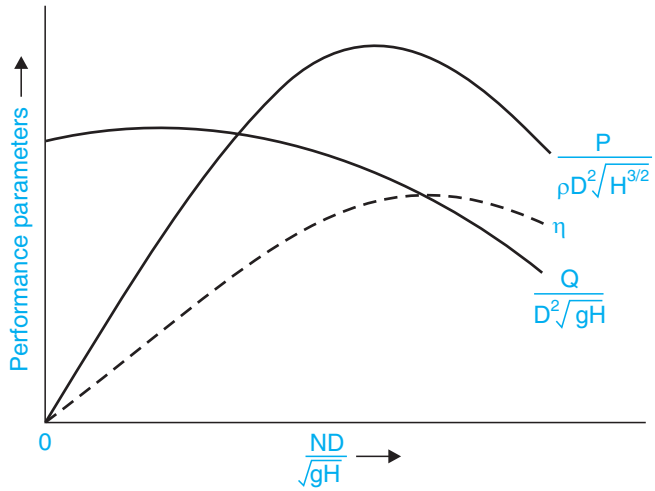
The specific speed, $N_s = \frac{N\sqrt{P/\rho}}{(gH)^{5/4}}$

Which is the type number of fluid machines that must also remain the same for a family of similar machines operating at the optimum efficiency?

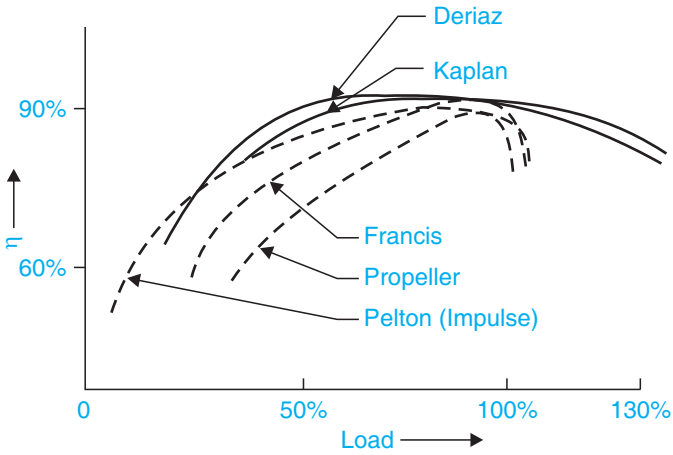
The terms '*unit speed*', '*unit power*' and '*unit discharge*' are frequently used to express the operational features of hydraulic turbines. The unit quantities are theoretical features for a head of 1 metre for the same turbine. Sometimes, the unit quantities are referred to a head of 1 metre for a turbine of 1 metre diameter.

	For unit head	*For unit head and unit diameter*
Unit speed N_u	$\frac{N}{\sqrt{H}}$	–
Unit power P_u	$\frac{P}{H^{3/2}}$	$\frac{P}{D^2H^{3/2}}$
Unit discharge Q_u	$\frac{Q}{\sqrt{H}}$	$\frac{Q}{D^2\sqrt{H}}$

These definitions follow from the definitions of the head, discharge and power coefficients respectively.



(a) Dimensionless turbine curves



(b) Comparison of turbines

Fig. 6.38. Performance of hydraulic turbines.

The characteristic curves for hydraulic reaction turbines are usually plotted in terms of unit quantities *vs* '*unit*' speed. A set of performance curves are shown plotted in Fig. 6.38 (*a*). A comparative set of curves for different types of turbines is shown in Fig. 6.38 (*b*). It can be seen that the *Deriaz and Kaplan turbines have the highest efficiency in the entire load range*. This is due to the fact that the runner blades of these two types of turbines are *adjustable during operation*. Consequently the flow is efficient and well-guided by the runner blades at all flow conditions unlike the other turbines where the rotor-vane adjustability is not provided. The guide vanes of each of reaction turbines are adjusted for varying the discharge.

Fig. 6.39 and Fig. 6.40 shows the *main characteristic curves* for a Pelton wheel and reaction turbine respectively.

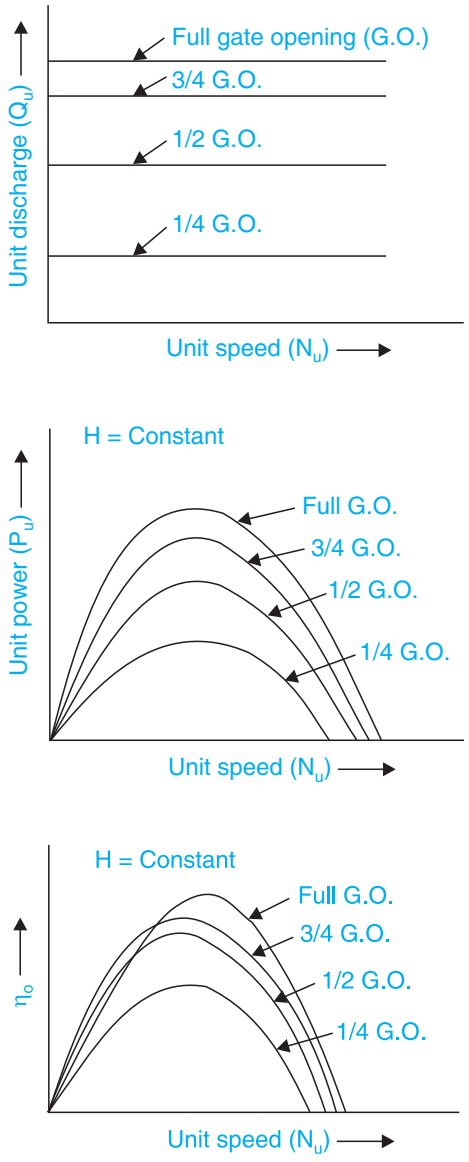
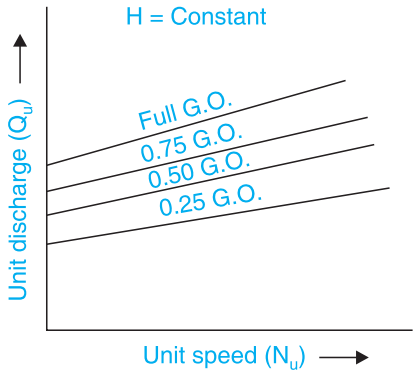
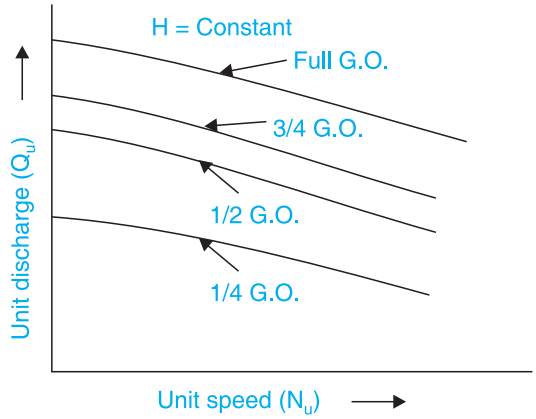


Fig. 6.39. Main characteristic curves for a Pelton wheel.



(a) For Kaplan turbine



(b) For Francis turbine

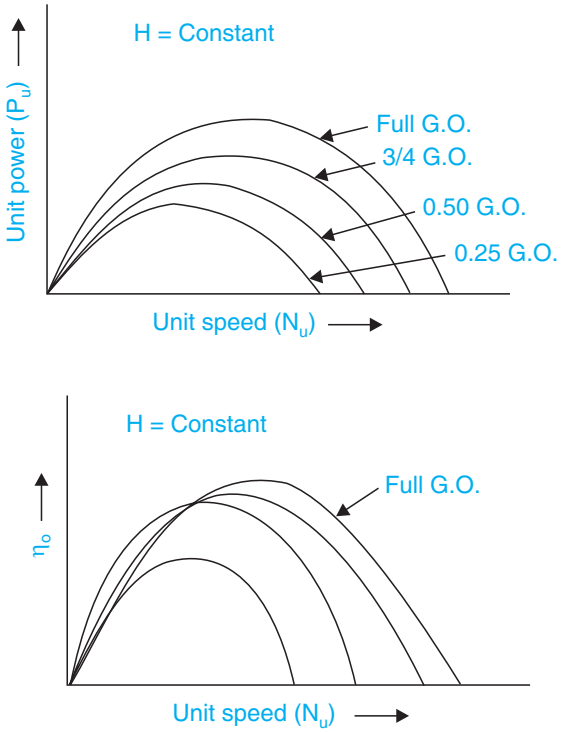


Fig. 6.40 Main characteristic curves for Kaplans turbine and Trancis turbine.

Efficiency load curves

The *efficiency load curves* of various types of *reaction turbines* are shown in Fig. 6.41. The efficiency load curve of a Pelton turbine is shown in Fig. 6.42. The efficiency curve of a Pelton turbine remains slightly lower than that of a Francis turbine but is less affected by variation of load.

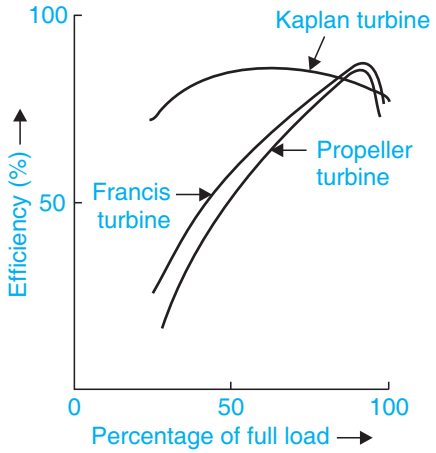


Fig. 6.41. Efficiency-load curves of reaction turbines.

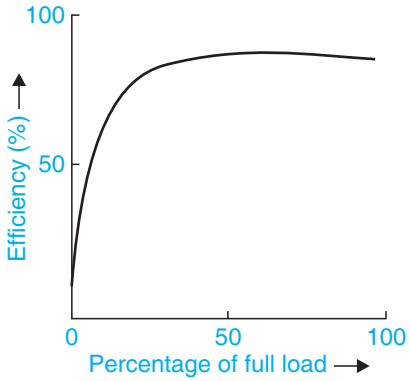


Fig. 6.42. Efficiency-load curve of a Pelton turbine.

6.7.7. Governing of Hydraulic Turbines

Governing of a hydraulic turbine means *speed regulation*. Under normal conditions the turbine should run at a constant speed irrespective of changes in load. This is achieved by means of a governor called oil pressure governor.

Governing of impulse turbine. The quantity of water rejected from the turbine nozzle and from striking the buckets may be regulated in one of the following ways:

1. Spear regulation
2. Deflector regulation
3. Combined spear and deflector regulation.

The spear and deflector in all cases are operated by the servomotor mechanism.

1. Spear regulation. To and fro movement of the spear inside the nozzle alters the cross-sectional area of stream, thus, making it possible to regulate the rate of flow according to the load. Spear regulation is satisfactory *when a relatively large penstock feeds a small turbine and the fluctuation of load is small*. With the sudden fall in load, the turbine nozzle has to be closed suddenly which way create *water hammer in the penstock.*

2. Deflector regulation. The deflector is generally a plate connected to the oil pressure governor by means of levers. When it is required to deflect the jet, the plate can be brought in between the nozzle and buckets, thereby diverting the water away from the runner and directing into the tailrace. Deflector control is adopted *when supply of water is constant* but the *load fluctuates*. The spear position can be adjusted by hand. As the nozzle has always a constant opening, it involves considerable wastage of water and *can be used only when supply of water is abundant*.

3. Combined spear and deflector regulation. Since both the above methods have some disadvantages, the modern turbines are provided with double regulation which is the combined spear and deflector control. Double regulation means regulation of speed and pressure. *The speed is regulated by spear and the pressure is regulated by deflector arrangement*.

Fig. 6.43 shows an arrangement for governing of Pelton turbine when the turbine is running at the *normal speed*.

When the load on the generator decreases, the speed of the generator *increases* and consequently the speed of the turbine and hence centrifugal governor increases beyond the normal speed. Due to increased speed the fly-ball of the centrifugal governor move outwards/upwards (due to increased centrifugal force) causing upward movement of the sleeve. As the sleeve moves up, the lever (a horizontal lever, supported over a fulcrum, connects the sleeve and the piston rod of control valve) turns about the fulcrum and the piston rod of the control valve moves downward. Subsequently the V_1 closes and valve V_2 opens as shown in Fig. 6.43. The oil, pumped from the oil sump to the control valve or relay valve, under pressure will flow through the valve V_2 to the servomotor (or relay cylinder) and will exert force on the face L of the piston of the relay cylinder. The piston along with piston rod and spear will move towards *right*. This will decrease the area of flow of water at the outlet of the nozzle and as a consequence of this the flow rate to the turbine is reduced and the speed of the turbine falls. After the speed of the turbine becomes normal the fly balls, sleeve, lever etc. will come to normal position.

On the other hand, when the load on the generator increases, the speed of the generator and hence that of the turbine and the centrifugal governor decreases due to which its (governor) balls move downward, the sleeve moves down and piston rod of the control valve moves in the upward direction. Subsequently valve V_1 opens and valve V_2 closes. The oil under pressure will move through valve V_1 and exert a force on face M of the piston. This will make the piston move towards left thereby increasing the area of flow of water at the outlet of the nozzle and hence increase the rate of flow of water to the turbine. As a result, the speed of the turbine will increase till it becomes normal.

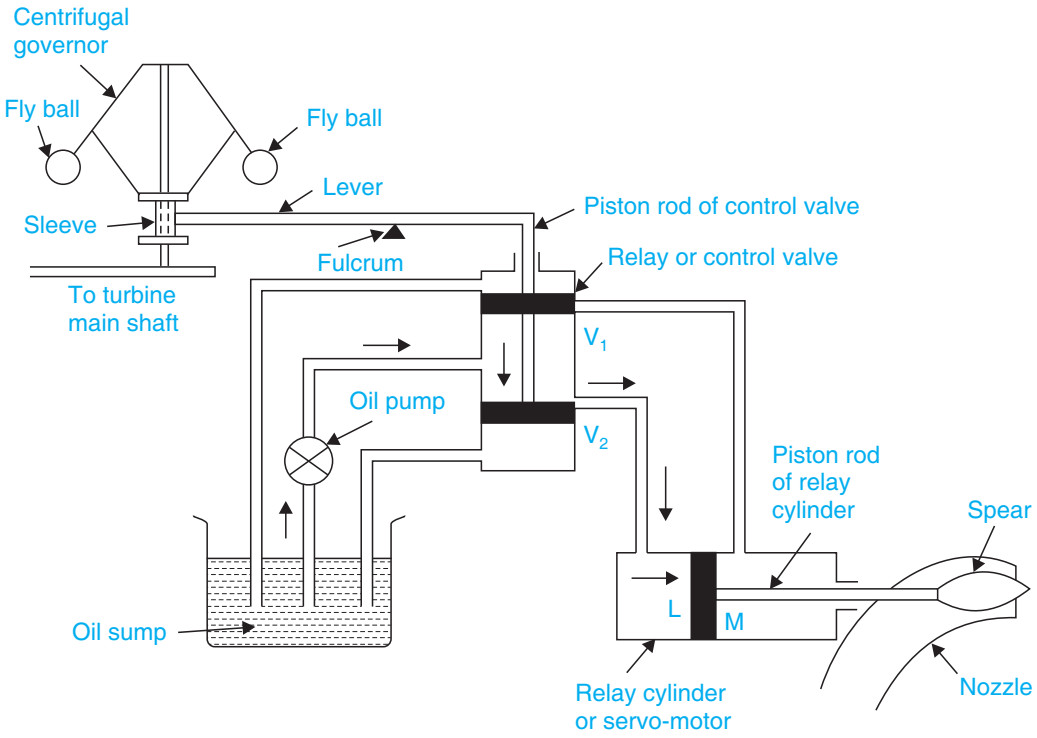


Fig. 6.43. Governing of Pelton turbine.

Governing of reaction turbines

Refer to Fig. 6.44. The guide blades of a reaction turbine are pivoted and connected by levers and links to the regulating ring. To the regulating ring are attached two long regulating rods connected to the regulating lever. The regulating lever is keyed to a regulating shaft which is turned by a servomotor piston of oil pressure governor. The penstock which feeds the turbine inlet, has a relief valve better known as '*Pressure Regulator*'. When the guide vanes have to the suddenly closed, the relief valve opens and diverts the water direct to the tailrace. Its function is therefore, similar to that of deflector in Pelton turbines. Thus the double regulation, which is the simultaneous operation, of two elements is accomplished by moving the guide vanes and relief valve in Francis turbines, by the governor.

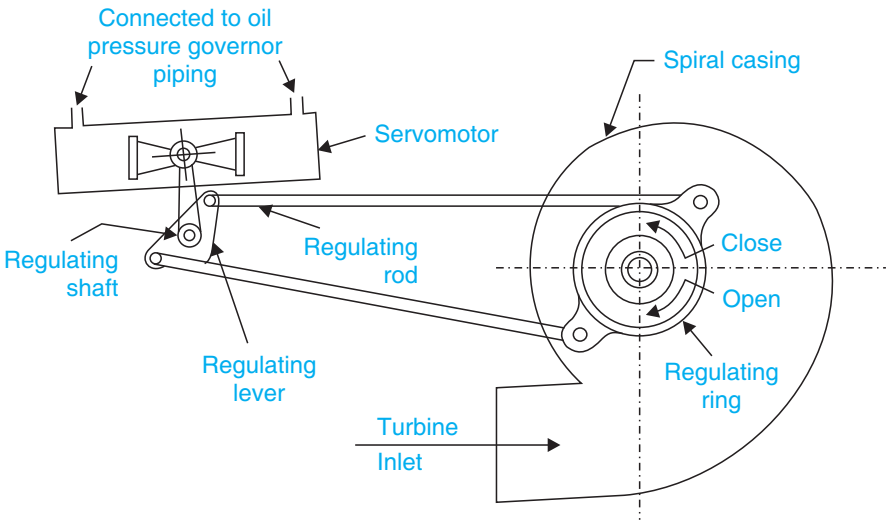


Fig. 6.44. Governing of reaction turbines.

Fig. 6.45 shows the speed governing systems for by hydraulic turbines schematically.

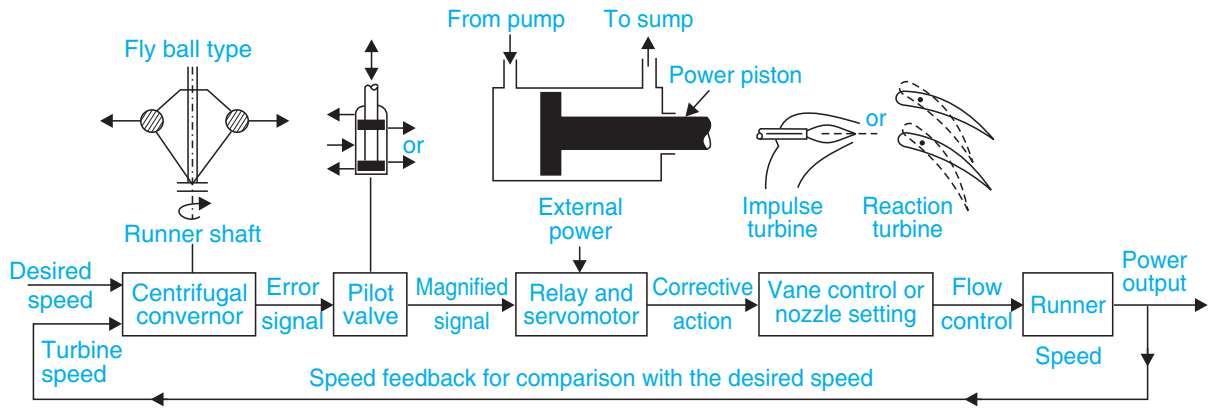


Fig. 6.45. Speed governing systems for hydraulic turbines.

6.7.8. Selection of Turbines

The following points should be considered while selecting the right type of hydraulic turbine :

1. Specific speed. High specific speed is essential where head is low and output is large, because otherwise the rotational speed will be low which means cost of turbo-generator and power house will be high. On the other hand there is practically no need of choosing a high value of specific speed for high head installations, because even with low specific speed, high rotational speed can be attained with medium capacity plants.

2. Rotational speed. Rotational speed depends on specific speed. Also the rotational speed of an electrical generator with which the turbine is to be directly coupled, depends on the frequency and number of pair of poles. The *value of specific speed adopted should be such that it will give the synchronous speed of the generator*.

3. Efficiency. The turbine selected should be such that it gives the *highest overall efficiency for various operating conditions*.

4. Part load operation. In general the efficiency at part-loads and overloads is less than normal. For the sake of economy the turbine should always run with maximum possible efficiency to get more revenue.

When the turbine has to run at part or overload conditions Deriaz turbine is employed. Similarly, for low heads, Kaplan turbine will be useful for such purposes in place of propeller turbine.

5. Cavitation. The installation of water turbines of reaction type over the tailrace level is effected by *cavitation*. The critical value of cavitation factor must be obtained to see that the turbine works in safe zone. Such a value of cavitation factor also effects the design of turbine, especially of Kaplan, propeller and bulb types.

6. Disposition of turbine shaft. Experience has shown that the vertical shaft arrangement is better for large-sized reaction turbines, therefore it is almost universally adopted. In case of large size impulse turbine, horizontal shaft arrangement is mostly employed.

7. Head. (*i*) *Very high heads (350 m and above)*. For heads greater than 350 m, Pelton turbine is generally employed and there is practically no choice except in very special cases.

(*ii*) *High heads (150 m to 350 m)*. In this range either Pelton or Francis turbine may by employed. *For higher specific speeds Francis turbine is more compact and economical than the Pelton turbine* which for the same working conditions would have to be much bigger and rather cumbersome.

(*iii*) *Medium heads (60 m to 150 m)*. A *Francis turbine* is usually employed in this range. Whether a high or low specific speed unit would be used depends on the selection of speed.

(*iv*) *Low heads (below 60 m)*. Between 30 to 60 *m* heads both Francis and Kaplan turbines may be used. The latter is more expensive but yields a higher efficiency at part loads and overloads. It is therefore preferable for variable loads. *Kaplan turbine is generally employed for heads under 30 m*. Propeller turbines are, however, commonly used for heads upto 15 m. *They are adopted only when there is practically no load variation*.

(*v*) *Very low heads*. For very low heads *bulb turbines* are employed these days. Although Kaplan turbines can also be used for heads from 2 m to 15 m but they are *not economical*.

6.8. PLANT LAYOUT

The plant layout is considerably affected by the nature of project.

In *low head plants*, the width of the dam is usually small and *suitable space* for fixing the turbines and generators is *limited*. On the other hand, in high head schemes the site for the power plants can be selected more conveniently to give desired layouts.

The *size and type of units* proposed to be installed also affect the layout of the power station.

For *reaction machines with vertical single runner*, the arrangement with the machines in a *line parallel to the length of the turbine house is usually preferred* ; the spacing between two units being controlled by the width of the flume or scroll case at entrance to the runner or the width of the draft tube at its month, or sometimes by the overall diameter of the alternator. *Horizontal machines of the reaction type* are best located at *right angles to the length of the turbine house* while for impulse machines with horizontal setting the wheel shaft is placed parallel to the longitudinal axis of the turbine house.

Unlike the reaction machines, the spacing of the impulse machines is fixed by the machine dimensions and necessary clearances rather than by the penstock flume or tailrace, as the amount of water discharged is comparatively small. For impulse machines with vertical setting the arrangement with centres on a line parallel to axis of turbine house is suggested. The use of such machines is rare.

6.9. HYDRO-PLANT AUXILIARIES

The following auxiliaries are essential for *starting the generating unit* :

(*i*) Exciter
(*ii*) Governor oil system
(*iii*) Lubricating oil pump.

The station can start usually independent of external power, but stand-by auxiliaries are needed for emergency service. Exciter for the main generator may be direct connected, motor-generator type engine driven or auxiliary water turbine driven. *Direct connected exciters make the unit independent of auxiliary power and also have higher efficiency than the other types*. Motor generator exciters depend upon electric power for starting, whereas an engine driven exciter is an independent unit. *The efficiency of water turbine driven exciter is very low and this is not suited for any other use except during emergencies*. The exciter is an essential piece of equipment and it is important to select a drive that is reliable and at the same time reasonably low in first cost and operation. The pressurised oil system for the governor is driven from the turbine main shaft and sufficient pressure is usually maintained in the oil tanks during the shut down, so that the turbine can be started. A stand-by motor driven pump is also installed for emergency service. The lubricating oil pumps may be driven from the turbine shaft and would work as soon as the unit starts. Sometimes a stand-by lubricating pump is also installed.

During starting of hydro-plants the following auxiliaries are *not directly* needed :

(*i*) Coolant pumps
(*ii*) Air compressors
(*iii*) Drainage pumps
(*iv*) Fans and cooling oil pumps
(*v*) Cranes
(*vi*) Gate hoists
(*vii*) Valves
(*viii*) Battery charging units etc.

These auxiliaries are generally electrically driven. Water may be used to cool the bearings of the turbine and generator and transformers and is circulated through water pumps. *Air compressors* maintain a supply of air under pressure for operation of generator brakes and other uses in the power station. Unwatering of turbine pits may be required during repairs or check up for which *water pumps* are necessary. *Fans* are required for ventilation of the turbine and switch gear room or for cooling transformers. *Oil pumps* handle transformer oil through the cleaning and cooling system. *Cranes* are required during machinery repairs and installations to lift heavy parts or place them in position. The head works *control gates* with *hoists* which may be manually or electrically operated. *Storage batteries* are needed to supply low voltage D.C. power for switch gear control. During failure of the main generators lighting and power for the station may also be obtained from the batteries.

Most of the station auxiliaries are electrically driven due to obvious advantages of using such drivers.

6.10. COST OF HYDRO-PLANT

The cost of hydro-plant varies from ₹ 850 to ₹ 950 per kW of capacity. A typical subdivision of investment under various items (*e.g.* as dam, tailrace, reservoir, turbines, generators, land, building and foundations, switching and wiring, switchyard etc.) is as follows :

1. Reservoir, dam, intake, tailrace	35%
2. Turbines and generators	20%
3. Land, building and foundations	30%
4. Switching and wiring	5%
5. Switchyard	5%
6. Miscellaneous	5%

6.11. AVERAGE LIFE OF HYDRO-PLANT COMPONENTS

The average life (approximate) of various components of hydro-electric power plant is given below :

Components	*Average life (years)*
1. Reservoirs	70–80
2. Dams	
(*i*) Earthen, concrete or masonry	150
(*ii*) Loose rock	60
3. Water ways	
(*i*) Canals, tunnels	50–100
(*ii*) Penstocks	
(*a*) Steel	40–50
(*b*) Concrete	25–50
4. Powerhouse and equipment	
(*i*) Building	35–50
(*ii*) Generators	25
(*iii*) Transformers	30
(*iv*) Turbines (hydraulic)	5
(*v*) Pumps	20–25

6.12. HYDRO-PLANT CONTROLS

The various controls which are provided in an hydro-electric power plant are enumerated and discussed below :

1. Hydraulic controls
2. Machine controls—Starting and stopping
3. Machine controls—Loading and frequency
4. Voltage control of generator and system
5. Machine protection.

1. Hydraulic controls. In a hydro-plant the following *hydraulic controls are provided* :

(*i*) Storage level indicators—primary and secondary
(*ii*) Flood control
(*iii*) River flow control
(*iv*) Intake gate control.

2. Machine controls—Starting and stopping. The control of water flowing to the turbine is exercised by providing gates and valves in the supplying conduit and at the turbine inlet. The quantity of water flowing to the turbine is regulated according to the load on the generator by the use of a governor system. While starting the turbines the casing should be filled gradually and to limit the rate of water flow by-pass valves are provided.

3. Machine controls—Loading and frequency. The load on the machine is controlled as follows :

(*i*) By adjusting the governor speed control
(*ii*) By controlling system frequency.

4. Voltage control of generator and system. The voltage regulators are employed to ensure that electric power is supplied at proper voltage.

5. Machine protection. In a hydro-plant provision of protective devices should be made to guard against breakdown of turbo-generator and auxiliary services, like transformers, switchgears, overhead lines etc. Protection measures are also required to guard against incorrect operation and failure of control system.

Automatic controls are efficient, safe and reliable

The control room should be designed for convenience of operation and the equipment should be so arranged/ spaced that it is easily accessible.

6.13. ELECTRICAL AND MECHANICAL EQUIPMENT IN A HYDRO-PLANT

In an hydro-electric power plant the electrical and mechanical equipment comprise of the following :

A. *Electrical equipment*

In electrical equipment the following elements items are included :

(*i*) Generators
(*ii*) Exciters
(*iii*) Voltage regulators
(*iv*) Transformers
(*v*) Switchgear
(*vi*) Control room equipment.

Generators. The generators employed in a hydro-plant are usually 3-phase synchronous machines and have either a vertical shaft arrangement or horizontal shaft arrangement ; but *vertical shaft arrangement is preferred*.

The generator cooling may be achieved by air circulation through the stator ducts. Cooling by water cooled heat exchangers is common.

The power output of a 3-phase alternator is given by:

$$P = \sqrt{3}\ VI \cos \phi \times 10^{-6} \text{ MW}$$

where, P = Power output,
V = Voltage (in volts),
I = Current (in amperes), and
$\cos \phi$ = Power factor (varies from 0.9 to 0.95).

Transformers. These may be of single phase or three phase type. They are oil filled for insulation and cooling purposes. The generated voltage is stepped up by means of step up transformers. Transformers may be of power or distribution type.

Switchgear. A switchgear consists of *switches, isolators, surge arrestors and circuit breakers*. Its main function is to *make and break the circuits*.

For generated voltage it is preferred to locate switchgear indoors whereas outdoor location is used for transmission voltage.

When switchgears and transformers are located outside they should be provided adequate lightening protection.

Control room equipment. It performs the following functions : (*i*) Machine starting and stopping, (*ii*) Generator and system voltage control, (*iii*) Machine loading control, (*iv*) Frequency control, (*v*) Hydraulic control, (*vi*) Machine running control.

B. *Mechanical equipment*

Mechanical equipment include the following :

(*i*) Compressors and air ducts

(*ii*) Shaft, coupling, bearings etc.

(*iii*) Braking equipment for the generator

(*iv*) The oil circuits and pumps

(*v*) Cranes and other lifting equipment

(*vi*) Ventilation and cooling systems

(*vii*) Equipment for water supply and drainage

(*viii*) Equipment for power house lighting.

6.14. COMBINED HYDRO AND STEAM POWER PLANTS

An electrical power system should fulfil the following objectives :

1. To ensure an *adequate and reliable electric power supply* at all loads and at all times.
2. The source of energy should be such as to give the *minimum overall cost of the system as a whole*.

The above objectives (unless a country/region is rich either in abundant supply of cheap fuel or ample water power resources which can be developed at suitable site) can be best realised by a *judicious combination of both hydro and thermal power*. Hydro-power represents a renewable source of energy which enjoys many intrinsic advantages as compared to thermal power. Although the cost of construction of hydro power plant is nearly same as that of a coal based steam power plant in terms of investment for MW, but hydro-power plant uses water for power generation which is available in abundance in nature.

It is known as that *hydro-plant can meet the demands of load variations more rapidly and easily*. Thus, *when the rate of flow of water is low, the steam plant can work at constant load producing a better efficiency and the hydro-plant will work most effectively as peak load plant and its output can be varied to meet the load fluctuations*. The steam and hydro-plants reverse their functions (*steam plant providing the peak load and the hydro-plant providing base load*) when high rate of water flow is available. But even under this condition, the *steam plant output will remain constant* and the hydro-plant output *will be varied to meet the load fluctuations*.

6.15. COMPARISON OF HYDRO-POWER STATION WITH THERMAL POWER STATIONS

The comparison between hydro-power stations and thermal power stations is given below :

S. No.	Aspects	Hydro-power station	Thermal power station
1.	*Raw material consumption*	Nil. Water power is in exhaustible and perpetual and is continuously replenished by the direct agency of sun.	Huge quantity of coal consumed, thereby exhausting "fuel reserves".
2.	*Cost of energy*	Cheaper	Costlier
3.	*Cost of energy generation*	Immune to inflation.	Very much influenced by the increase in the cost of fuel.
4.	*Life of plant*	Long useful life.	Not so long comparatively. The component parts deteriorate and become obsolete at a faster rate.
5.	*Pollution*	Free from problems of pollution.	Causes pollution and sub-sequently create health hazards.
6.	*Design, construction and reliability*	Simple in design, robust in construction and reliable in operation.	Comparatively more complicated in design, less robust in construction and less reliable in operation.
7.	*Running below a certain minimum load factor.*	Can be run	Cannot be run
8.	*Reserve capacity and variation in power demands.*	Particularly suited to provide reserve capacity as well as meeting the exacting needs of daily variation in power demands.	Comparatively not suited for the mentioned requirements.

9.	*Employment potential*	More. Affords a relatively high employment potential and better utilization of the available local talent and resources.	Less
10.	*Man power required* *Labour problem*	Small Less	Large More
11.	*Foreign exchange requirements for equipment*	Less	More
12.	*Construction time required*	Almost same as thermal power station.	Almost same as hydro-power station.
13.	*Overall capital expenditure requirements*	Low	High

6.16. UNDERGROUND HYDRO-PLANTS

The conventional hydro-plant is usually located overground at the foot of a dam or a hill slope on the banks of a river. The first of these plants was set up in U.S.A as far back as 1898. Since then several underground stations have been set up in Germany, France, Sweden, Switzerland and other countries.

Consideration supporting the construction of underground hydro-plants

1. A suitable site for a conventional surface station/ plant and good slope for penstock *not available*.
2. There may be danger of falling rocks and snow avalanches particularly in narrow valleys.
3. Availability of underground sound rock and avoidance of a long pressure tunnel and facility for a convenient tailrace outlet.
4. Possibility of elimination of surge tank required for surface station due to long pressure channel.
5. The rugged topographical features and the difficulties in finding a suitable short and steep slope for pipe lines make it more economical to install the water conduit, the machine, transformer hall and tailrace system underground.

Types of layouts for underground hydro-plant

The following are two distinctly different types of layouts for underground hydro-power stations :

(*i*) The head development

(*ii*) The tail development.

In the *head development* the powerhouse is located at the intake and provides a long unlined tailrace tunnel. The necessity of surge shafts and penstocks is eliminated and quicker opening and closing of the turbine is possible. The same crew can operate the power house and headworks which gives an operational advantage.

In the *tail development* the power house is placed at the surge end of the low pressure tunnel. This requires a short tailrace. Access tunnels and shafts are necessary in both types. Between these two extreme layouts there is a wide range of intermediate possibilities for plant location.

Before taking a decision in favour of the underground station, *thorough geological investigations of the site are essential. Rock should be properly tested to devise economical tunneling method which may considerably affect the cost of construction of the power station.*

Advantages of the underground Powerhouse/ Station

1. Better rock bearing properties.
2. Foundation difficulties are easier to come.
3. In planning the design and location of the principal works surface topography does not interfere at all.
4. There is greater freedom in positioning stations.
5. Maintenance cost of power station including painting, heating etc. are practically eliminated.
6. These stations are safer from defence point of view and are immune to bombardment. They are also protected against such natural hazards as rain, wind, loose rocks etc.
7. There is saving in cost of land.
8. Land acquisition problem is minimum.
9. There is greater uniformity in climatic conditions during all seasons.
10. In steep and rugged countryside, the site selection for an outdoor plant may cause difficulties due to the risk of avalanches and land slips. At some places there might be added hazard due to forest fire.
11. Uninterrupted construction work in adverse weather.
12. Shorter conduit lengths and therefore smaller surge tanks.

13. A tailrace tunnel may be easier to design and construct compared to the headrace pressure tunnel.
14. The useful life of the structures excavated in the rock is considerably longer than that of concrete and reinforced concrete structures.
15. It is possible to improve the governing of the turbines with the construction of underground power station.
16. The construction period is reduced mainly due to the possibility of full-scale construction work in winter.
17. At places, where there is extreme difference in climate of winter and summer, a uniform temperature can be maintained inside the plant with adequate control of ventilation regardless of outside weather.

Disadvantages :

1. The cost of construction of power station and accessories is more.
2. Increased cost of lighting, special ventilation and air conditioning.
3. The tailrace tunnels and additional surge chambers are costly.
4. Additional cost of underground location of transformers etc.

6.17. AUTOMATIC AND REMOTE CONTROL OF HYDRO-STATION

Some automatic controlling devices such as *relays, governors*, *voltage regulators* etc. are employed in every hydro-station, big or small. However, a few operations may still be needed to start or stop the units and distribute load on two or more units in operation at a time. For stations where full shift operation is not required, the services of the operators are not fully utilized. A saving in working cost of plant can be effected if the functions of the operators are derived from an automatic control system.

An automatic system is more safe, efficient and reliable and usually works through the governor and the voltage regulator. Due to these reasons automatic hydro-stations have been developed. Automatic plants may be divided into following three classes :

1. Fully automatic plant
2. Partly automatic plant
3. Remote controlled plant.

1. Fully automatic plant. This type of plant may be controlled by :

(*i*) A time switch (*ii*) A float switch
(*iii*) A load sensitive device.

The *time switch* may start and stop the power station at preset clock timings.

The *float switch* works with the change in level of water in the reservoir, so that if the water level rises the generator output is increased and *vice versa*. Thus the station shares the load in interconnected system according to availability of water in the reservoir.

The *load sensitive device* is actuated by the demand for power in the area served by the plant, so that increase in power demand would increase the output of the generators automatically. In case of any trouble arising anywhere in the system, the plant is automatically shut-down till such time as the source of trouble is removed.

2. Partly automatic plant. In partly automatic system the units are manually started and synchronised, but in case of a fault shutdown automatically. The partly automatic system is cheaper than fully automatic control system.

3. Remote control plant. When the control on a power system is exercised from a distance, usually from another generating station or control centre, the automatic control system becomes a remote controlled one. In such a system the operator at the control point transmits a signal to the controlled station and this actuates the automatic system at the station to perform the desired effect such as starting and stopping of the units and load distribution among the sets in operation. The automatic remote control system also receives from the controlled stations all necessary information such as water level in the reservoir, share of load supplied by each unit etc.

Small hydro-plants which are not justified to be developed for manual control, can usually be justified by the application of remote automatic control.

6.18. SAFETY MEASURES IN HYDRO-ELECTRIC POWER PLANTS

Following safety measures need to be taken for the safe operation of an hydro-electric power plant :

1. Surge tanks
2. Screens
3. Sand traps
4. Jet dispersers
5. Pressure regulator.

Surge tanks. A surge tank is used to *prevent sudden increase of pressure* in the supply line or the penstock. It is placed as near as possible to the turbine. The tank may be open at the top or closed. In case it is open at the top, it must not be lower than the level of the water in the reservoir.

Screens. These are provided to prevent logs, fishes, ice blocks and other obstructive elements from entering the pipe lines and turbines.

Sand traps. Sand traps are provided to prevent the sand flowing with water in pipes since sand blast action of solid matter in the water causes rapid wear of nozzles, spears, blades etc. of the turbine.

Jet dispersers. The discharged water at the bottom of the high dams possesses large amount of energy which is likely to cause scouring of the channel below the dam and consequent damage to the dam foundation unless some means are provided to dissipate it. The possible remedies for this are either *to discharge water into a cushion pool* or *to provide a jet dispersers* at the end of outlet pipe so that the end of the outlet pipe is such that the jet is broken up into a conical shower of drops and their energy is absorbed by air.

Pressure regulator. It is usually operated by a governor of the turbine. It is provided on the pipeline near the turbine inlet so that when the turbine gates are suddenly closed, pressure surges so produced are kept within the safe limits of the pipeline. The water discharged from the regulator is passed on to tailrace through a separate pipeline.

6.19. PREVENTIVE MAINTENANCE OF HYDRO-PLANT

The purpose of preventive maintenance is to minimise breakdown and excessive depreciation resulting from neglect. In a hydro-plant (using reaction turbines) monthly, quarterly, half yearly and yearly inspection and maintenance are carried out on the following parts :

Inspection/ Maintenance	Parts
Monthly	*Turbine cover parts* (*e.g.* leakage unit, drainage holes, servomotor connections, turbine shaft and cover, oil pump etc.)
	Operating ring of turbines
	Guide vane mechanism
Quarterly	*Servomotor*
	Governor oil system
	Ejector cabinet
	Feedback system
Half yearly	*Governor mechanism*
	Gauges
	Grease pumps for guide vanes and guide bearings
	Grease pipes connected to grease pumps
Yearly	*Turbine auxiliaries* (*e.g.* oil pressure tank, turbine guide bearing, turbine instruments)
	Scroll casing runner with guide vanes
	Emergency slide valve
	Pit liner
	Draft tube
	Runner blades checked for cavitational effects, cracks and wearing out.

6.20. CALCULATION OF AVAILABLE HYDRO-POWER

The theoretical power available from falling water can be calculated using the following formula :

$$P_{th} = \frac{wQH}{1000} \text{ kW} \qquad ...(6.29)$$

where, P_{th} = Theoretical output in *kW*,

w = Weight density of water in N/m^3,

Q = Flow through turbine (or quantity of water available for hydro-power generation) in m^3/s, and

H = Head available in *metres*.

The actual useful or *effective output* depends upon the efficiency of the various parts of the installation.

If η_1 = Efficiency of pipelines, intake etc., and

η_2 = Efficiency of hydraulic turbine,

Then *overall efficiency* $\eta_o = \eta_1 \times \eta_2$.

Since the turbine and the generator are directly coupled on common shaft the hydro-electrical power available will be given by the equation :

$$P_{actual} = P_{th} \times \eta_o \qquad ...(6.30)$$

or

$$P_{actual} = \frac{wQH}{1000} \times \eta_o \text{ kW} \qquad ...(6.31)$$

6.21. COST OF HYDRO-POWER

The initial cost of any hydro-plant is very high but the power produced by it is the cheapest. The following costs are included in development of a hydro-plant :

1. Cost of land and riparian rights
2. Cost of railways and highway required for the construction work
3. Cost of construction
4. Cost of engineering supervision of the project
5. Cost of building etc.
6. Cost of equipment
7. Cost of equipment used for power transmission.

6.22. HYDROLOGY

6.22.1. Introduction

Hydrology may be defined as the *science which deals with the depletion and replenishment of water resources.* It deals with the surface water as well as the ground water. It is also concerned with the *transportation of water* from one place to another, and from one form to another. It helps us in determining the occurrence and availability of water.

Hydrology aims at answering the following major questions :

(*i*) How is the water going to precipitate ?

(*ii*) How is water going to behave ?

(*iii*) What will happen to water after precipitation ?

The basic knowledge of this science is a must for every civil engineer, particularly the one who is engaged in the design, planning or construction of irrigation structures, bridges and highway culverts, or flood control works, etc.

6.22.2. The Hydrologic Cycle

Most of the earth's water sources, such as rivers, lakes, oceans and underground sources, etc. get their supplies from rains, while the rain water itself is the evaporation from these sources. Water is lost to the atmosphere as vapour from earth, which is then precipitated back in the form of rain, snow, hail, dew, sleet or frost, etc. This evaporation and precipitation continues for ever, and thereby, a balance is maintained between the two. This process is known as *Hydrologic Cycle*. It can be represented graphically as shown in Fig. 6.46. Hydrologic equation is expressed as follows :

$$P = R + E \qquad ...(6.32)$$

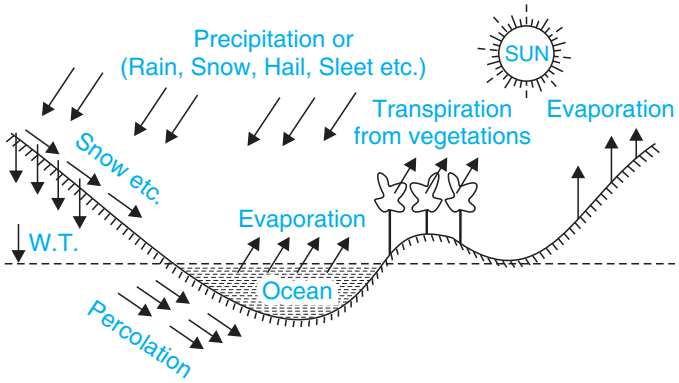


Fig. 6.46. Hydrologic cycle.

where, P = Precipitation,

R = Run-off, and

E = Evaporation.

Precipitation. It includes all the water that falls from atmosphere to earth surface. Precipitation is of two types : (*i*) Liquid precipitation (rain fall), (*ii*) Solid precipitation (snow, hail).

Run-off and surface run-off. Run-off and surface run-off are two different terms and should not be confused. *Run-off* includes all the water flowing in the stream channel at any given section. While the *surface run-off* includes only the water that reaches the stream channel without first percolating down to the water table.

Run-off can, therefore, also be named as Discharge or Stream flow. Rainfall duration, its intensity and a real distribution influence the rate and volume of run-off.

Evaporation. Transfer of water from liquid to vapour state is called *evaporation*.

Transpiration. The process by which water is released to the atmosphere by the plants is called *transpiration*.

6.22.3. Measurement of Run-off

Run-off can be measured daily, monthly, seasonal or yearly. It can be measured by the following *methods* :

1. From rainfall records.
2. Empirical formulae.
3. Run-off curves and tables.
4. Discharge observation method.

1. From rainfall records. In this method consistent rainfall record for a sufficiently long period is taken and then average depth of rainfall over the catchment is determined. Then considering all the factors which affect run-off process, a coefficient is arrived at for that catchment. Now a simple equation can be used to find out the run-off over the catchment.

$$\text{Run-off} = \text{Rainfall} \times \text{coefficient} \qquad ...(6.33)$$

2. Empirical formulae. In this method an attempt is made to derive a direct relationship between the rainfall and subsequent run-off. For this purpose some constants are established which give fairly accurate result for a specified region. Some important formulae are given below:

(*a*) Khosla's formula :

$$R = P - 4.811\ T$$

where, R = Annual run-off in mm,

P = Annual rainfall in mm, and

T = Mean temperature in °C.

(*b*) Inglis formulae for hilly and plain areas of Maharashtra :

For *Ghat region*

$$R = 0.88\ P - 304.8$$

For *plain region*

$$R = \frac{(P - 177.8) \times P}{2540}$$

(*c*) *Lacey's formula* :

$$R = \frac{P}{1 + \dfrac{3084\ F}{PS}}$$

where, R = Monsoon run-off in mm,

P = Monsoon rainfall in mm,

S = Catchment area factor, and

F = Monsoon duration factor.

Values of S for various types of catchment are given below :

Type of catchment	*Value of S*
Flat, cultivated and black cotton soils	0.25
Flat, partly cultivated, various soils	0.6
Average catchment	1.00
Hills and places with little cultivation	1.70
Very hilly and steep, with hardly any cultivation	3.45

Values of F for various durations of monsoon are given below :

Class of monsoon	*Value of F*
Very short	0.50
Standard length	1.00
Very long	1.50

3. Run-off curves and tables. Each region has its own catchment area and rainfall characteristics. Thus formulae given above and coefficients derived there in cannot be applied universally. However, for the same region the characteristics mostly remain unchanged. Based on this fact the run-off coefficients are derived once for all. Then a graph is plotted in which one axis represents rainfall and the other run-off. The curves obtained are called *run-off curves*. Alternatively a *table* can be prepared to give the run-off for a certain value of rainfall for a particular region.

4. Discharge observation method. By actual measurement of discharge at an outlet of a drainage basin run-off over a catchment can be computed. The complication in this method is that the discharge of the stream at the outlet comprises surface run-off as well as sub-surface flow. To find out the sub-surface run-off it is essential to separate the sub-surface flow from the total flow. The separation can be done on an approximate basis but with correct analysis.

Factors affecting the run-off

The following factors affect run-off :

1. Rainfall pattern
2. Character of catchment area
3. Topography
4. Shape and size of the catchment area
5. Vegetation
6. Geology of the area
7. Weather conditions.

6.22.4. Hydrograph

Hydrograph is defined as *a graph showing discharge (run-off) of flowing water with respect to time for a specified time.* Discharge graphs are known as flood or run-off graphs. Each hydrograph has a reference to a particular river site. The time period for discharge hydrograph may be hour, day, week or month.

Hydrograph of stream of river will depend on the characteristics of the catchment and precipitation over the catchment. Hydrograph will access the flood flow of rivers hence it is essential that anticipated hydrograph could be drawn for river for a given storm.

Hydrograph indicates the power available from the stream at different times of day, week or year.

Typical hydrographs are shown in Figs. 6.47 and 6.48.

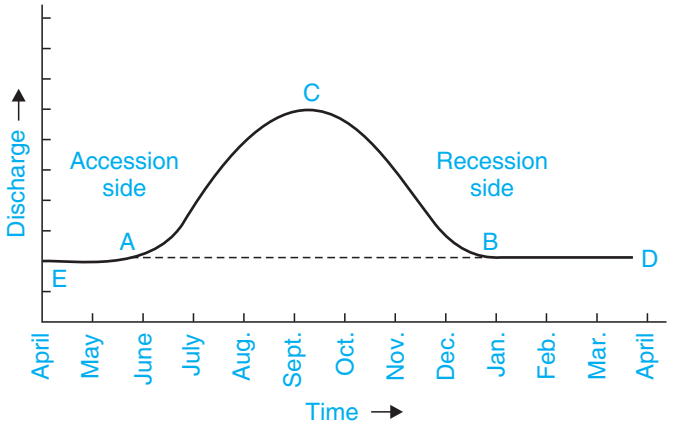


Fig. 6.47. Typical hydrograph.

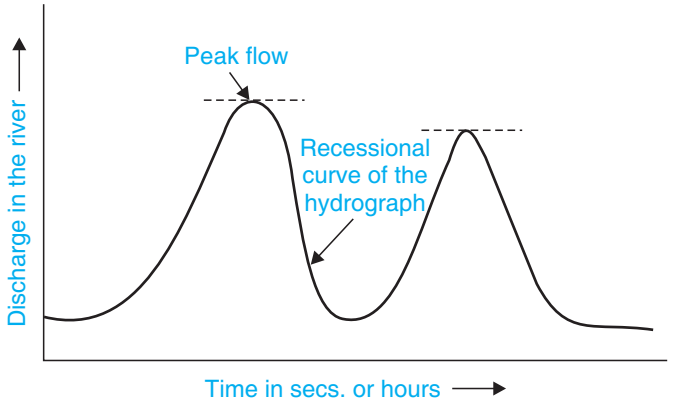


Fig. 6.48. Typical hydrograph.

The Unit Hydrograph

The peak flow represents a momentary value. Therefore the peak flow alone does give sufficient information about the run-off. It is necessary to understand the full hydrograph of flow. Introduction of unit hydrograph theory in 1932 made it possible to predict a run-off hydrograph corresponding to an observed or hypothetical storm. *The basic concept of unit hydrograph is that the hydrographs of run-off from two identical storms would be the same.* In practice identical storms occur very rarely. The rainfall generally varies in duration, amount and areal distribution. This makes it necessary to construct a typical hydrograph for a basin which could be used as a unit of measurement of run-off.

A ***unit hydrograph*** may be defined as a *hydrograph which represents unit run-off resulted from an intense rainfall of unit duration and specific areal distribution.*

The *following steps* are used for the *construction of unit hydrograph :*

1. Choose an isolated intense rainfall of unit duration *from past records.*
2. Plot the discharge hydrograph for outlet from the rainfall records.
3. Deduct the base flow from stream discharge hydrograph to get hydrograph of surface run-off.
4. Find out the volume of surface run-off and convert this volume into cm of run-off over the catchment area.
5. Measure the ordinates of surface run-off hydrograph.
6. Divide these ordinates by obtained run-off in cm to get ordinates of unit hydrograph.

Thus for any catchment unit hydrograph can be prepared once. Then whenever peak flow is to be found out, *multiply the maximum ordinate of unit hydrograph by the run-off value expressed in cm.* Similarly to obtain run-off hydrograph of the storm of same unit duration multiply the ordinates of the unit hydrograph by the run-off value expressed in cm. If the storm is of longer duration calculate the run-off in each unit duration of the storm. Then super-impose the run-off hydrographs in the same order giving a lag of unit period between each of them. Finally draw a summation hydrograph by adding all the overlapping ordinates. Generally the computations are done in a tabular form before the hydrograph is plotted.

Fig. 6.49 is self explanatory and shows how a run-off hydrograph is constructed from a unit hydrograph.

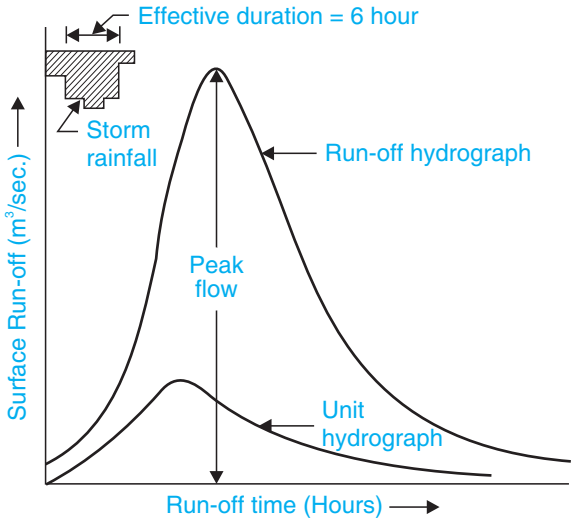


Fig. 6.49

Limitations to the use of unit hydrographs :

1. Its use is limited to areas about 5000 sq. kilometres since similar rainfall distribution over a large area from storm to storm is rarely possible.
2. The odd-shaped basins (particularly long and narrow) have very uneven rainfall distribution, therefore, unit hydrograph method is not adopted to such basins.
3. In mountain areas, the areal distribution is very uneven, even then unit hydrograph method is used because the distribution pattern remains same from storm to storm.

6.22.5. Flow Duration Curve

Refer to Fig. 6.50. Flow duration curve is another useful form *to represent the run-off data for the given time. This curve is plotted between flow available during a period versus the fraction of time.* If the magnitude on the ordinate is the potential power contained in the stream flow, then the curve is known as "*power duration curve*". This curve is a very useful tool in the analysis for the development of water power.

The flow duration curve is drawn with the help of a hydrograph from the available run-off data and, here it is necessary to find out the length of time duration which certain flows are available. This information either from run-off data or from hydrograph is tabulated. Now the flow duration curve taking 100 per cent time on *X*-axis and run-off on *Y*-axis can be drawn.

The area under the flow duration curve (Fig. 6.50) gives the total quantity of run-off during that period as the flow duration curve is representation of graph with its flows arranged in order of descending magnitude.

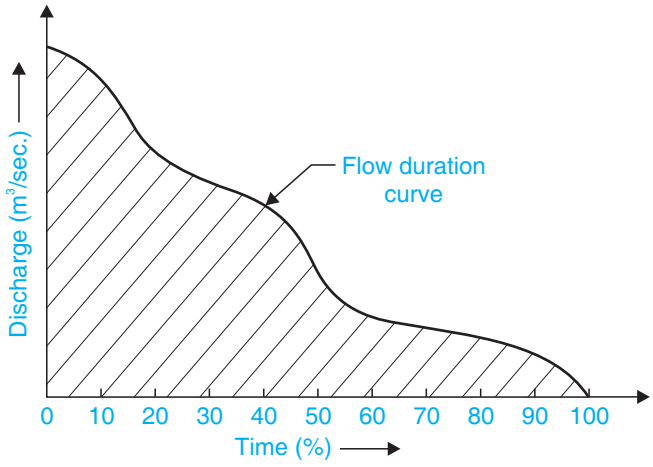


Fig. 6.50. Flow duration curve.

If the head of discharge is known, the possible power developed from water in kW can be determined from the following equation :

$$\text{Power (kW)} = \frac{wQH}{1000} \times \eta_o$$

where, Q = Discharge, m^3/sec.,

H = Head available, m,

w = Weight density of water, N/m^3, and

η_o = Overall efficiency.

Thus the *flow duration curve can be converted to a power duration with some other scale on the same graph.*

Flow duration curves are most useful in the following cases :

(*i*) *For preliminary studies*

(*ii*) *For comparison between streams.*

Uses of flow duration curve

1. A flow duration curve allows the evaluation of low level flows.

2. It is highly useful in the planning and design of water resources projects. In particular, for hydro-power studies, the flow duration curve serves to determine the potential for *firm power* generation. In the case of a run-of-the-river plant, with no storage facilities, the firm power is usually computed on the basis of flow available 90 to 97% of the time. The *firm power* is also known as the *primary power*. *Secondary power* is the power generated at the plant utilising water other than that used for the generation of firm power.

3. If a sediment rating curve is available for the given stream, the flow duration curve can be converted into cumulative sediment transport curve by multiplying each flow rate by its rate of sediment transport. The area under this curve represents the total amount of sediment transported.

4. The flow duration curve also finds use in the design of drainage systems and in flood control studies.

5. A flow duration curve plotted on a log-log paper provides a qualitative description of the run-off variability in the stream. If the curve is having steep slope throughout, it indicates a stream with highly variable discharge. This is typical of the conditions where the flow is mainly from surface run-off. A flat slope indicates small variability which is a characteristic of the streams receiving both surface run-off and ground water run-off. A flat portion at the lower end of the curve indicates substantial contribution from ground water run-off, while the flat portion at the upper end of the curve is characteristic of streams with large flood plain storage, such as lakes and swaps, or where the high flows are mainly derived from snowmelt.

6. The shape of the flow duration curve may change with the length of record. This aspect of the flow duration curve can be utilised for extrapolation of short records.

Shortcomings/Defects of Flow Duration Curve

1. It does not present the flows in natural source of occurrence.

2. It is also not possible to tell from flow duration curve whether the lowest flows occurred in consecutive periods or were scattered throughout the considered period.

6.22.6. Mass Curve

*A **'mass curve'** is the graph of the cumulative values of water quantity (run-off) against time*. A mass curve (Fig. 6.51) is an *integral curve of the hydrograph* which expresses the area under the hydrograph from one time to another.

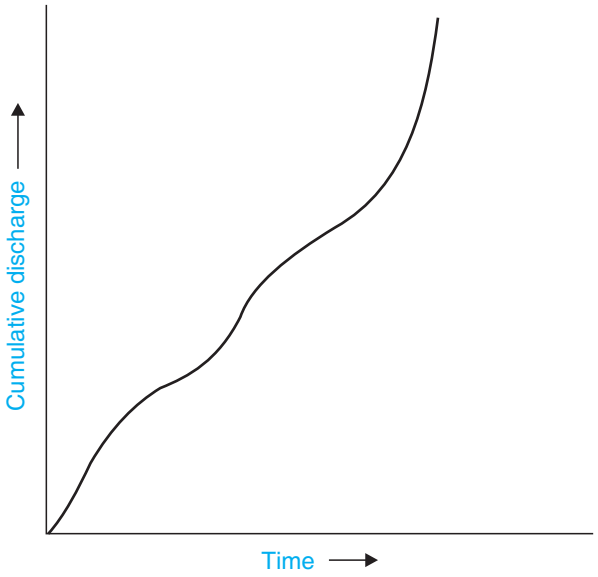


Fig. 6.51. Mass curve.

It is a convenient device *to determine storage requirement* that is needed to produce a certain dependable flow from fluctuating discharge of a river by a reservoir.

Mass curve can also be used to solve the reserve problem of determining the maximum demand rate that can be maintained by a given storage volume. However, it is a trial and error procedure.

The mass curve *will always have a positive shape* but of a greater or less degree depending upon the variations in the quantity of inflow water available. The negative inclination of mass curve would show that the amount of water flowing in the reservoir was less than the loss due to evaporation and seepage.

6.23. HYDRO-POWER DEVELOPMENT IN INDIA

Hydro-power is a renewable source of energy which entails many intrinsic advantages. In India the scope of water power development is tremendous. The first hydro-power

station in India dates back to year 1897 when a small power station of 200 kW capacity was constructed at Darjeeling. Since then many big and small hydro-power stations have been installed in the country. Total hydro-potential in our country is estimated to be equivalent to about 75000 MW at 60 per cent load factor of which only 12 to 14 per cent has been exploited so far.

Important hydro-plants in India

State/Name of power plant	*Installed capacity (MW)*
Andhra Pradesh	
Machkand (stage I and II)	114
Upper silern	120
Lower silern	600
Srisailam	770
Nagarjun sagar pumped storage	100
Assam	
Umiam	54
Gujarat	
Ukai	300
Himachal Pradesh	
Baira suil	200
Jammu and Kashmir	
Salal	270
Karnataka	
Tungabhadra	72
Sharavati	890
Kailindi	396
Kerala	
Parambikulam-Aliyar	185
Sabarigiri	300
Idikki (Stage I)	390
Maharashtra	
Koyna (stages I, II and III)	860
Manipur	
Loktak	70
Odisha	
Hirakud (stages I and II)	270
Balimela	480
Punjab	
Bhakra Nangal	1084
Beas-Sutlej link	780
Rajasthan	
Chambal	287
Uttar Pradesh	
Rihand	300
Yamuna (stage I and II)	424
Tamil Nadu	
Kundah (stages I, II and III)	425
Kodiar	100

Although the present utilization of hydro-power in over country is relatively small with the present tempo of development and need for power resources it would not be long before the available potential is fully harnessed. Hydro-field provides immense scope for sophisticated study requiring application of modern mathematical and operational research techniques with the help of computers.

WORKED EXAMPLES

Penstock

Example 6.1. *A penstock is working under a water head of 210 metres. Its diameter is 2.4 metres. Find its thickness if the joint efficiency is 82 per cent and allowable stress in the material is 105 MN/m².*

Solution. Working head, $H = 210$ m

Diameter of the penstock, $d = 2.4$ m

Efficiency of the joint, $\eta = 82\%$

Allowable stress in the material, $f = 105$ MN/m²

Thickness, t :

Pressure, $p = wH$

(w = weight density of water = 9810 N/m³)

i.e., $$p = \frac{9810 \times 210}{10^6} = 2.06 \text{ MN/m}^2$$

Using the relation

$$f = \frac{pd}{2t\eta}$$

or, $$t = \frac{pd}{2f\eta} = \frac{2.06 \times 2.4}{2 \times 105 \times 0.82}$$

$$= 0.0287 \text{ m or } 28.7 \text{ mm}$$

Hence thickness of the penstock = **28.7 mm.** **(Ans.)**

Hydraulic Turbines

Example 6.2. *A Pelton wheel is receiving water from a penstock with a gross head of 510 m. One-third of gross head is lost in friction in the penstock. The rate of flow through the nozzle fitted at the end of the penstock is 2.2 m³/sec. The angle of deflection of the jet is 165°. Determine*:

(i) The horse power given by the water to the runner

(ii) Hydraulic efficiency of the Pelton wheel.

Take C_v (co-efficient of velocity = 1.0) and speed ratio = 0.45.

Solution. Gross head, $H_g = 510$ m

Head lost in friction, $h_f = \frac{H_g}{3} = \frac{510}{3} = 170$ m

$\therefore$ Net head, $H = H_g - h_f = 510 - 170 = 340$ m

Discharge, $Q = 2.2$ m^3/s

Angle of deflection $= 165°$

$\therefore$ Angle $\phi = 180 - 165° = 15°$

Coefficient of velocity, $C_v = 1.0$

Speed ratio $= 0.45$

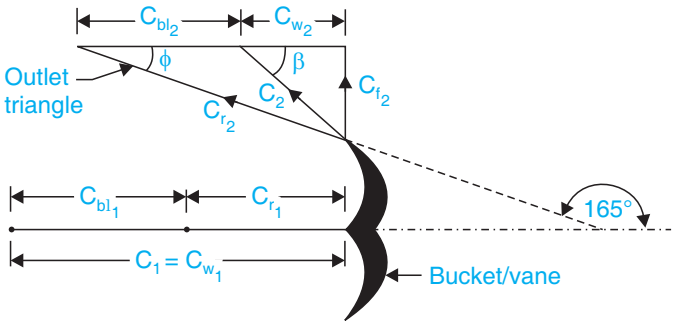


Fig. 6.52

Velocity of jet, $C_1 = C_v \sqrt{2gH}$

$= 1.0 \sqrt{2 \times 9.81 \times 340}$

$= 81.67$ m/s

Velocity of wheel,

C_{bl} = Speed ratio $\times \sqrt{2gH}$

$C_{bl} = C_{bl_1} = C_{bl_2}$

$= 0.45 \times \sqrt{2 \times 9.81 \times 340}$

$= 36.75$ m/s

$C_{r_1} = C_1 - C_{bl_1}$

$= 81.67 - 36.75 = 44.92$ m/s

Also, $C_{w_1} = C_1 = 81.67$ m/s

From outlet velocity triangle, we have

$C_{r_2} = C_{r_1} = 44.92$ m/s

Also, $C_{r_2} \cos \phi = C_{bl_2} + C_{w_2}$

$44.92 \cos 15° = 36.75 + C_{w_2}$

or $C_{w_2} = 44.92 \cos 15° - 36.75$

$= 6.64$ m/s

Work done by the jet on the runner per second is given by the equation

$= \rho Q (C_{w_1} + C_{w_2}) \times C_{bl}$

$= 1000 \times 2.2 (81.67 + 6.64) \times 36.75$

$= 7139863$ Nm/s

(i) Power given by the water to the runner

$= 7139863$ J/s or

W $\simeq$ **7139.8 kW.** **(Ans.)**

(ii) Hydraulic efficiency of the turbine,

$$\eta_h = \frac{2(C_{w_1} + C_{w_2}) \times C_{bl}}{C_1^2} = \frac{2(81.67 + 6.64) \times 36.75}{(81.67)^2}$$

$= \mathbf{0.973}$ **or 97.3%.** **(Ans.)**

Example 6.3. *A Pelton wheel is to be designed for the following specifications :*

Power	*9650 kW*
Head	*350 metres*
Speed	*750 r.p.m.*
Overall efficiency	*85%*
Jet diameter	*not to exceed $\frac{1}{6}$th of the wheel diameter*

Determine the following :

(i) The wheel diameter,

(ii) Diameter of the jet,

(iii) The number of jets required.

Take $C_v = 0.985$, speed ratio = 0.45.

Solution. Shaft or brake power,

$= 9650$ kW

Head, $H = 350$ m

Speed, $N = 750$ r.p.m.

Overall efficiency,

$\eta_o = 85\%$

Ratio of jet dia. to wheel dia. $= \frac{d}{D} = 1/6$

Coefficient of velocity,

$C_v = 0.985$

Speed ratio $= 0.45$

(i) Wheel diameter, D :

Velocity of jet, $C_1 = C_v \sqrt{2gH}$

$= 0.985 \sqrt{2 \times 9.81 \times 350}$

$= 81.62$ m/s

The velocity of wheel,

$C_{bl} = C_{bl_1} = C_{bl_2}$

$=$ Speed ratio $\times \sqrt{2gH}$

$= 0.45 \times \sqrt{2 \times 9.81 \times 350}$

$= 37.3$ m/s

But $C_{bl} = \frac{\pi DN}{60}$

or $37.3 = \frac{\pi \times D \times 750}{60}$

$\therefore$ $D = \frac{37.3 \times 60}{\pi \times 750} =$ **0.95 m.** **(Ans.)**

(ii) Diameter of the jet, d :

$\frac{d}{D} = 1/6$ (Given)

$\therefore$ $d = 1/6D = 1/6 \times 0.95$

$=$ **0.158 m.** **(Ans.)**

(iii) **The number of jets required :**

Discharge of one jet,

$$q = \text{Area of jet} \times \text{velocity of jet}$$

$$= \frac{\pi}{4} d^2 \times C_1 = \pi/4 \times (0.158)^2 \times 81.62$$

$$= 1.6 \text{ m}^3/\text{s}$$

Now, overall efficiency

$$\eta_o = \frac{\text{Shaft power}}{\text{Water power}} = \frac{9560}{wQH}$$

or $$0.85 = \frac{9560}{9.81 \times Q \times 350} \quad (\because w = 9.81 \text{ kN/m}^3)$$

or $$Q = \frac{9560}{9.81 \times 350 \times 0.85} = 3.27 \text{ m}^3/\text{s}$$

$\therefore$ *Number of jets*

$$= \frac{\text{Total discharge}}{\text{Discharge of one jet}} = \frac{Q}{q}$$

$$= \frac{3.27}{1.6} = \mathbf{2 \text{ jets.}} \quad \textbf{(Ans.)}$$

Example 6.4. *A Francis turbine with an overall efficiency of 76% is required to produce 150 kW. It is working under a head of 8 m. The peripheral velocity = 0.25* $\sqrt{2gH}$ *and the radial velocity of flow at inlet is 0.95* $\sqrt{2gH}$ *. The wheel runs at 150 r.p.m. and the hydraulic losses in the turbine are 20% of the available energy. Assuming radial discharge, determine :*

(i) The guide blade angle,

(ii) The wheel angle at inlet,

(iii) Diameter of the wheel at inlet, and

(iv) Width of the wheel at inlet.

Solution. Overall efficiency,

$$\eta_o = 76\%$$

Shaft power produced,

$$P = 150 \text{ kW}$$

Head, $H = 8$ m

Peripheral velocity,

$$C_{bl} = 0.25 \sqrt{2gH}$$

Radial velocity of flow at inlet,

$$C_{f_1} = 0.95\sqrt{2gH}$$

Wheel speed, $N = 150$ r.p.m.

Since discharge at the outlet is radial,

$\therefore$ $C_{w_2} = 0$ and $C_{f_2} = C_2$

Hydraulic losses in the turbine = 20% of available energy

Now, $$C_{bl_1} = 0.25\sqrt{2 \times 9.81 \times 8} = 3.13 \text{ m/s}$$

$$C_{f_1} = 0.95\sqrt{2 \times 9.81 \times 8} = 11.9 \text{ m/s}$$

Hydraulic efficiency is given as

$$\eta_h = \frac{\text{Total head at inlet} - \text{Hydraulic losses}}{\text{Head at inlet}}$$

$$= \frac{H - 0.2H}{H} = 0.8$$

But $$\eta_h = \frac{C_{w_1} C_{bl_1}}{gH}$$

$\therefore$ $$0.8 = \frac{C_{w_1} \times 3.13}{9.81 \times 8}$$

or $$C_{w_1} = \frac{0.8 \times 9.81 \times 8}{3.13} = 20 \text{ m/s}$$

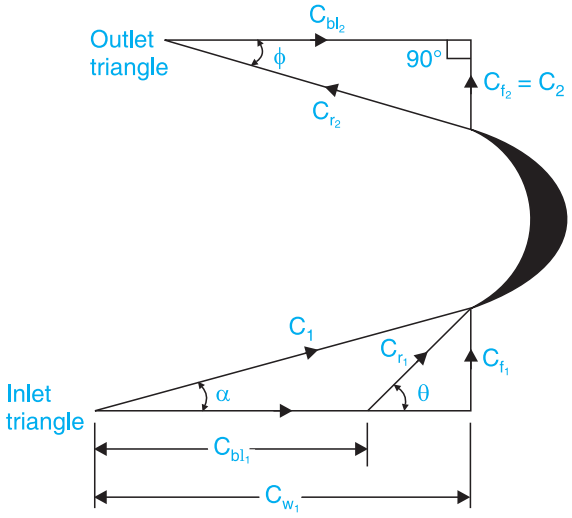


Fig. 6.53

(i) **The guide blade angle, α :**

From inlet velocity triangle (Fig. 6.53),

$$\tan \alpha = \frac{C_{f_1}}{C_{w_1}} = \frac{11.9}{20} = 0.595$$

$\therefore$ $\alpha = \tan^{-1}(0.595) = \mathbf{30°45'}$. **(Ans.)**

(ii) **The wheel vane angle at inlet, θ :**

$$\tan \theta = \frac{C_{f_1}}{C_{w_1} - C_{bl_1}} = \frac{11.9}{20 - 3.13}$$

$$= 0.705$$

$\therefore$ $\theta = \tan^{-1}(0.705) = \mathbf{35° 11'}$. **(Ans.)**

(iii) **Diameter of the wheel at inlet, D_1 :**

Using the relation,

$$C_{bl_1} = \frac{\pi D_1 N}{60}$$

or $$D_1 = \frac{C_{bl_1} \times 60}{\pi N} = \frac{3.13 \times 60}{\pi \times 150}$$

$$= \mathbf{0.398 \text{ m.}} \quad \textbf{(Ans.)}$$

(iv) **Width of the wheel at inlet, B_1 :**

$$\eta_o = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{wQH}$$

or $$0.76 = \frac{150}{9.81 \times Q \times 8}$$

$$\therefore \quad Q = \frac{150}{0.76 \times 9.81 \times 8} = 2.515 \text{ m}^3/\text{s}$$

Also, $$Q = \pi D_1 B_1 C_{f_1}$$

or $$2.515 = \pi \times 0.398 \times B_1 \times 11.9$$

$$\therefore \quad B_1 = \frac{2.515}{\pi \times 0.398 \times 11.9}$$

$$= \mathbf{0.169 \text{ m.}} \quad \textbf{(Ans.)}$$

Example 6.5. *The following data relate to a Francis turbine:*

Net head	*70 m*
Speed	*700 r.p.m.*
Shaft power	*330 kW*
Overall efficiency	*85%*
Hydraulic efficiency	*92%*
Flow ratio	*0.22*
Breadth ratio	*0.1*
Outer diameter of the runner	*= 2 × inner diameter of runner*
Velocity of flow	*constant*
Outlet discharge	*radial*

The thickness of vanes occupy 6 per cent of circumferential area of the runner. Determine :

(i) Guide blade angle,

(ii) Runner vane angles at inlet and outlet,

(iii) Diameters of runner at inlet and outlet, and

(iv) Width of the wheel at inlet.

Solution. Net head, $H = 70$ m ;

Speed, $N = 700$ r.p.m.

Shaft power $= 330$ kW

Overall efficiency, $\eta_o = 85\%$;

Hydraulic efficiency, $\eta_h = 92\%$

Flow ratio $= 0.22$;

Breadth ratio, $\frac{B_1}{D_1} = 0.1$; D_1 (= outer dia.)

$= 2D_2$ (inner dia.)

Thickness of vanes = 6% of circumferential area of runner

$$C_{f_1} = C_{f_2}$$

Now, flow ratio $= 0.22 = \frac{C_{f_1}}{\sqrt{2gH}}$

or $$C_{f_1} = 0.22 \times \sqrt{2gH}$$

$$= 0.22 \times \sqrt{2 \times 9.81 \times 70} = 8.15 \text{ m/s}$$

Actual area of flow

$$= \left(1 - \frac{6}{100}\right) \pi D_1 B_1 = 0.94 \, \pi \, D_1 B_1$$

Since discharge at outlet is radial

$$C_{w_2} = 0 \quad \text{and} \quad C_{f_2} = C_2$$

Using relation,

$$\eta_o = \frac{\text{Shaft power}}{\text{Water power}}$$

$$0.85 = \frac{330}{wQH} = \frac{330}{wQH} = \frac{330}{9.81 \times Q \times 70}$$

or $$Q = \frac{330}{0.85 \times 9.81 \times 70} = 0.565 \text{ m}^3/\text{s}.$$

But Q = Actual area of flow × velocity of flow

$$= 0.94 \, \pi D_1 B_1 \times C_{f_1}$$

$$0.565 = 0.94 \, \pi \times D_1 \times 0.1 \, D_1 \times 8.15$$

$$\left(\because \quad \frac{B_1}{D_1} = 0.1 \quad \text{... Given} \right)$$

$$\therefore \quad D_1 = \left(\frac{0.565}{0.94 \times \pi \times 0.1 \times 8.15} \right)^{1/2} = 0.484 \text{ m}$$

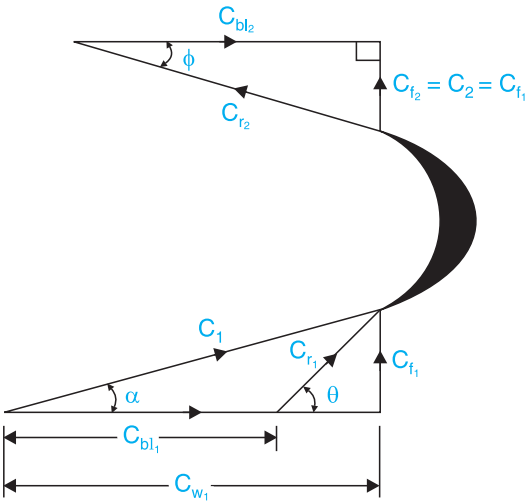


Fig. 6.54

But $$\frac{B_1}{D_1} = 0.1$$

$$\therefore \quad B_1 = 0.1 \, D_1 = 0.1 \times 0.484$$

$$= 0.0484 \text{ m} = 4.84 \text{ cm}$$

Tangential speed of the runner at inlet

$$C_{bl_1} = \frac{\pi D_1 N}{60} = \frac{\pi \times 0.484 \times 700}{60}$$

$$= 17.74 \text{ m/s}$$

Using relation for hydraulic efficiency,

$$\eta_h = \frac{C_{w_1} C_{bl_1}}{gH} \qquad (\because \ C_{w_2} = 0)$$

$$0.92 = \frac{C_{w_1} \times 17.74}{9.81 \times 70}$$

$$\therefore \qquad C_{w_1} = \frac{0.92 \times 9.81 \times 70}{17.74} = 35.6 \text{ m/s}$$

(*i*) Guide blade angle, α :

From inlet velocity triangle,

$$\tan \alpha = \frac{C_{f_1}}{C_{w_1}} = \frac{8.15}{35.6} = 0.229$$

$$\therefore \qquad \alpha = \tan^{-1} (0.229) = \mathbf{12.9°}. \quad \textbf{(Ans.)}$$

(*ii*) Runner vane angles at inlet and outlet θ, ϕ = ?

$$\tan \theta = \frac{C_{f_1}}{C_{w_1} - C_{bl_1}} = \frac{8.15}{35.6 - 17.74} = 0.456$$

$$\therefore \qquad \theta = \tan^{-1} (0.459) = \mathbf{24.5°}. \quad \textbf{(Ans.)}$$

From outlet velocity triangle,

$$\tan \phi = \frac{C_{f_2}}{C_{bl_2}} = \frac{C_{f_1}}{C_{bl_2}} \qquad \ldots(i)$$

But $$C_{bl_2} = \frac{\pi D_2 N}{60} = \frac{\pi \times D_1}{2} \times \frac{N}{60}$$

$$\left[\because \ D_2 = \frac{D_1}{2} \ \text{(given)}\right]$$

$$= \frac{\pi \times 0.484 \times 700}{2 \times 60} = 8.87 \text{ m/s}$$

Putting the value of C_{bl_2} in eqn. (*i*), we get

$$\tan \phi = \frac{8.15}{8.87} = 0.9188$$

or $$\phi = \tan^{-1} (0.9188) = \mathbf{42.58°}. \quad \textbf{(Ans.)}$$

(*iii*) Diameters of the runner at inlet and outlet, D_1, D_2 :

$$D_1 = \mathbf{0.484 \text{ m}}. \quad \textbf{(Ans.)}$$

$$D_2 = \frac{0.484}{2} = \mathbf{0.242 \text{ m}}. \quad \textbf{(Ans.)}$$

(*iv*) Width of the wheel at inlet, B_1 = 4.84 cm. (Ans.)

Example 6.6. *A Kaplan turbine develops 22,000 kW at an average head of 35 metres. Assuming a speed ratio of 2, flow ratio of 0.6, diameter of the boss equal to 0.35 times the diameter of the runner and an overall efficiency of 88%, calculate the diameter, speed and specific speed of the turbine.*

Solution. Shaft power, P = 22,000 kW

Head, H = 35 m

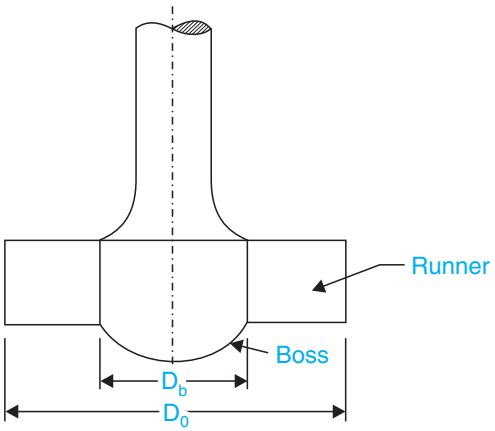


Fig. 6.55. Kaplan turbine runner.

Speed ratio,

$$\frac{C_{bl_1}}{\sqrt{2gH}} = 2.0$$

$$C_{bl_1} = 2 \times \sqrt{2gH} = 2 \times \sqrt{2 \times 9.81 \times 35}$$

$$= 52.4 \text{ m/s}$$

Flow ratio,

$$\frac{C_{f_1}}{\sqrt{2gH}} = 0.6$$

$$C_{f_1} = 0.6\sqrt{2gH} = 0.6 \times \sqrt{2 \times 9.81 \times 35}$$

$$= 15.7 \text{ m/s}$$

Diameter of boss

= 0.35 × diameter of the runner

$$\therefore \qquad D_b = 0.35 \ D_0$$

Overall efficiency,

$$\eta_o = 88\%.$$

(*i*) Diameter of the runner, D_0 :

Using the relation,

$$\eta_o = \frac{\text{Shaft power (P)}}{\text{Water power}} = \frac{22000}{wQH}$$

$$\therefore \qquad 0.88 = \frac{22000}{w \times Q \times H} = \frac{22000}{9.81 \times Q \times 35}$$

or $$Q = \frac{22000}{0.88 \times 9.81 \times 35} = 72.8 \text{ m}^3/\text{s}$$

Also, $$Q = \pi/4 \ (D_0^2 - D_b^2) \times C_{f_1}$$

$$\therefore \qquad 72.8 = \pi/4 \ [D_0^2 - (0.35 \ D_0)^2] \times 15.7$$

$$[\because \ D_b = 0.35 \ D_0]$$

$$= \pi/4 \ D_0^2 \times 0.8775 \times 15.7$$

$$\therefore \qquad D_0^2 = \frac{72.8 \times 4}{\pi \times 0.8775 \times 15.7}$$

and $$D_0 = \mathbf{2.6 \text{ m/s}}. \quad \textbf{(Ans.)}$$

$$\therefore \qquad D_b = 0.35 \times 2.6 = \mathbf{0.91 \text{ m/s}}. \quad \textbf{(Ans.)}$$

(ii) **Speed of the turbine, N :**

$$C_{bl_1} = \frac{\pi D_0 N}{60}$$

$$\therefore \quad 52.4 = \frac{\pi \times 2.6 \times N}{60}$$

or $$N = \frac{52.4 \times 60}{\pi \times 2.6} = \textbf{384.9 r.p.m.} \quad \textbf{(Ans.)}$$

(iii) **Specific speed of the turbine, N_s :**

$$N_s = \frac{N\sqrt{P_t}}{H^{5/4}}$$

(where P_t = power output of the turbine)

$$= \frac{384.9 \times \sqrt{22000}}{(35)^{5/4}}$$

$$= \textbf{670.6 r.p.m.} \quad \textbf{(Ans.)}$$

Draft Tube

Example 6.7. *A Kaplan turbine develops 1500 kW under a head of 6 m. The turbine is set 2.5 m above the tail race level. A vacuum gauge inserted at the turbine outlet records a suction head of 3.1 m. If the hydraulic efficiency is 82 per cent, what would be the efficiency of draft tube having inlet diameter of 3 m ?*

What will be the reading of suction gauge if power developed is reduced to 750 kW, the head and speed remaining constant ?

Solution. Power developed = 1500 kW ;

Head, H = 6 m

Height of turbine above tailrace level = 2.5 m ;

Hydraulic efficiency, η_h = 82%

Draft tube inlet diameter, d_i = 3 m

Efficiency of draft tube, η_d :

Hydraulic efficiency,

$$\eta_h = \frac{\text{Power developed}}{\text{Water power}}$$

$$= \frac{\text{Power developed}}{wQH}$$

$$\therefore \quad \text{Power developed} = wQH \times \eta_h$$

$$1500 = 9.81 \times Q \times 6 \times 0.82$$

or $$Q = \frac{1500}{9.81 \times 6 \times 0.82} = 31.08 \text{ m}^3/\text{s}$$

Velocity of water at inlet of draft tube,

$$V_2 = \frac{Q}{\frac{\pi}{4} d_i^2} = \frac{31.08}{\frac{\pi}{4} \times 3^2} = 4.397 \text{ m/s}$$

Pressure head required

$$= 3.1 - 2.5 = 0.6 \text{ m}$$

$\therefore$ Efficiency of draft tube,

$$\eta_d = \frac{0.6}{\frac{V_2^2}{2g}} = \frac{0.6}{\frac{4.397^2}{2 \times 9.81}}$$

$$= \textbf{0.6088} \quad \text{or} \quad \textbf{60.88\%}. \quad \textbf{(Ans.)}$$

Reading of suction gauge :

For reduced output of 750 kW assuming constant efficiency, we have

Discharge

$$Q_1 = \frac{Q}{2} = \frac{31.08}{2} = 15.54 \text{ m}^3/\text{s}$$

Also, $$V_2 = \frac{15.54}{\frac{\pi}{4} \times 3^2} = 2.198 \text{ m/s}$$

Head gained in draft tube

$$= \eta_d \times \frac{2.198^2}{2g}$$

$$= 0.6088 \times \frac{2.198^2}{2 \times 9.81} \simeq 0.15 \text{ m}$$

$\therefore$ Reading of gauge

$$= 2.5 + 0.15 = \textbf{2.65 m.} \quad \textbf{(Ans.)}$$

Example 6.8. *Determine the overall efficiency of a Kaplan turbine developing 2850 kW under a head of 5.2 m. It is provided with a draft tube with its inlet (diameter 3 m) set 1.8 m above the tailrace level. A vacuum gauge connected to the draft tube indicates a reading of 5.2 m of water. Assume draft tube efficiency as 75 per cent.*

Solution. Power developed = 2850 kW; Head, H = 5.2 m

Height of draft inlet tube above tailrace level,

H_s = 1.8 m

Reading of the gauge = – 5.2 m

Draft tube efficiency, η_d = 75%

Overall efficiency of the turbine, η_o :

$$\frac{p_2}{w} = \frac{p_a}{w} - H_s - \left(\frac{V_2^2 - V_3^2}{2g} - h_f \right) \quad \text{...[Eqn. 6.10(}a\text{)]}$$

$$-5.2 = 0 - 1.8 - \left(\frac{V_2^2 - V_3^2}{2g} \right),$$

neglecting h_f (head loss in draft tube)

or $$\frac{V_2^2 - V_3^2}{2g} = 3.4$$

Also, $$\eta_d = \frac{(V_2^2 - V_3^2)/2g}{(V_2^2/2g)} \quad \text{...[Eqn. 6.11]}$$

or $$0.75 = \frac{3.4}{(V_2^2/2g)} \quad \text{or} \quad \frac{V_2^2}{2g} = \frac{3.4}{0.75} = 4.533$$

$\therefore$ $$V_2 = \sqrt{4.533 \times 2g} = \sqrt{4.533 \times 2 \times 9.81}$$

$$= 9.43 \text{ m/s}$$

Discharge

$$Q = \frac{\pi}{4} \times 3^2 \times 9.43 = 66.65 \text{ m}^3/\text{s}$$

$\therefore$ Overall efficiency,

$$\eta_o = \frac{\text{Power developed}}{\text{Water power}} = \frac{2850}{wQH}$$

$$= \frac{2850}{9.81 \times 66.65 \times 5.2}$$

$$= \mathbf{0.8382} \quad \text{or} \quad \mathbf{83.82\%}. \quad \textbf{(Ans.)}$$

Example 6.9. *A conical draft tube having inlet and outlet diameters 1.2 m and 1.8 m discharges water at outlet with a velocity of 3 m/s. The total length of the draft tube is 7.2 m and 1.44 m of the length of draft tube is immersed in water. If the atmospheric pressure head is 10.3 m of water and loss of head due to friction in the draft tube is equal to 0.2 × velocity head at outlet of the tube, determine :*

(i) Pressure head at inlet, and

(ii) Efficiency of the draft tube.

Solution. Inlet diameter of the draft tube,

$$d_i = 1.2 \text{ m}$$

Outlet diameter,

$$d_0 = 1.8 \text{ m}$$

Velocity at outlet

$$V_3 = 3 \text{ m/s}$$

Total length of draft tube,

$$H_s + y = 7.2 \text{ m}$$

Length of draft tube in water,

$$y = 1.44 \text{ m}$$

$\therefore$ $$H_s = 7.2 - 1.44 = 5.76 \text{ m}$$

Atmospheric pressure head,

$$\frac{p_a}{w} = 10.3 \text{ m}$$

Loss of head due to friction,

$$h_f = 0.2 \times \text{velocity head at outlet}$$

$$= 0.2 \frac{V_3^2}{2g}$$

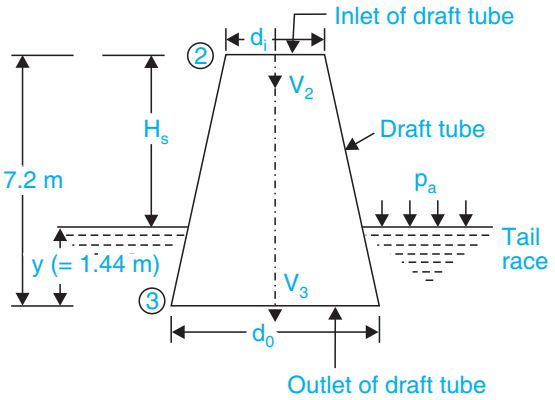


Fig. 6.56

(i) Pressure head at inlet, $\frac{p_2}{w}$:

Discharge through the draft tube,

$$Q = A_3 V_3 = \frac{\pi}{4} \times d_0^2 \times V_3$$

$$= \frac{\pi}{4} \times 1.8^2 \times 3 = 7.634 \text{ m/s}$$

Velocity of inlet,

$$V_2 = \frac{Q}{A_2} = \frac{7.634}{\frac{\pi}{4} d_i^2} = \frac{7.634}{\frac{\pi}{4} \times 1.2^2} = 6.75 \text{ m/s}$$

Using eqn. (6.10)

$$\frac{p_2}{w} = \frac{p_a}{w} - H_s - \left(\frac{V_2^2 - V_3^2}{2g} - h_f \right)$$

$$= \frac{p_a}{w} - H_s - \left(\frac{V_2^2 - V_3^2}{2g} - 0.2 \frac{V_3^2}{2g} \right)$$

$$= 10.3 - 5.76 - \left(\frac{6.75^2 - 3^2}{2 \times 9.81} - 0.2 \times \frac{3^2}{2 \times 9.81} \right)$$

or $$\frac{p_2}{w} = 4.54 - (1.863 - 0.092)$$

$$= \mathbf{2.769 \text{ m (abs)}}. \quad \textbf{(Ans.)}$$

(ii) Efficiency of the draft tube, η_d :

$$\eta_d = \frac{\left(\frac{V_2^2 - V_3^2}{2g} - h_f \right)}{\frac{V_2^2}{2g}} = \frac{\frac{V_2^2 - V_3^2}{2g} - 0.2 \frac{V_3^2}{2g}}{\frac{V_2^2}{2g}}$$

$$= \frac{\frac{V_2^2}{2g} - \left(\frac{V_3^2}{2g} + 0.2 \frac{V_3^2}{2g} \right)}{\frac{V_2^2}{2g}}$$

$$= 1 - 1.2 \left(\frac{V_3}{V_2} \right)^2 = 1 - 1.2 \left(\frac{3}{6.75} \right)^2$$

$$= \mathbf{0.763} \quad \text{or} \quad \mathbf{76.3\%}. \quad \textbf{(Ans.)}$$

Example 6.10. *Give the range of specific speed of values of the Kaplan, Francis turbines and Pelton Wheels. What factors decide whether Kaplan, Francis or a Pelton wheel type turbine would be used in a hydro-electric project ?* **(UPSC)**

Solution. The **specific speed** of a turbine is defined as *the speed of a turbine which is identical in shape, geometrical dimensions, blade angles, gate opening etc. which would develop unit power when working under a unit head.*

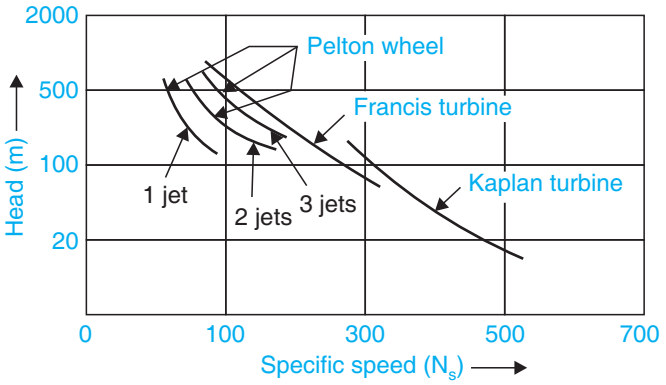


Fig. 6.57

- Based on specific speed, the turbines for the project are selected as shown in Fig. 6.57.
- In general, the selection of a turbine for hydro-electric project is based on the following considerations :

1. For *high heads, Pelton wheels* are invariably selected.
2. For *intermediate heads, Francis turbines* are selected.
3. For *low head and high discharge,* Kaplan turbines are selected.

Example 6.11. *A turbine develops 6620 kW under a head of 20 metres at 130 r.p.m. Calculate the specific speed of the turbine and state the type of the turbine.*

Solution. Power developed,

$P = 6620$ kW

Head, $H = 20$ metres

Speed, $N = 130$ r.p.m.

Specific speed of the turbine,

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{130 \times \sqrt{6620}}{(20)^{5/4}}$$

$$= \mathbf{250\ r.p.m.} \quad \textbf{(Ans.)}$$

Since for specific speeds between 50 and 350 (SI units) the type of turbine is Francis, therefore as the specific speed lies in this range, the turbine in question is **Francis.** **(Ans.)**

Example 6.12. *In a hydro-electric station, water is available at the rate of 175 m^3/s under a head of 18 m. The turbines run at a speed of 150 r.p.m. with overall efficiency of 82%. Find the number of turbines required if they have the maximum specific speed of 460.* **(GATE)**

Solution. *Given :* $Q = 175$ m^3/s ; $H = 18$ m ; $N = 150$ r.p.m.; $\eta_o = 82\%$; $N_s = 460$.

Number of turbines required :

Specific speed of the turbine,

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} \qquad \text{...[Eqn. (6.12)]}$$

$$460 = \frac{150\sqrt{P}}{(18)^{5/4}}$$

(where P is in kW and H is in metres)

or Power available at turbine shaft,

$$P = \left[\frac{460 \times (18)^{5/4}}{150}\right]^2 = 12927.5 \text{ kW}$$

Power available from turbines

$$= wQH \times \eta_o$$

$$= 9.81 \times 175 \times 18 \times 0.82$$

$$= 25339.23 \text{ kW}$$

No. of turbines required

$$= \frac{25339.23}{12927.5} = 1.96 \text{ say } \mathbf{2.} \quad \textbf{(Ans.)}$$

Example 6.13. *The turbine is to operate under a head of 24 m at 200 r.p.m. The discharge is 8.5 m^3/s. If the overall efficiency is 88%, determine :*

(i) Power generated,

(ii) Specific speed of the turbine,

(iii) Type of turbine.

Solution. Head, $H = 24$ m

Speed, $N = 200$ r.p.m.

Discharge, $Q = 8.5$ m^3/s

Overall efficiency, $\eta_o = 88\%$

(i) Power generated, P :

$$\eta_o = \frac{\text{Power developed}}{\text{Water power}} = \frac{P}{wQH}$$

$$\therefore \quad P = \eta_o \times wQH = 0.88 \times 9.81 \times 8.5 \times 24$$

or $\mathbf{P = 1761\ kW.}$ **(Ans.)**

(ii) Specific speed of the turbine, N_s :

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{200 \times \sqrt{1761}}{(24)^{5/4}}$$

$$= \mathbf{158\ r.p.m.} \quad \textbf{(Ans.)}$$

(iii) Type of turbine :

As the specific speed lies between 50 and 350, the turbine is a **Francis turbine.** **(Ans.)**

Example 6.14. *Calculate the specific speed of a turbine and suggest the type of turbine required for a river having a discharge of 240 litres/sec with a available head of 45 metres.*

Take the efficiency of the turbine = 82% and speed = 450 r.p.m.

Solution. Discharge,

$$Q = 240 \text{ litres/s} \left(= \frac{240}{1000} = 0.24 \text{ m}^3/\text{s}\right)$$

Head, $H = 45$ m

Turbine efficiency,

$\eta = 82\%$

Speed, $N = 450$ r.p.m.

Now, $\eta = \dfrac{P}{wQH}$

$\therefore$ Power developed,

$P = \eta \times wQH$

$= 0.82 \times 9.81 \times 0.24 \times 45 = 86.88$ kW

Specific speed,

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{450 \times \sqrt{86.88}}{(45)^{5/4}}$$

$\simeq$ **3.6 r.p.m.** **(Ans.)**

For this specific speed **Pelton turbine** is suitable. **(Ans.)**

Example 6.15. *A hydro-electric power station is desired to be built across a river having a discharge of 28000 litres/s at a head of 11 m. Assuming turbine efficiency 78% and speed ratio as 0.82, determine :*

(i) Can we use two turbines with a speed not less than 120 r.p.m. and specific speed more than 350 r.p.m. ?

(ii) Specify the type of turbine/runner that can be used. Also calculate the runner diameter.

Solution. Discharge,

$$Q = 28000 \text{ litres/sec.} \left(= \frac{28000}{1000} = 28 \text{ m}^3/\text{s}\right)$$

Turbine efficiency, $\eta = 78\%$

Speed ratio $= 0.82$

Head, $H = 11$ m

(i) Power developed,

$P = \eta \times wQH = 0.78 \times 9.81 \times 28 \times 11$

$= 2356.7$ kW

Using *two* turbines each of capacity 1200 kW, the specific speed of the turbine is calculated as follows :

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{120\sqrt{1200}}{(11)^{5/4}}$$

$= 207.5$ r.p.m.

(ii) For the specific speed calculated above *Francis* turbine is suitable.

Diameter of the runner, D :

Tangential velocity of the runner,

C_{bl} = Speed ratio $\times \sqrt{2gH}$

$= 0.82 \times \sqrt{2 \times 9.81 \times 11} = 12.05$ m/s

But $C_{bl} = \dfrac{\pi DN}{60}$

$\therefore \quad 12.05 = \dfrac{\pi D \times 120}{60}$

$\therefore \quad D = \dfrac{12.05 \times 60}{\pi \times 120} =$ **1.92 m.** **(Ans.)**

Example 6.16. *The quantity of water available for hydro-electric station is 250 m^3/sec. under a head of 1.6 m. If the speed of the turbine is 50 r.p.m. and efficiency 82% determine the number of turbine units required. Take specific speed as 740.*

Solution. Quantity of water available,

$Q = 250$ m^3/s

Head, $H = 1.6$ m

Speed, $N = 50$ r.p.m.

Efficiency, $\eta = 82\%$

Specific speed, $N_s = 740$

Number of turbine units required :

Total power (P_{total}) to be developed can be calculated using the following equation,

$P_{total} = \eta\, wQH$

$= 0.82 \times 9.81 \times 250 \times 1.6$

$= 3217.7$ kW

The power developed by each turbine can be calculated be using the following equation :

$$N_s = \frac{N\sqrt{P}}{H^{5/4}}$$

$$740 = \frac{50 \times \sqrt{P}}{(1.6)^{5/4}}$$

$$\sqrt{P} = \frac{740 \times (1.6)^{5/4}}{50}$$

$$\therefore \quad P = \left[\frac{740 \times (1.6)^{5/4}}{50}\right]^2$$

or $P = 709.3$ kW

$\therefore$ Number of turbine units required

$$= \frac{P_{total}}{P} = \frac{3217.7}{7093}$$

$= 4.54 \simeq$ **5.** **(Ans.)**

☞ **Example 6.17.** *At a proposed site of hydro-electric power plant the available discharge and head is 330 m^3/s and 28 m respectively. The turbine efficiency is 86%. The generator is directly coupled to the turbine. The frequency of generator is 50 Hz and number of poles used are 24. Find the least number of machines required if,*

(i) A Francis turbine with a specific speed of 260 is used.

(ii) A Kaplan turbine with a specific speed of 700 is used.

Solution. Available discharge,

$Q = 330$ m^3/s

Head, $H = 28$ m

Turbine efficiency,

$\eta = 86\%$

Frequency of generation,

$f = 50$ Hz

Number of poles used,

$$p = 24$$

As the generator is directly coupled to the turbine, the speed of turbine used must be equal to the synchronous speed of the generator.

$$\therefore \quad N = \frac{120f}{p} = \frac{120 \times 50}{24}$$

$$= 250 \text{ r.p.m.}$$

$$P = \eta \times wQH = 0.86 \times 9.81 \times 330 \times 28$$

$$= 77954.2 \text{ kW.}$$

(*i*) The power capacity of each Francis turbine (P_1) can be calculated by using the following formula :

$$N_s = \frac{N\sqrt{P_1}}{H^{5/4}}$$

$$260 = \frac{250\sqrt{P_1}}{(28)^{5/4}}$$

$$\therefore \quad P_1 = \left[\frac{260 \times (28)^{5/4}}{250}\right]^2 = 4487 \text{ kW}$$

$\therefore$ Number of Francis turbines required

$$= \frac{P}{P_1} = \frac{77954.2}{4487} = \mathbf{17.4 \approx 18.} \quad \textbf{(Ans.)}$$

(*ii*) The power capacity of each Kaplan turbine can be calculated by using the following formula :

$$N_s = \frac{N\sqrt{P_1}}{H^{5/4}}$$

$$770 = \frac{250\sqrt{P_2}}{(28)^{5/4}}$$

$$\therefore \quad P_2 = \left[\frac{700 \times (28)^{5/4}}{250}\right]^2 = 32524.5 \text{ kW}$$

$\therefore$ Number of Kaplan turbines required

$$= \frac{P}{P_2} = \frac{77954.2}{32524.5} = \mathbf{2.4 \approx 3.} \quad \textbf{(Ans.)}$$

Example 6.18. *A turbine is to operate under a head of 25 m at 200 r.p.m. The discharge is 9 m^3/s. If the efficiency is 90 per cent determine the performance of turbine under a head of 20 m.* **(M.U.)**

Solution. Head under which turbine works,

$$H_1 = 25 \text{ m}$$

Speed of the turbine,

$$N_1 = 200 \text{ r.p.m.}$$

Discharge through the turbine,

$$Q_1 = 9 \text{ m}^3/\text{s}$$

Efficiency (overall),

$$\eta_o = 90\%$$

Performance of turbine under a head of 20 m ; N_2, Q_2, P_2 :

Performance of turbine under a head, H_2 = 20 m means to find speed (N_2), discharge (Q_2), and power generated (P_2) by the turbine when working under a head of 20 m.

Overall efficiency,

$$\eta_o = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{wQH} = \frac{P_1}{wQ_1H_1}$$

$$\therefore \quad P_1 = \eta_o \times wQ_1H_1 = 0.9 \times 9.81 \times 9 \times 25$$

$$= 1986.5 \text{ kW}$$

Now, $\frac{N_1}{\sqrt{H_1}} = \frac{N_2}{\sqrt{H_2}}$ ...[Eqn. (6.19)]

$$\therefore \quad N_2 = \frac{N_1\sqrt{H_2}}{\sqrt{H_1}} = \frac{200 \times \sqrt{20}}{\sqrt{25}}$$

$$= \mathbf{178.88 \text{ r.p.m.}} \quad \textbf{(Ans.)}$$

and $\frac{Q_1}{\sqrt{H_1}} = \frac{Q_2}{\sqrt{H_2}}$ ...[Eqn. (6.20)]

$$\therefore \quad Q_2 = \frac{Q_1\sqrt{H_2}}{\sqrt{H_1}} = \frac{9 \times \sqrt{20}}{\sqrt{25}}$$

$$= \mathbf{8.05 \text{ m}^3/\text{s}} \quad \textbf{(Ans.)}$$

and $\frac{P_1}{H_1^{3/2}} = \frac{P_2}{(H_2)^{3/2}}$ ...[Eqn. (6.21)]

$$\therefore \quad P_2 = \frac{P_1 \times (H_2)^{3/2}}{(H_1)^{3/2}} = \frac{1986.5 \times (20)^{3/2}}{(25)^{3/2}}$$

$$= \mathbf{1421.4 \text{ kW.}} \quad \textbf{(Ans.)}$$

Example 6.19. *A hydro-turbine is required to give 25 MW at 50 m head and 90 r.p.m. runner speed. The laboratory facilities available, permit testing of 20 kW model at 5 m head. What should be the model runner speed and model to prototype scale ratio?* **(GATE)**

Solution. *Given :* P_p = 25 MW ; H_p = 50 m ; N_p = 90 r.p.m.; P_m = 20 kW ; H_m = 5 m

N_m ; $\frac{D_p}{D_m}$ (= L_r) :

Prototype specific speed,

$$(N_s)_p = \frac{N_p\sqrt{P_p}}{(H_p)^{5/4}} \text{ (where } P \text{ is in kW)}$$

$$= \frac{90 \times \sqrt{25 \times 10^3}}{(50)^{5/4}} = 107$$

For model,

$$107 = \frac{N_m\sqrt{P_m}}{(H_m)^{5/4}} \qquad [\because \ (N_s)_p = (N_s)_m]$$

or $$\mathbf{N_m} = \frac{107 \times (H_m)^{5/4}}{\sqrt{P_m}} = \frac{107 \times (5)^{5/4}}{\sqrt{20}}$$

$$= \mathbf{178.89 \text{ r.p.m.}} \quad \textbf{(Ans.)}$$

For similar turbines $\frac{P}{H^{3/2}D^2}$ should be equal.

$$\therefore \quad \frac{P}{H_p^{3/2}D_p^{2}} = \frac{P_m}{H_m^{3/2}D_m^{2}}$$

or
$$\frac{D_p}{D_m} (= L_r) = \sqrt{\frac{P_p}{P_m} \times \left(\frac{H_m}{H_p}\right)^{3/2}}$$

$$= \sqrt{\frac{25 \times 10^3}{20} \times \left(\frac{5}{50}\right)^{3/2}}$$

$$= \mathbf{6.287.} \quad \textbf{(Ans.)}$$

Example 6.20. *A water turbine delivering 10 MW power is to be tested with the help of a geometrically similar 1 : 8 model, which runs as the same speed as the prototype.*

(i) Find the power developed by the model assuming the efficiencies of the model and the prototype are equal.

(ii) Find the ratio of the heads and the ratio of mass flow rates between the prototype and the model. **(GATE)**

Solution. *Given :* $P_p = 10$ MW ;

$$N_p = N_{m,} ; \frac{L_m}{L_p} = \frac{D_m}{D_p} = \frac{1}{8} ; \quad \eta_p = \eta_m.$$

(*i*) Power developed by the model, P_m :

We know that,

$$P \propto N^3 \times D^5 \qquad \text{...[Eqn. (6.24)]}$$

(where N is the speed and D is the diameter)

$$\therefore \quad P_p \propto N_p^{\,3} D_p^{\,5} \text{ and } P_m \propto N_m^{\,3} D_m^{\,5}$$

or
$$\frac{P_p}{P_m} = \left(\frac{N_p}{N_m}\right)^3 \times \left(\frac{D_p}{D_m}\right)^5$$

$$= (1)^3 \times \left(\frac{8}{1}\right)^5 = 8^5 \qquad (\because \quad N_p = N_m)$$

$$\therefore \quad P_m = \frac{P_p}{(8)^5} = \frac{10 \times 10^6}{(8)^5} = \mathbf{305.2\ W.} \quad \textbf{(Ans.)}$$

(*ii*) Ratio of heads $\left(\frac{H_p}{H_m}\right)$ and ratio of mass flow rates $\left(\frac{m_p}{m_m}\right)$:

We know that $H \propto N^2 D^2$ ...[Eq. (6.22)]

$$\therefore \quad \frac{H_p}{H_m} = \left(\frac{N_p}{N_m}\right)^2 \times \left(\frac{D_p}{D_m}\right)^2$$

$$= (1)^2 \times (8)^2 = \mathbf{64.} \quad \textbf{(Ans.)}$$

Also, Discharge, $Q \propto ND^3$ ...[Eqn. (6.23)]

$\therefore$ Ratio of mass flow rates,

$$\frac{Q_p}{Q_m} = \frac{m_p}{m_m} = \left(\frac{N_p}{N_m}\right)\left(\frac{D_p}{D_m}\right)^3$$

$$= 1 \times (8)^3 = \mathbf{512.} \quad \textbf{(Ans.)}$$

Example 6.21. *A hydraulic turbine is to develop 1015 kW when running at 120 r.p.m. under a net head of 12 m. Work out the maximum flow rate and specific speed for the turbine if the overall efficiency at the best operating point is 92 per cent. In order to predict its performance, a 1 : 10 scale model is tested under a head of 7.2 m. What would be the speed, power output and water consumption of the model if it runs under the conditions similar to the prototype ?*

Solution. Shaft power,

$$P = 1015 \text{ kW} ;$$

Speed, $N = 120$ r.p.m.

Overall efficiency,

$$\eta_o = 92\% ;$$

Head, $H = 12$ m

Flow rate (Q), Specific speed (N_s) :

$$\eta_o = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{wQH} ;$$

$$Q = \frac{P}{\eta_o wH}$$

or Flow rate,
$$Q = \frac{1015}{0.92 \times 9.81 \times 12}$$

$$= \mathbf{9.372\ m^3/s.} \quad \textbf{(Ans.)}$$

Specific speed,

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{120\sqrt{1015}}{(12)^{5/4}}$$

$$= \mathbf{171.2\ r.p.m.} \quad \textbf{(Ans.)}$$

Model scale = 1 : 10 (Given)

Head under which model is tested,

$$H_m = 7.2 \text{ m} \qquad \text{(Given)}$$

N_m, P_m, Q_m :

For similar turbines each of the following parameters must be same for both model and prototype.

(*i*) Head co-efficient, $C_H = \frac{H}{N^2D^2}$;

(*ii*) Flow co-efficient, $C_Q = \frac{Q}{ND^3}$

(*iii*) Power co-efficient, $C_p = \frac{P}{N^3D^5}$

(*i*) $$\left(\frac{H}{N^2D^2}\right)_m = \left(\frac{H}{N^2D^2}\right)_p \text{ or } \frac{H_m}{N_m^{\,2}D_m^{\,2}} = \frac{H_p}{N_p^{\,2}D_p^{\,2}}$$

or
$$N_m^{\,2} = N_p^{\,2} \frac{D_p^{\,2}}{D_m^{\,2}} \times \frac{H_m}{H_p}$$

$\therefore$ Model speed, $N_m = N_p \times \frac{D_p}{D_m} \times \left(\frac{H_m}{H_p}\right)^{1/2}$

$$= 120 \times 10 \times \left(\frac{7.2}{12}\right)^{1/2}$$

$$= \mathbf{929.5\ r.p.m.} \quad \textbf{(Ans.)}$$

(*ii*) $\left(\frac{Q}{ND^3}\right)_m = \left(\frac{Q}{ND^3}\right)_p$ or $\frac{Q_m}{N_m D_m{}^3} = \frac{Q_p}{N_p D_p{}^3}$

∴ Discharge in the model,

$$Q_m = Q_p \times \frac{N_m}{N_p} \times \left(\frac{D_m}{D_p}\right)^3$$

$$= 9.372 \times \frac{929.5}{120} \times \left(\frac{1}{10}\right)^3$$

$$= \mathbf{0.0726\ m^3/s.}\ \textbf{(Ans.)}$$

(*iii*) $\left(\frac{P}{N^3D^5}\right)_m = \left(\frac{P}{N^3D^5}\right)_p$ or $\frac{P_m}{N_m{}^3 D_m{}^5} = \frac{P_p}{N_p{}^3 D_p{}^5}$

∴ Power produced by the model,

$$P_m = P_p \times \left(\frac{N_m}{N_p}\right)^3 \times \left(\frac{D_m}{D_p}\right)^5$$

$$= 1015 \times \left(\frac{929.5}{120}\right)^3 \times \left(\frac{1}{10}\right)^5$$

$$= \mathbf{4.72\ kW.}\ \textbf{(Ans.)}$$

Hydro-electric Power Station

Example 6.22. *The following data relate to a hydro-electric power station :*

Head = 400 m ; Discharge = 4.5 m^3/s ; Turbine efficiency = 8.2% ; Generator frequency = 50 Hz. Determine:

(i) Power developed, (ii) Type of the turbine,

(iii) Speed of the turbine.

Solution. Head, $H = 400$ m

Discharge, $Q = 4.5$ m^3/s

Turbine efficiency, $\eta = 82\%$

Generator frequency, $f = 50$ Hz

(*i*) Power developed, P :

$$P = \eta \times wQH$$

$$= 0.82 \times 9.81 \times 4.5 \times 400$$

$$= \mathbf{14479\ kW.}\ \textbf{(Ans.)}$$

(*ii*) Type of turbine :

Pelton turbine should be used for a head of 400 m. **(Ans.)**

(*iii*) Speed of the turbine, N :

N = Actual speed of the turbine

N_s = Specific speed of the turbine.

Choosing an approximate speed of about 50.

Also, $N_s = \frac{N\sqrt{P}}{H^{5/4}}$

∴ $N = \frac{N_s \times (H)^{5/4}}{\sqrt{P}} = \frac{50 \times (400)^{5/4}}{\sqrt{14479}}$

$= 743.3$ r.p.m.

Again, $N = \frac{120f}{p}$ or $p = \frac{120f}{N}$

(where p = Number of poles)

∴ $p = \frac{120 \times 50}{743.3} = 8.07 \approx 8$ (say)

Corrected speed

$$= \frac{120f}{p} = \frac{120 \times 50}{8}$$

$$= \mathbf{750\ r.p.m.}\ \textbf{(Ans.)}$$

Example 6.23. *A flow of 75 m^3/s under a head of 110 m is available at a site for a hydro-power station. If the efficiency of the turbine is 88% and generator efficiency is 92%, determine :*

(i) Power developed,

(ii) Number of units required and their capacities.

Solution. Discharge, $Q = 75$ m^3/s

Head, $H = 110$ m

Turbine efficiency, $\eta_t = 88\%$

Generator efficiency, $\eta_g = 92\%$

(*i*) Power developed, P :

$$P = \eta_t \times wQH$$

or $$P = 0.88 \times 9.81 \times 75 \times 110$$

$$= \mathbf{71220\ kW.}\ \textbf{(Ans.)}$$

(*ii*) **Two turbines** each of $\frac{71220}{2} = 35610$ kW capacity may be used. **(Ans.)**

Generator capacity of each unit

$$= \eta_g \times 35610$$

$$= 0.92 \times 35610 = 32761\ \text{kW}$$

Total power generated by the generators

$$= 32761 \times 2$$

$$= \mathbf{65522\ kW\ or\ 65.5\ MW.}\ \textbf{(Ans.)}$$

Example 6.24. *A proposed hydro-electric station has an available head of 120 metres, a catchment area of 200 sq. km, the rainfall of which is 120 cm per annum. If 62% of the total rainfall can be collected, calculate the power that could be generated. Suggest suitable ratings of generators.*

Solution. Available head, $H = 120$ m

Catchment area,

$A = 200$ sq. km ($= 200 \times 10^6$ m^2)

Rainfall = 120 cm per annum (= 1.2 m)

Rainfall collected/annum,

h = 62% of the total rainfall

$= (0.62 \times 1.2)$ m.

Power developed, P :

Total quantity of water available for power generation

$$= A \times h = 200 \times 10^6 \times (0.62 \times 1.2)$$

$$= 148.8 \times 10^6\ m^3/\text{year}$$

Hence quantity of water available per second

$$= \frac{148.8 \times 10^6}{(365 \times 24) \times 60 \times 60}$$

$$= \frac{148.8 \times 10^6}{8760 \times 3600} = 4.7 \text{ m}^3/\text{s}$$

Now, $P = \eta_o \times wQH$

$= 0.95 \times 9.81 \times 4.7 \times 120$

(Assuming $\eta_o = 0.95$)

$=$ **5256 kW.** **(Ans.)**

Suitable ratings of generators :

Two generators of 2800 kW capacity each may be installed. However, ratings of generators may need upward revision if various efficiencies and load factors are taken into account.

☞ **Example 6.25.** *The following data relate to a proposed hydro-electric station :*

Available head = 28 m ; Catchment area = 420 sq. km ; rainfall = 140 cm/year ; percentage of total rainfall utilized = 68% ; Penstock efficiency = 94% ; turbine efficiency = 80% ; generator efficiency = 84% and load factor = 44%.

(i) Calculate the power developed.

(ii) Suggest suitable machines and specify the same.

Solution. Head available, $H = 28$ m

Catchment area, $A = 420$ sq. km

$(= 420 \times 10^6 \text{ m}^2)$

Rainfall $= 140$ cm/year $(= 1.4$ m$)$

Rainfall utilized, $h = 68\%$ of the total rainfall

$= (0.68 \times 1.4)$ m per year

Penstock efficiency, $\eta_p = 94\%$

Turbine efficiency, $\eta_t = 80\%$

Generator efficiency, $\eta_g = 84\%$

Load factor $= 44\%$.

(*i*) Power developed, P :

Quantity of water available *per year*

$= A \times h = (420 \times 10^6) \times (0.68 \times 1.4)$

$= 399.84 \times 10^6 \text{ m}^3$

Hence the quantity of water available *per second,*

$$Q = \frac{399.84 \times 10^6}{(365 \times 24) \times 3600} = 12.6 \text{ m}^3$$

$\therefore$ $P = \eta_o \times wQH$

(where η_o = Overall efficiency = $\eta_p \times \eta_t \times \eta_g$)

or $P = \eta_p \times \eta_t \times \eta_g \times wQH$

$= 0.94 \times 0.8 \times 0.84 \times 9.81 \times 12.6 \times 28$

$= 2186$ kW

Hence *average output of generating units*

$=$ **2186 kW.** **(Ans.)**

(*ii*) Machines to be used :

Total ratings of generators $= \frac{2186}{0.44} = 4968$ kW

Providing *two machines* of equal rating,

Capacity of each unit $= \frac{4968}{2 \times 0.84} = 2957$ each.

As the available head is low, **Kaplan turbines** (propeller type) are suggested, each having a *generating capacity of* **2957 kW.** **(Ans.)**

☞ **Example 6.26.** *The following data is available for a hydro-power plant :*

Available head = 140 m ; catchment area = 2000 sq. km ; annual average rainfall = 145 cm ; turbine efficiency = 85% ; generator efficiency = 90% ; percolation and evaporation losses = 16%.

Determine the following :

(i) Power developed.

(ii) Suggest type of turbine to be used if runner speed is to be kept below 240 r.p.m.

Solution. Head available, $H = 140$ m

Catchment area, $A = 200$ sq. km

$(= 200 \times 10^6 \text{ m}^2)$

Annual average rainfall, $h = 145$ cm $(= 1.45$ m$)$

Turbine efficiency, $\eta_t = 85\%$

Generator efficiency, $\eta_g = 90\%$

Percolation and evaporation losses,

$z = 16\% = 0.16$

(*i*) Power developed, P :

Quantity of water available for power generation *per year*

$= A \times h \times (1 - z)$

$= 200 \times 10^6 \times 1.45 \times (1 - 0.16)$

$= 2.436 \times 10^8 \text{ m}^3/\text{year}$

Hence, quantity of water available per second,

$$Q = \frac{2.436 \times 10^8}{(365 \times 24) \times 3600} = 7.72 \text{ m}^3/\text{s}$$

$\therefore$ $P = \eta_o \times wQH$

$= \eta_t \times \eta_g \times wQH$

$= 0.85 \times 0.9 \times 9.81 \times 7.72 \times 140$

$=$ **8111 kW or 8.111 MW.** **(Ans.)**

(*ii*) Type of turbine to be used :

Specific speed,

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{240\sqrt{8111}}{(140)^{5/4}} = 44.28 \text{ r.p.m.}$$

Single Pelton turbine with 4 jets can be used. Further since head available is large and discharge is low, Pelton turbine will work satisfactorily. **(Ans.)**

Example 6.27. *From the investigation of a hydro-site the following data is available :*

Available head	*45 m*
Total catchment area	*60 sq. km*
Rainfall per annum	*140 cm*
Percentage of rainfall utilized	*68%*
Turbine efficiency	*82%*
Generator efficiency	*90%*
Percentage efficiency	*74%*

Calculate the suitable capacity of a turbo-generator.

Solution. Head available, $H = 45$ m

Catchment area, $A = 60$ sq. km $(= 60 \times 10^6 \text{ m}^2)$

Available rainfall, $h = (0.68 \times 1.4)$ m

Turbine efficiency, $\eta_t = 82\%$

Generator efficiency, $\eta_g = 90\%$

Penstock efficiency, $\eta_p = 74\%$

Quantity of water available per annum

$= A \times h = 60 \times 10^6 \times (0.68 \times 1.4)$

$= 57.12 \times 10^6$ m^3/annum

Hence, quantity of water available per second,

$$Q = \frac{57.12 \times 10^6}{(365 \times 24) \times 3600} = 1.81 \text{ m}^3/\text{s}$$

Now overall efficiency,

$$\eta_o = \eta_p \times \eta_t \times \eta_g$$
$$= 0.74 \times 0.82 \times 0.9 = 0.546$$

$\therefore$ Power developed,

$$P = \eta_o \times wQH$$
$$= 0.546 \times 9.81 \times 1.81 \times 45 = 436 \text{ kW}$$

If a load factor of 55 per cent is assumed, then

$$\text{Maximum kW} = \frac{436}{0.55} = 793 \text{ kW}$$

So a generator of 800 kW maximum rating can be selected. **(Ans.)**

$\therefore$ *Power of the turbine* $= \dfrac{793}{0.82} =$ **967 kW.** **(Ans.)**

For a head of 45 m, which is low, a *vertical shaft Francis* or *Kaplan turbine* may be employed.

Example 6.28. *A hydro-electric power plant produces 20 MW under a head of 15 metres. If the overall efficiency of the plant is 72%, determine :*

(i) Type of turbine

(ii) Synchronous speed of the generator.

Solution. Power developed, $P = 20$ MW $(= 20 \times 10^3 \text{ kW})$

Head, $H = 15$ m

Overall efficiency, $\eta_o = 72\%$

(i) Type of turbine :

$$P = \eta_o \times wQH$$
$$20 \times 10^3 = 0.72 \times 9.81 \times Q \times 15$$

$$\therefore \quad Q = \frac{20 \times 10^3}{0.72 \times 9.81 \times 15} = 188.8 \text{ m}^3/\text{s}$$

As the head is low and discharge is high so a propeller type of turbine should be used. **(Ans.)**

(ii) Synchronous speed of the generator, N_{syn} :

Specific speed, $N_s = \dfrac{1150}{H^{1/4}}$ (approx.)

$$= \frac{1150}{(15)^{1/4}} = 584.3 \text{ r.p.m.}$$

Speed of rotation, $N = \dfrac{N_s \times H^{5/4}}{\sqrt{P}}$ $\left(\because N_s = \dfrac{N\sqrt{P}}{H^{5/4}}\right)$

$$= \frac{584.3 \times (15)^{5/4}}{\left(\dfrac{20 \times 10^3}{0.7355}\right)^{1/2}}$$

$= 104.6$ r.p.m.

For generator, $N = \dfrac{120f}{p}$

$$104.6 = \frac{120 \times 50}{p}$$

[where f = frequency (= 50 Hz)]

$$\therefore \quad p = \frac{120 \times 50}{104.6} = 57.36 = 60 \text{ (say)}$$

(as the number of poles is necessarily an even number)

Again, $N_{syn} = \dfrac{120f}{p} = \dfrac{120 \times 50}{60}$

$=$ **100 r.p.m.** **(Ans.)**

☞**Example 6.29.** *Calculate the power developed in MW from a hydro-electric power plant with the following data :*

Available head	*50 m*
Catchment area	*250 sq. km*
Average annual rainfall	*120 cm*
Rainfall lost due to evaporation	*20%*
Turbine efficiency	*82%*
Generator efficiency	*84%*
Head lost in penstock	*4%*

Solution. Head available, $H = 50$ m

Catchment area, $A = 250$ sq. km $(= 250 \times 10^6 \text{ m}^2)$

Average annual rainfall $= 120$ cm $(= 1.2$ m$)$

Evaporation loss $= 20\%$

∴ Average annual rainfall available,

$$h = (1 - 0.2) \times 1.2 = 0.96 \text{ m}$$

Turbine efficiency, $\eta_t = 82\%$

Generator efficiency, $\eta_g = 84\%$

Penstock efficiency, $\eta_p = 100 - 4 = 96\%$

Quantity of water available *per annum*

$$= A \times h = 250 \times 10^6 \times 0.96$$
$$= 2.4 \times 10^8 \text{ m}^3$$

Hence, quantity of water available *per second,*

$$Q = \frac{2.4 \times 10^8}{(365 \times 24) \times 3600} = 7.61 \text{ m}^3/\text{s}$$

Overall efficiency,

$$\eta_o = \eta_p \times \eta_t \times \eta_g$$
$$= 0.96 \times 0.82 \times 0.84 = 0.66$$

Power developed,

$$P = \eta_o \times wQH$$
$$= 0.66 \times 9.81 \times 7.61 \times 50 \text{ kW}$$
$$= 2463.6 \text{ kW or } 2.463 \text{ MW}$$

Hence power developed = **2.463 MW.** **(Ans.)**

Example 6.30. *The following data is supplied for a hydro-electric power station :*

Catchment area	*100 sq. km*
Annual rainfall	*1200 mm*
Available head	*220 m*
Load factor	*45%*
Yield factor to allow for run-off and evaporation loss	*55%*
Power plant efficiency	*72%*

Calculate the following :

(i) Average power produced

(ii) Capacity of the power plant.

Solution. Volume of water available per annum

= Catchment area × annual rainfall × yield factor

$= 100 \times 10^6 \times 1.2 \times 0.55 = 6.6 \times 10^7 \text{ m}^3$

Hence, quantity of water available per second

$$= \frac{6.6 \times 10^7}{(365 \times 24) \times 60 \times 60} = 2.09 \text{ m}^3/\text{s}$$

(i) Average power produced, P :

$$P = \eta \times wQH \text{ kW}$$
$$= 0.72 \times 9.81 \times 2.09 \times 220 \text{ kW}$$
$$= \mathbf{3247.6 \text{ kW.}} \quad \textbf{(Ans.)}$$

(ii) Capacity of the power plant :

$$\text{Load factor} = \frac{\text{Average power}}{\text{Maximum demand}}$$

∴ Maximum demand

$$= \frac{\text{Average power}}{\text{Load factor}}$$

$$= \frac{3247.6}{0.45} = 7216.9 \text{ kW}$$

The *capacity of the plant can be taken equal to maximum demand.*

∴ *Capacity* = **7216.9 kW.** **(Ans.)**

☞**Example 6.31.** *In a hydro-electric power plant the reservoir is 225 m above the turbine house. The annual replenishment of reservoir is 3.5 × 10^{12} N. Calculate the energy available at the generating station bus bars if the loss of head in the hydraulic system is 25 m and the overall efficiency of the system is 85%.*

If maximum demand of 45 MW is to be supplied determine the diameter of two steel penstocks.

Solution. Actual head available, $H = 225 - 25 = 200$ m

Overall efficiency, $\eta_o = 85\%$

Annual replenishment, $W = 3.5 \times 10^{12}$ N

(i) Energy output :

E = Energy available at the turbine house

$$= WH = 3.5 \times 10^{12} \times 200$$
$$= 7 \times 10^{14} \text{ Nm or J}$$
$$= \frac{7 \times 10^{14}}{36 \times 10^5} = 1.944 \times 10^8 \text{ kWh}$$

[∵ 1 kWh = 36×10^5 J]

Energy output $= \eta_o \times E$

$$= 0.85 \times 1.944 \times 10^8$$
$$= \mathbf{1.652 \times 10^8 \text{ kWh.}} \quad \textbf{(Ans.)}$$

(ii) Diameter of steel penstock, D :

Kinetic energy of water

= Loss of potential energy

$$\therefore \quad \frac{1}{2} mC^2 = mgH$$

$$\therefore \quad C = \sqrt{2gH} = \sqrt{2 \times 9.81 \times 200}$$
$$= 62.64 \text{ m/s}$$

(where C = Velocity water in each penstock, m = mass of water in kg)

Now, $\frac{1}{2} mC^2$ = Energy to be supplied

$$\frac{1}{2} m \times (62.64)^2 = 45 \times 10^6 \text{ W}$$

$$\therefore \quad m = \frac{45 \times 10^6 \times 2}{(62.64)^2} = 22937 \text{ kg}$$

Let A = Area of two penstocks, m^2,

A_1 = Area of each penstock = $\frac{A}{2}$,

D = Diameter of each penstock,

Then, $m = A \times C \times \rho$

(where ρ = Mass density of water)

$$22973 = A \times 62.64 \times 1000$$

$$\left(\rho = \frac{w}{g} - \frac{9810}{9.81} = 1000 \text{ kg/m}^3\right)$$

$$A = \frac{22973}{62.64 \times 1000} = 0.366 \text{ m}^2$$

and $$A_1 = \frac{A}{2} = \frac{0.366}{2} = 0.183 \text{ m}^2$$

Now, $$0.183 = \frac{\pi}{4} D^2$$

$$\therefore \quad D = \left(\frac{0.183 \times 4}{\pi}\right)^{1/2}$$

$$= \mathbf{0.483 \text{ m.}} \quad \textbf{(Ans.)}$$

Example 6.32. *It is observed that a run-of-river plant operates as peak load plant with a weekly load factor of 25% all this capacity being firm capacity. Determine the minimum flow in river so that power plant may act as a base load plant. The following data is supplied : Rated installed capacity of generating plant = 10 MW, operating head = 16 m. Plant efficiency = 86%.*

If the stream flow is 15 m³/s, find the daily load factor of the plant.

Solution. Weekly load factor = 25%

Rated installed capacity of generating plant = 10 MW (= 10000 kW)

Operating head, $H = 16$ m

Plant efficiency, $\eta_o = 86\%$

Minimum flow in river in m³/sec, Q :

$\because$ Load factor $= \dfrac{\text{Average load}}{\text{Maximum demand}}$

$\therefore$ Average load = Load factor × Maximum demand

$= 0.25 \times 10000 = 2500$ kW

E = Total energy generated in one *week*

$= 2500 \times 24 \times 7 = 42 \times 10^4$ kWh

Now, Power developed,

$P = \eta_o \, wQH$ kW

$= 0.86 \times 9.81 \times Q \times 16$ kW

$= 134.98 \, Q$ kW

$\therefore$ E_1 = Total energy generated in one *week*

$= 134.98 \, Q \times 24 \times 7$

$= 22676.6 \, Q$ kWh

Now, $E = E_1$

$42 \times 10^4 = 22676.6 \, Q$

$$\therefore \quad Q = \frac{42 \times 10^4}{22676.6} = 18.52 \text{ m}^3/\text{s}$$

Hence minimum flow rate = **18.52 m³/s.** **(Ans.)**

Power developed when stream flow is 15 m³/s,

$P_1 = 134.98 \times 15 = 2024.7$ kW

Energy generated per day,

$E_2 = P_1 \times \text{time} = 2024.7 \times 24$

$= 48592.8$ kWh

$\therefore$ *Daily load factor*

$$= \frac{\text{Average load}}{\text{Maximum load}} = \frac{48592.8}{10000 \times 24}$$

$$= \mathbf{0.2025 \text{ or } 20.25\%.} \quad \textbf{(Ans.)}$$

Example 6.33. *Calculate the firm capacity of a run-of-river hydro-power plant to be used as 8 hours peaking plant assuming daily flow in a river to be constant at 15 m³/s. Also calculate pondage factor and pondage if the head of the plant is 11 m and overall efficiency is 85%.*

Solution. Discharge, $Q = 15$ m³/s

Plant head, $H = 11$ m

Overall efficiency, $\eta_o = 85\%$

Specific weight of water, $w = 9.81$ kN/m³

P = Firm capacity without pondage

$= \eta_o \times wQH = 0.85 \times 9.81 \times 15 \times 11$

$= 1375.8$ kW

$$PF = \text{Pondage factor} = \frac{t_1}{t_2}$$

where, t_1 = Total hours in one day = 24, and

t_2 = Number of hours for which plant runs = 8

[***Pondage factor*** *is the ratio of total inflow hours in a given period to the total number of hours for which plant runs during the same period.*]

$$PF = \frac{24}{8} = \mathbf{3.} \quad \textbf{(Ans.)}$$

$Q_1 = 15 \times 3 = 45$ m³/s

P_1 = Firm power with pondage

$= 1375.8 \times 3 = 4127.4$ kW

Pondage (magnitude)

$= (24 - 8) = 16$ hours flow

$= 16 \times 60 \times 60 \times 15$

$= \mathbf{8.64 \times 10^5 \text{ m}^3.}$ **(Ans.)**

Example 6.34. *The following data relate to a pump storage power plant :*

Gross head	*280 m*
Dia. of headrace tunnel	*4.0 m*
Length of headrace tunnel	*620 m*
Flow velocity	*6.5 m/s*
Friction factor	*0.018*
Pumping efficiency	*85%*
Generation efficiency	*90%*

If the power plant discharges directly in the lower reservoir determine the plant efficiency.

Solution. Head, $H = 280$ m

Dia. of headrace tunnel, $D = 4.0$ m

Length of headrace tunnel, $L = 620$ m

Flow velocity, $C = 6.5$ m/s

Friction factor, $f = 0.018$

Pumping efficiency, $\eta_p = 85\%$

Generation efficiency, $\eta_g = 90\%$

Plant efficiency, η_{plant} :

Loss of head due to friction (h_f) is given by the equation :

$$h_f = \frac{fLC^2}{2gD} = \frac{0.018 \times 620 \times 6.5^2}{2 \times 9.81 \times 4.0}$$

$$= 6.0 \text{ m}$$

Now, $h_f = xH$

$$6 = x \times 280$$

$$\therefore \quad x = \frac{6}{280} = 0.0214$$

$$\therefore \quad \eta_{plant} = \frac{1-x}{1+x} \times \eta_p \times \eta_g$$

$$= \frac{(1-0.0214)}{(1+0.0214)} \times 0.85 \times 0.9$$

$$= \mathbf{0.7329 \text{ or } 73.29\%.} \quad \textbf{(Ans.)}$$

Hydrology

Example 6.35. *At a particular site the mean monthly discharge is as follows :*

Month	*Discharge, m^3/s*	*Month*	*Discharge, m^3/s*
January	*100*	*July*	*1000*
February	*225*	*August*	*1200*
March	*300*	*September*	*900*
April	*600*	*October*	*600*
May	*750*	*November*	*400*
June	*800*	*December*	*200*

Draw the following :

(i) Hydrograph *(ii) Flow duration curve.*

Solution. (*i*) The **hydrograph** is plotted between discharge (m^3/sec) and time (months) as shown in Fig. 6.58.

(*ii*) **Flow duration curve :**

In order to draw *flow duration curve* it is essential to find the *length* of *time* during which certain flows are available, *e.g.* 100 m^3/s is available for all 12 months, flow of 200 m^3/s for 11 months, 225 m^3/s for 10 months and so on. This information is indicated in the table.

Discharge, m^3/s	Length of time, months	%age time
100 (and more)	12	100
200 (and more)	11	91.7
225 (and more)	10	83.3
300 (and more)	9	75.0
400 (and more)	8	66.7
600 (and more)	7	58.3
750 (and more)	5	41.7
800 (and more)	4	33.3
900 (and more)	3	25.0
1000 (and more)	2	16.7
1200 (and more)	1	8.3

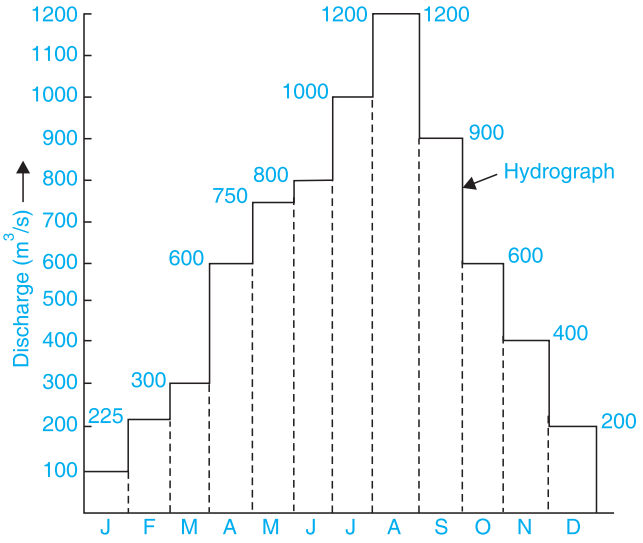


Fig. 6.58. Hydrograph.

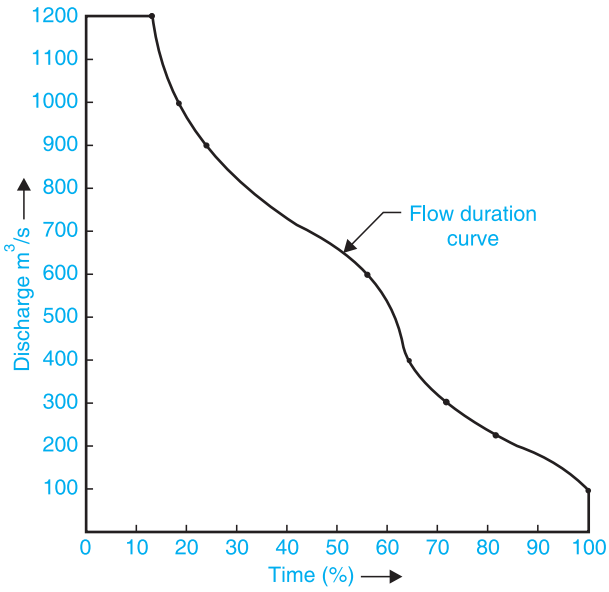


Fig. 6.59. Flow duration curve.

The flow duration curve is then plotted as shown in Fig. 6.59.

Note. When selecting a suitable site for a hydro-power plant the flow data for a number of years is collected and hydrographs and flow duration curves and the various periods are determined.

Example 6.36. *The runoff data of a river at a particular site is tabulated below :*

Month	*Mean discharge per month (millions of cu m)*
January	*40*
February	*25*
March	*20*
April	*10*
May	*0*
June	*50*
July	*75*
August	*100*
September	*110*
October	*60*
November	*50*
December	*40*

(i) Draw a hydrograph and find the mean flow,

(ii) Also draw the flow duration curve,

(iii) Find the power in MW available at mean flow if the head available is 80 m and overall efficiency of generation is 85%.

Take each month of 30 days.

Solution. *(i)* **Hydrograph :**

The *hydrograph* for the given data is drawn as shown in Fig. 6.60.

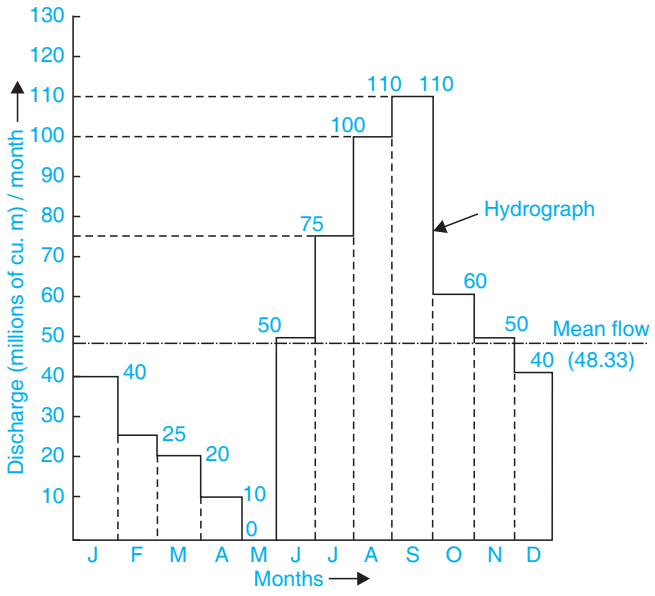


Fig. 6.60. Hydrograph.

The mean discharge for the given data

$$= \frac{40 + 25 + 20 + 10 + 0 + 50 + 75 + 100 + 110 + 60 + 50 + 40}{12}$$

$$= \frac{580}{12} = 48.33 \text{ millions of } m^3/\text{month}.$$

(ii) **Flow duration curve :**

To obtain the *flow duration curve* it is necessary to find the *lengths of time* during which certain flows are available. This information is tabulated, using the hydrograph, in the table below :

Discharge per month (millions of m^3)	Total number of months during which flow is available	Percentage time
0	12	100
10	11	91.7
20	10	83.3
25	9	75
40	8	66.7
50	6	50
60	4	33.3
75	3	25.0
100	2	16.7
110	1	8.3

The flow duration curve can be drawn using the data tabulated as shown in Fig. 6.61.

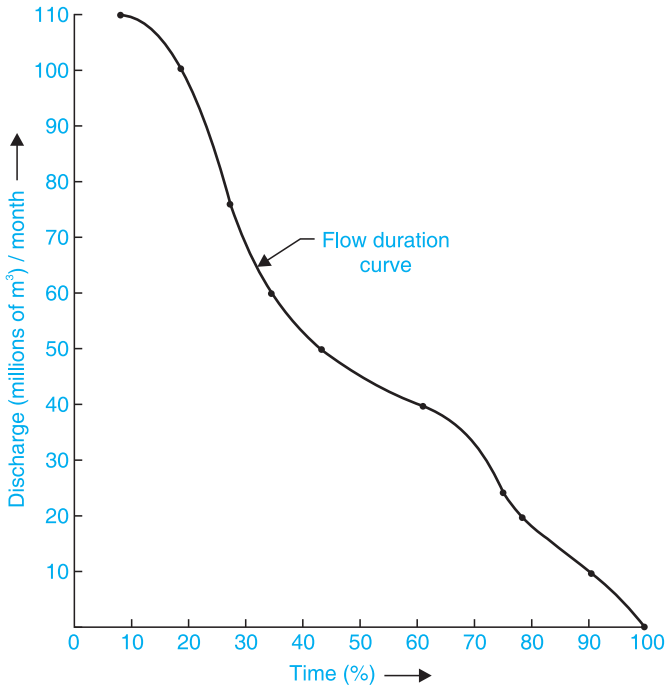


Fig. 6.61. Flow duration curve.

(iii) Average MW energy available :

$$= \eta_o \, wQH \times \frac{1}{1000} \text{ MW}$$

(where $w = 9.81$ kN/m^3)

$$\left[\text{where } Q \text{ (discharge in m}^3\text{/s)} = \frac{48.33 \times 10^6}{30 \times 24 \times 3600}\right]$$

$$= 0.85 \times \frac{9.81 \times 48.33 \times 10^6 \times 80}{(30 \times 24 \times 3600)} \times \frac{1}{1000} \text{ MW}$$

$$= \mathbf{12.4 \text{ MW.}} \quad \textbf{(Ans.)}$$

Example 6.37. *The nature of load required for 24 hours and thermal efficiencies of the plant at the respective loads are given in the table below :*

Time period	*Load (MW)*	*Thermal efficiency (% age)*
10 A.M. to 6 P.M.	*120*	*32%*
6 P.M. to 8 P.M.	*60*	*24%*
8 P.M. to 12 A.M.	*30*	*15%*
12 A.M. to 6 A.M.	*15*	*10%*
6 A.M. to 10 A.M.	*75*	*25%*

(i) Find the total input to the thermal plant if the load is supplied by the single thermal plant only.

(ii) If the above load is taken by combined thermal and pump storage plant, then find the percentage saving in the input to the plant. Thermal efficiency at full load = 32%.

(iii) The overall efficiencies in both cases.

In pump storage plant, the pump and turbine are separate. The efficiency of pump is 82% and water turbine is 92%.

Solution. The load curve, drawn as per the data given, is shown in Fig. 6.62.

Total output per day

$$= 75 \times 4 + 120 \times 8 + 60 \times 2 + 30 \times 4 + 15 \times 6$$

$$= 300 + 960 + 120 + 120 + 90 = 1590 \text{ MWh}$$

(i) Total input to the thermal plant :

The input to the thermal plant

$$= \frac{75 \times 4}{0.25} + \frac{120 \times 8}{0.32} + \frac{60 \times 2}{0.24} + \frac{30 \times 4}{0.15} + \frac{15 \times 6}{0.1}$$

$$= 1200 + 3000 + 500 + 800 + 900$$

$$= \mathbf{6400 \text{ MWh.}} \quad \textbf{(Ans.)}$$

(ii) Percentage saving in the input to plant :

The overall efficiency of the pump storage plant

$$= 0.82 \times 0.92$$

$$= 0.7544 \text{ or } 75.44\%.$$

Assume that the capacity of the thermal plant is x MW when it is working in combination with pump-storage plant.

The energy used from the thermal plant to pump the water of pump storage plant during off-peak period *must be equal to* the energy supplied by the pump-storage plant during peak period.

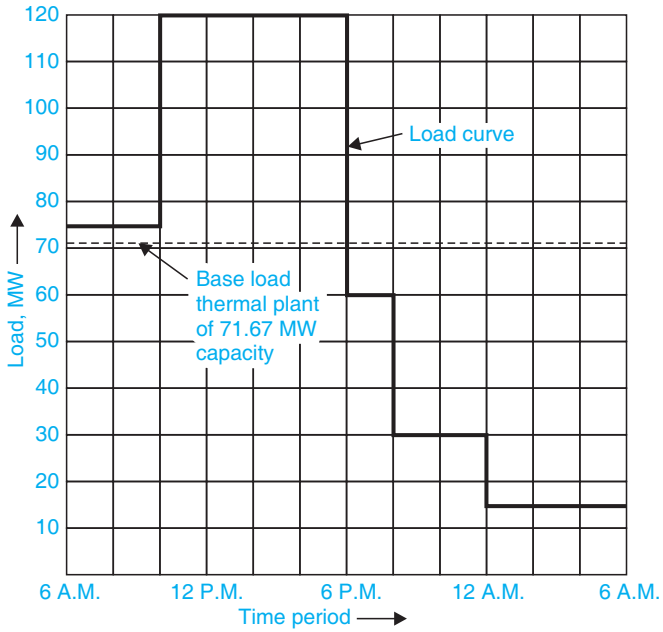


Fig. 6.62. Load curve.

From the Fig. 6.62, we have:

$$[(x - 60) \times 2 + (x - 30) \times 4 + (x - 15) \times 6] \times 0.7544$$

$$= (75 - x) \times 4 + (120 - x) \times 8$$

or $$[(2x - 120) + (4x - 120) + (6x - 90)] \times 0.7544$$

$$= (300 - 4x) + (960 - 8x)$$

or $$(12x - 330) \times 0.7544 = 1260 - 12x$$

or $$9.053x - 248.95 = 1260 - 12x$$

$$\therefore \quad x = \frac{1260 + 248.95}{(9.053 + 12)} = 71.67 \text{ MW}$$

The energy supplied in the second case

$$= \frac{71.67 \times 24}{0.32} = 5375 \text{ MWh}$$

The percentage saving in input if the load is taken by combined thermal and pump storage plant.

$$= \frac{6400 - 5375}{6400}$$

$$= 0.16 \text{ or } \mathbf{16\%.} \quad \textbf{(Ans.)}$$

(iii) **The overall efficiency** in the *first case*

$$= \frac{1590}{6400} = 0.2484$$

$$= \mathbf{24.84\%.} \quad \textbf{(Ans.)}$$

The overall efficiency in the *second case*

$$= \frac{1590}{5375}$$

$$= 0.2958 \text{ or } \mathbf{29.58\%.} \quad \textbf{(Ans.)}$$

Example 6.38. *At a particular site of a river, the mean monthly discharge for 12 months is tabulated below :*

Month	*Discharge (millions of m^3 per month)*
April	*250*
May	*100*
June	*750*
July	*1250*
Aug.	*1500*
Sep.	*1200*
Oct.	*1000*
Nov.	*750*
Dec.	*750*
Jan.	*500*
Feb.	*400*
Mar.	*300*

(i) Draw hydrograph for the given discharges and find the average monthly flow.

(ii) Also draw the flow duration curve.

(iii) The power available at mean flow of water if available head is 90 metres at the site and overall efficiency of the generation is 82 per cent.

Take 30 days in a month.

Solution. *(i)* **Hydrograph :**

The hydrograph, drawn as per data given, is shown in Fig. 6.63.

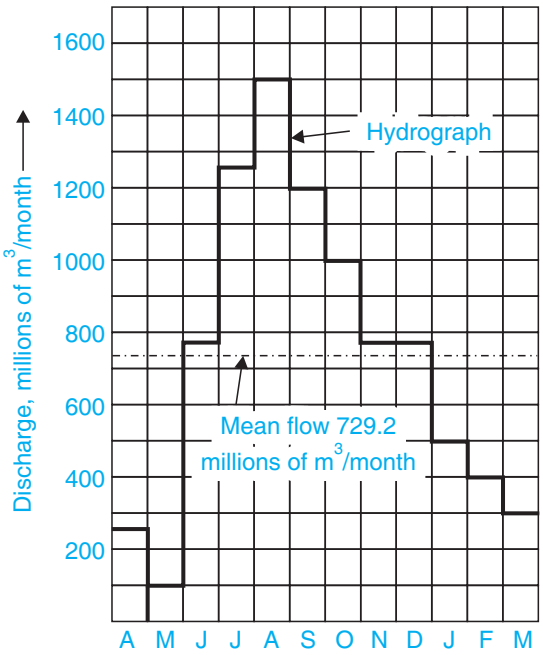


Fig. 6.63. Hydrograph.

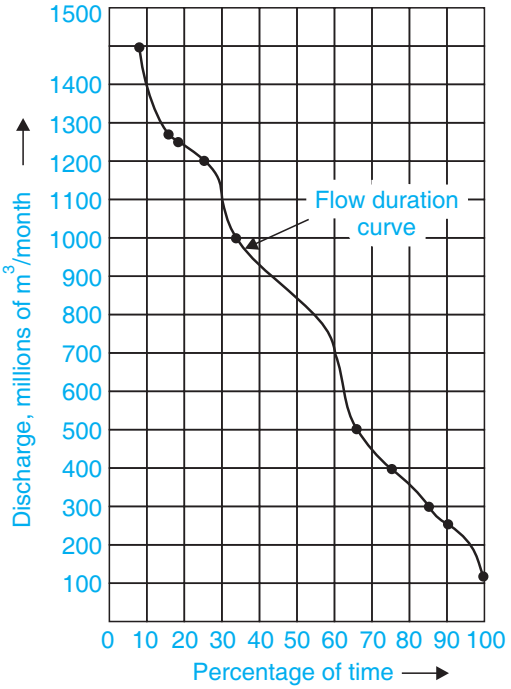


Fig. 6.64. Flow duration curve.

The average monthly flow (Refer to Fig. 6.63)

$$= \frac{250 + 100 + 750 + 1250 + 1500 + 1200 + 1000 + 750 + 750 + 500 + 400 + 300}{12}$$

= 729.2 millions of m^3/month.

(ii) **Flow duration curve :**

In order to obtain the *flow duration curve* it is necessary to find the lengths of time during which certain flows are available.This information is tabulated, using the hydrograph, in the following table :

Discharge per month million of m^3	*Total number of months during which flow is available*	*Percentage time during which flow is available*
100	12	100
250	11	91.8
300	10	83.40
400	9	76.00
500	8	66.60
750	7	58.40
1000	4	33.30
1200	3	25.00
1250	2	16.65
1500	1	8.325

By using the above tabulated data, the *flow duration curve* can be drawn as shown in Fig. 6.64.

(*iii*) Power available at mean flow of water :

The mean/average flow available per second

$$= \frac{729.2 \times 10^6}{30 \times 24 \times 3600} = 281.3 \text{ m}^3/\text{s}$$

Average kW available at the site

$$= \frac{wQH}{1000} \times \eta_g \text{ MW}$$

$(\because \quad w = \rho_g = 1000 \times 9.81 = 9.81 \text{ kN/m}^3)$

$$= \frac{9.81 \times 281.3 \times 90}{1000} \times 0.82$$

$$= \mathbf{203.6 \text{ MW.}} \quad \textbf{(Ans.)}$$

Example 6.39. *The data for a weekly flow at a particular site is given below for 12 weeks :*

Week	*Weekly flow, m^3/s*	*Week*	*Weekly flow, m^3/s*
1	*3000*	*7*	*600*
2	*2000*	*8*	*2250*
3	*2700*	*9*	*4000*
4	*1000*	*10*	*2000*
5	*750*	*11*	*1500*
6	*500*	*12*	*1000*

With the help of mass curve, find the size of the reservoir and the possible rate of available flow after the reservoir has been built.

Solution. In order to draw *mass curve,* we need to find the cumulative volume of water that can be stored week after week. This is done as tabulated in the table.

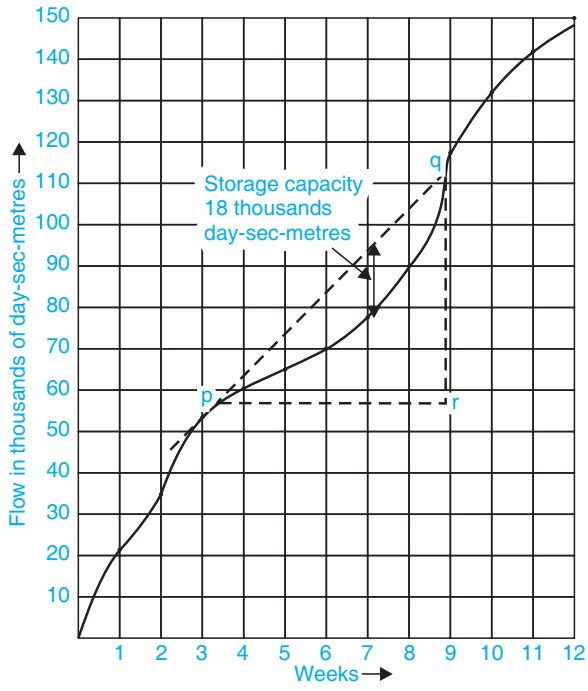


Fig. 6.65

Week (a)	*Weekly flow in m^3/s (b)*	*Weekly flow in day-sec-metre (c) = (b) × 7*	*Cumulative volume in day-sec-metres (d)*
1	3000	21000	21000
2	2000	14000	35000
3	2700	18900	53900
4	1000	7000	60900
5	750	5250	66150
6	500	3500	69650
7	600	4200	73850
8	2250	15750	89600
9	4000	28000	117600
10	2000	14000	131600
11	1500	10500	142100
12	1000	7000	149100

If the *mean flow* is available in the week at the given rate, then the total flow in the week = 7 × day × m^3/sec = 7 × day-sec-metres.

By using the above tabulated data, the mass curve can be drawn as shown in Fig. 6.65.

- Draw the tangent at the highest point on the mass curve from '*p*' and *measure the highest distance between the tangent drawn and mass curve which gives the capacity of the reservoir.*

  In this **capacity of the reservior = 18 × 10^3 day-sec-metres. (Ans.)**

- The *slope of the line 'pq' gives the flow rate available for the given capacity reservoir.*

$\therefore$ **Flow rate available**

$$= \frac{qr}{pr} = \frac{54 \times 10^3 \text{ (day - sec - metres)}}{5.5 \times 7 \text{(days)}}$$

$$= \mathbf{1402.6 \text{ m}^3/\text{s.}} \quad \textbf{(Ans.)}$$

Example 6.40. *The following run-off data is collected for twelve months at a particular site :*

Month	*Flow per month, millions of m^3*	*Month*	*Flow per month, millions of m^3*
1	*50*	*7*	*95*
2	*25*	*8*	*20*
3	*10*	*9*	*15*
4	*40*	*10*	*100*
5	*5*	*11*	*85*
6	*5*	*12*	*40*

Determine the following :

(i) The required capacity for the uniform flow of 25 millions m^3 per month throughout the year.

(ii) Spill-way capacity.

(iii) Average flow capacity if whole water is used and required capacity of the reservoir for this condition.

Solution. In order to draw the ***mass curve,*** we need to find the cumulative volume of water that can be stored month after month. This is done as shown in the following table :

Month	Flow per month (millions of m^3)	Cumulative volume, (millions of m^3)
1	50	50
2	25	75
3	10	85
4	40	125
5	5	130
6	5	135
7	95	230
8	20	250
9	15	265
10	100	365
11	85	450
12	40	490

By using the above tabulated data, the mass curve can be drawn as shown in Fig. 6.66.

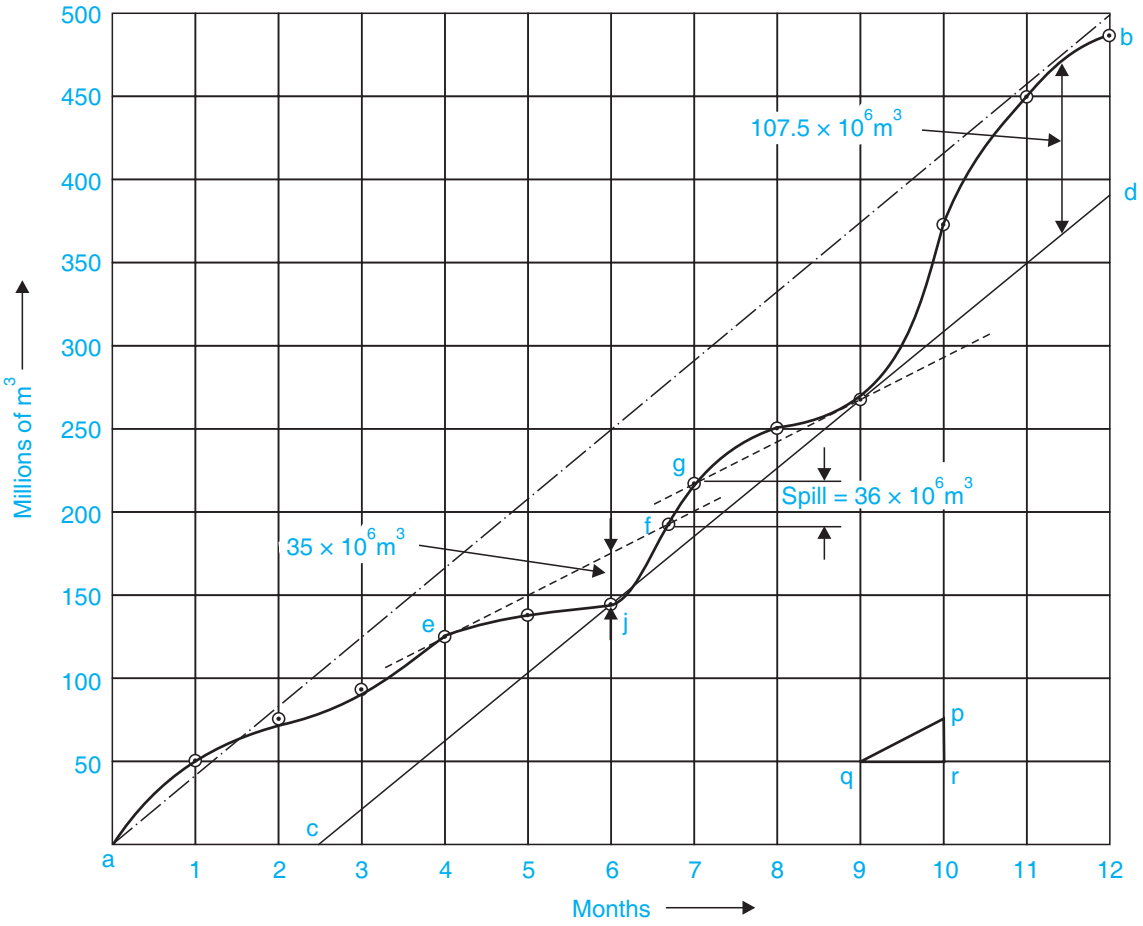


Fig. 6.66. Mass curve.

(i) Required capacity for the uniform flow of 25 millions m^3 per month :

- For finding the capacity of the reservoir for uniform flow of 25 millions m^3 per month, construct the Δpqr as shown in Fig. 6.66. *qr* repersents one month and *pr* represents 25 millions m^3.
- Now draw the parallel lines to the line *pq* through the points *e* and *g* which are apex of mass curve. The greatest departure of the mass curve from these lines represents the storage capacity.

$\therefore$ *Storage capacity* $= 35 \times 10^6 \text{ m}^3$. **(Ans.)**

(ii) Spillway capacity :

Spillway capacity required (Fig. 6.66)

$= 36 \times 10^3 \text{ m}^3$. **(Ans.)**

(iii) Average flow capacity

- Join points *a* and *b*, then the slope of the line *ab* represents the uniform discharge throughout the year,

$$= \frac{490}{12} \times 10^6$$

$= 40.83 \times 10^6 \text{ m}^3/\text{month}$. **(Ans.)**

- Draw the line *cd* parallel to *ab* which touches the mass curve to its lowest point *'j'*. The *maximum departure of the line cd from the mass curve represents the required* ***storage capacity*** *for the uniform supply of* $40.83 \times 10^6 \ m^3/month$. In this case, storage capacity required

$= 107.5 \times 10^6 \text{ m}^3$. **(Ans.)**

HIGHLIGHTS

1. A *dam* is a barrier to confine or raise water for storage or diversion to create a hydraulic head.
2. A *canal* is an open waterway excavated in natural ground. A *flume* is an open channel excavated on the surface or supported above ground on a trestle. A *tunnel* is a closed channel excavated through a natural obstruction such as a ridge of higher land between the dam and the powerhouse.
3. A *surge tank* is a small reservoir or tank in which the water level rises or falls to reduce the pressure swings so that they are not transmitted in full to a closed circuit.
4. A *draft tube* serves the following two purposes :
   (*i*) It allows the turbine to be set above tail-water level, without loss of head, to facilitate inspection and maintenance.
   (*ii*) It regains, by diffuser action, the major portion of the kinetic energy delivered to it from the runner.
5. The plants which cater for the base load of the system are called *'base load plants'* whereas the plants which can supply the power during peak loads are known as *peak load plants.*
6. Microhydel plants (microstations) make use of standardized *bulb sets* with unit output ranging from 100 to 1000 kW working under heads between 1.5 to 10 metres.
7. The *specific speed* of a turbine is defined as the speed of a geometrically similar turbine that would develop one brake horse power under a head of one metre.
8. The *Pelton* turbine is a tangential flow impulse turbine. The pressure over the Pelton wheel is constant and equal to atmosphere, so that energy transfer occurs due to purely impulse action.
9. The modern *Francis* water turbine is an inward mixed flow reaction turbine. It operates under medium heads and also requires medium quantity of water.
10. In the *propeller turbine* the runner blades are fixed and non-adjustable. In *Kaplan turbine*, which is a modification of propeller turbine the runner blades are adjustable and can be rotated about the pivots fixed to the boss of the runner.
11. *'Cavitation'* may be defined as the phenomenon which manifests itself in the pitting of the metallic surfaces of turbine parts because of formation of cavities.
12. *'Hydrology'* may be defined as the science which deals with the depletion and replenishment of water resources.
13. Run-off includes all the water flowing in the stream channel at any given section. It can be measured by the following methods :
   (*i*) From rainfall records
   (*ii*) Empirical formulae
   (*iii*) Run-off curves and tables
   (*iv*) Discharge observation method.
14. *Hydrograph* is defined as a graph showing discharge (run-off) of flowing water with respect to time for a specified time. It indicates the power available from the stream at different times of day, week or year.
15. *Flow duration curve* represents the run-off data for the given time. It is plotted between flow available during a period *versus* the fraction of time.
16. *Mass curve* is the graph of the cumulative values of water quantity (run-off) against time. It is an integral curve of the hydrograph which expresses the area under the hydrograph from one time to another.

THEORETICAL QUESTIONS

1. Give the application of hydro-electric plants.
2. Enumerate advantages and disadvantages of hydro-plants.
3. Enumerate and explain briefly the factors which should be considered while selecting the site for hydro-electric plant.
4. Enumerate essential elements of hydro-electric power plant.
5. What is a catchment area ?
6. What is a reservoir ?
7. What is a dam ? What are its various types ?
8. Explain briefly any two of the following dams :
   (*i*) Rockfill dams
   (*ii*) Buttress dams
   (*iii*) Timber dams.
9. What is a spillway ? Explain any two types of spillways.
10. What is the difference between canal, flume and tunnel ?
11. What is a surge tank ?
12. Explain with a neat diagram any one of the following surge tanks :
    (*i*) Inclined surge tank
    (*ii*) Restricted orifice surge tank
    (*iii*) Differential surge tank.
13. What are the functions of a draft tube ?
14. How are hydro-electric power plants classified ?
15. Explain a high head power plant giving its layout clearly.
16. Explain with a neat sketch a pumped storage plant.
17. What is the function of a hydraulic turbine ? How are the turbines classified ?
18. Explain the working of a 'Pelton turbine' with the help of a neat diagram.
19. With the help of a schematic diagram explain the working of the modern Francis turbine.
20. What is a Kaplan turbine ? How does it differ from a propeller turbine ?
21. What are tubular or bulb turbines ?
22. What do you mean by 'specific speed' of a turbine ?
23. What is cavitation ? How can it be avoided/checked ?
24. Describe briefly the methods of governing an impulse turbine ?
25. What points should be considered while selecting a right type of turbine ?
26. Enumerate the various controls which are provided in an hydro-electric power plant.
27. Explain the advantages of combined operation of hydro-electric station and thermal station.
28. Compare hydro and thermal power plants.
29. List the advantages and disadvantages of underground power house/station.
30. What safety measures need to be taken for the safe operation of an hydro-electric plant ?
31. What do you mean by 'preventive maintenance' of hydro-plant ?
32. Define hydrology.
33. Draw and explain the hydrologic cycle.
34. Define run-off. How is it measured ?
35. List the factors which affect run-off.
36. What is a hydrograph ?
37. What is a unit hydrograph ? What are the limitations to the use of unit hydrographs ?
38. What is a flow duration curve ?
39. What is a mass curve ?
40. Write a short note on hydropower development in India.

UNSOLVED EXAMPLES

1. A penstock is working under a water head of 200 metres. Its diameter is 2.5 metres. Find its thickness if the efficiency of the joint is 80% and allowable stress in the material is 1100 kgf/cm^2. [**Ans.** 2.8 cm]
2. A Pelton wheel has a mean bucket speed of 10 metres per second with a jet of water flowing at the rate of 700 litres/sec. under a head of 30 metres. The buckets deflect the jet through an angle of 160°. Calculate :
   (*i*) The horse power (*ii*) Efficiency of the turbine
   Assume coefficient of velocity as 0.98.
   [**Ans.** (*i*) 254.12 H.P., (*ii*) η_h = 94.54%]
3. A Pelton wheel is to be designed for the following specifications :
   Power = 16000 B.H.P. ; Head = 380 metres ; Speed = 750 r.p.m. ; Overall efficiency = 86% ; Jet diameter is not to exceed one-sixth of the wheel diameter.
   Determine : (*i*) The wheel diameter, (*ii*) The number of jets required, and (*iii*) Diameter of the jet.
   Take C_v (coefficient of velocity) = 0.985 and speed rated = 0.45. [**Ans.** (*i*) 0.989 m, (*ii*) 2, (*iii*) 0.165 m]
4. A Francis turbine with an overall efficiency of 75% is required to produce 203 H.P. It is working under a head of 7.62 m. The peripheral velocity = 0.26 $\sqrt{2gH}$ and the radial velocity of flow at inlet is 0.96 $\sqrt{2gH}$. The wheel runs at 150 r.p.m. and the hydraulic losses in the turbine are 22% of the available energy. Assuming radial discharge, determine :
   (*i*) The guide blade angle,
   (*ii*) The wheel vane angle at inlet,
   (*iii*) Diameter of the wheel at the inlet, and
   (*iv*) Width of the wheel at inlet.
   [**Ans.** (*i*) 37° 37′, (*ii*) 37° 44.4′, (*iii*) 0.4047 m, (*iv*) 0.177 m]
5. The following data is given for a Francis turbine. Net head H = 60 m ; Speed N = 700 r.p.m. ; Shaft horse power = 400 H.P. ; η_o = 84% ; η_h = 93% ; Flow ratio = 0.20 ; breadth ratio n = 0.1 ; Outer diameter of the runner = 2 × inner

diameter of runner. The thickness of vanes occupy 5% of circumferential area of the runner, velocity of flow is constant at inlet and outlet and discharge is radial at outlet. Determine :

(*i*) Guide blade angles,

(*ii*) Runner vane angles at inlet and outlet,

(*iii*) Diameters of runner of inlet and outlet, and

(*iv*) Width of wheel at inlet.

[**Ans.** (*i*) 13° 55.7′, (*ii*) 41° 5.4′, (*iii*) 34° 44.4′, (*iv*) 5.4 cm]

6. A Kaplan turbine develops 33500 H.P. at an average head of 39 metres. Assuming a speed ratio of 2, flow ratio of 0.6, diameter of the boss equal to 0.35 times the diameter of the runner and an overall efficiency of 90%, calculate the diameter, speed and specific speed of the turbine.

[**Ans.** 0.875 m, 422.61 r.p.m., 7963.65 r.p.m.]

7. A turbine develops 10000 H.P. under a head of 25 metres at 135 r.p.m. Calculate the specific speed of the turbine and state the type of the turbine. [**Ans.** 241.49, Francis]

8. A turbine is to operate under a head of 25 m at 200 r.p.m. The discharge is 9 m^3/sec. If the efficiency is 90%, determine :

(*i*) Specific speed of the machine

(*ii*) Power generated, and

(*iii*) Type of turbine.

[**Ans.** (*i*) 185.89 r.p.m., (*ii*) 2700 H.P., (*iii*) Francis]

9. Calculate the specific speed of a turbine and suggest the type of turbine required for a river having a discharge of 250 litres/sec. with a available head of 50 metres. Assume efficiency of turbine as 80% and speed 450 r.p.m.

[**Ans.** 39.9, Pelton turbine]

10. The quantity of water available for hydro-electric station is 260 m^3/sec. under a head of 1.7 m. Assuming the speed of the turbine 50 r.p.m. and its efficiency of 82.5%, determine the number of turbine units required. Assume the specific speed of 890. [**Ans.** 4]

11. A run-off rate of 400 m^3/sec and head of 45 m is available at a site proposed for hydro-electric power plant. Assuming the turbine efficiency of 90% and speed of 250 r.p.m., find the least number of machines all of equal size required if (*i*) Francis turbine not greater than 200 specific speed or (*ii*) Kaplan turbine not greater than 600 specific speed is used. [**Ans.** (*i*) 16, (*ii*) 3]

12. At a proposed site of hydro-electric power plant the available discharge and head is 340 m^3/sec. and 30 m respectively. The turbine efficiency is 88%. The generator is directly coupled to the turbine. The frequency of generation is 50 Hz and number of poles used are 24. Find least number of machines required if (*i*) A Francis turbine with a specific speed of 300 is used, (*ii*) A Kaplan turbine with a specific speed of 800 is used. [**Ans.** (*i*) 17, (*ii*) 2]

13. The following data relates to a hydro-electric power station :

Head = 380 m ; Discharge = 4 m^3/sec ; Turbine efficiency = 80% ; Generator frequency = 50 Hz.

Determine : (*i*) Output, (*ii*) Type of turbine, (*iii*) Speed of turbine.

[**Ans.** (*i*) 16200 H.P., (*ii*) Pelton, (*iii*) 333 r.p.m., (corrected)]

14. At a particular hydro-electric power plant site, the discharge of water is 400 m^3/sec and the head is 25 m. The turbine efficiency is 88%. The generator is directly coupled to the turbine having frequency of generation of 50 Hz, and number of poles as 24. Calculate the least number of turbines required if,

(*i*) A Francis turbine is used with a specific speed of 300,

(*ii*) A Kaplan turbine is used with a specific speed of 750.

[**Ans.** (*i*) 26, (*ii*) 5]

15. A flow of 80 m^3/sec. under a head of 120 m is available at a site for a hydro-power plant. If the turbine efficiency is 90% and generator efficiency is 94% determine the following :

(*i*) Power developed

(*ii*) Number of units required and their capacities.

[**Ans.** (*i*) 115200 H.P. ; (*ii*) Two, 39.85 mW (each generator)]

16. A proposed hydro-electric station has an available head of 100 metres, a catchment area of 225 sq. km, the rainfall of which is 140 cm per annum. If 60% of the total rainfall can be collected, calculate the power that could be generated. Suggest suitable ratings of generators.

[**Ans.** 5880 kW, 3000 kW capacity]

17. The following data is available for a hydro-power plant :

Available head = 130 m ; catchment area = 2200 sq. km. ; annual average rainfall = 150 cm ; turbine efficiency = 86% ; generator efficiency = 91% , percolation and evaporation losses = 18%.

Determine power developed in MW taking load factor as unity. [**Ans.** 8.546 MW]

18. From the investigation of a hydrosite the following data is available :

Available head = 50 m ; catchment area = 50 sq. km. ; rainfall = 150 cm per year ; 70% of rainfall can be utilized; turbine efficiency = 80% ; generator efficiency = 91% ; penstock efficiency = 75% ; load factor = 60%.

Determine the suitable capacity of a turbo-generator.

[**Ans.** 750 kW (maximum rating), Francis or Kaplan turbine]

19. Calculate the power that can be developed from a hydro-electric power station having the following data :

Catchment area = 100 sq. km. ; average value of annual rainfall = 120 cm ; Run-off = 80% ; available head = 300 m; overall efficiency of the power station = 75%.

[**Ans.** 7.48 MW]

20. In a hydro-electric power plant the reservoir is 200 m above the turbine house. The annual replenishment of reservoir is 40×10^{10} kg. Calculate the energy available at the generating station bus bars if the loss of head in the hydraulic system is 20 m and the overall efficiency of the station is 80%.

In the maximum demand of 40 MW is to the supplied determine the diameter of two steel penstocks.

[**Ans.** 13.48×10^7 kWh ; 0.49 m]

21. It is observed that a run-of-river power plant operates as peak load point with a weekly load factor of 24% all this capacity being firm capacity. Determine the minimum flow in river so that power plant may act as base load point.

The following data is supplied : Rated installed capacity of generating plant = 12 MW ; Operating head = 18 m ; Plant efficiency = 85%.

If the stream flow is 17 m^3/sec, calculate the daily load factor of the plant. [**Ans.** 19.36 m^3/sec. ; 21.2%]

22. Find the firm capacity of a run-of-river hydropower plant to be used as 9 hours peaking plant assuming daily flow in a river to be constant at 16 m^3/sec. Also calculate pondage factor and pondage if the head of the plant is 12 m and overall efficiency is 80%.

[**Ans.** 2048 H.P. ; 2.67 ; 5468 H.P. ; 8.64×10^5 m^3]

23. The gross head of a pump storage power plant is 300 m. The diameter and length of the headrace tunnel are 3.8 m and 650 m respectively. The flow velocity is 7 m/sec. and friction factor is 0.017. If the overall efficiency of pumping and generation are 84% and 89% respectively, determine the plant efficiency. The power plant discharges directly in the lower reservoir. [**Ans.** 71.2%]

24. At a particular site the mean discharge (in millions of m^3) of a river in 12 months from January to December is respectively 80, 50, 40, 20, 0, 100, 150, 200, 220, 120, 100, 80.

(*i*) Draw a hydrograph and find the mean flow

(*ii*) Also draw the flow duration curve

(*iii*) Find the power in MW available at mean flow if the head available is 100 m and overall efficiency of generation is 80%.

Take the each month of 30 days.

[**Ans.** (*i*) 96.67 millions of m^3/month, (*iii*) 29.2 MW]

COMPETITIVE EXAMINATIONS QUESTIONS

1. (*a*) Name the types of dam used for hydro-electric power plants.

(*b*) With the help of diagram explain the functions of the following parts of a hydro-electric power station :

(*i*) Spillway ; (*ii*) Forebay ; (*iii*) Penstock.

(*c*) The mean weekly discharge for 12 weeks of a river is given below :

Week	Discharge m^3/sec
1st	100
2nd	200
3rd	300
4th	1200
5th	600
6th	900
7th	800
8th	600
9th	1000
10th	600
11th	400
12th	200

Calculate the average power in kW that can be generated by a hydro-electric station with the above mentioned discharge characteristic and a head of 100 m. The overall efficiency of the plant may be assumed to be 60%.

2. (*a*) Why is it necessary to have combined operation of different types of power stations ?

(*b*) Explain how the operations of hydro-electric and thermal power plants in a power system can be combined economically.

(*c*) Two units, each of 200 MW, in a steam power station are operating in parallel and have their fuel incremental cost characteristics as,

$$\frac{dF_2}{dF_1} = ₹\ (0.08\ P_1 + 15)/\text{MWh ; and}$$

$$\frac{dF_1}{dF_2} = ₹\ (0.1\ P_2 + 13)/\text{MWh.}$$

If the total load is 300 MW, what will be the economic sharing of load between the units ? If the load is shared equally for 1000 hours, what will be the loss in comparison to the case when the load is shared economically ?

3. (*a*) What is the function of surge tank in a hydro-electric plant ? Explain with the help of neat diagram.

(*b*) Explain the governing system of a modern Pelton turbine with the help of a neat sketch.

(*c*) What is the significance of specific speed in the selection of hydro-electric turbines ? Derive the equation for the specific speed of the turbine.

4. (*a*) Explain a method of drawing flow duration curves and explain their use in selecting the site for hydro-electric plant.

(*b*) What are the different types of spillways used in practice ? Discuss the advantages of one over the other.

5. (*a*) Explain the construction of flow duration curve and discuss its importance in comparing the power potentiality of different storages used for power generation.

(*b*) It is proposed to develop 2000 H.P. at a site where 150 m of head is available. What type of turbine would be employed if it had to run at 300 r.p.m. ? If the same turbine is now used under a head of 30 m, find the power developed and its r.p.m.

6. (*a*) What do you understand by hydrology ? How does the study of hydrology help in selecting the site for a hydro-electric plant ?

(*b*) Describe briefly the working of a pumped storage plant. Where can such type of plants be installed ?

7. (*a*) Explain the working of combined hydro and steam plants. Under what circumstances will you classify them as peak load and base load plants ?

(*b*) A run-off rate of 400 m^3/sec and head of 45 m is available at a site proposed for hydro-electric power plant. Assuming the turbine efficiency of 90% and speed of 50 r.p.m., find out the least number of machines, all of equal size required, if Francis turbine not greater than 200 specific speed is used.

8. Write in brief on the following :

(*a*) Type of hydro-electric plants and their field of use

(*b*) Solar power and its uses

(*c*) Function of surge tanks in hydro-electric plants.

9. (*a*) Explain the combined working of hydro and steam plants.

(*b*) Write a note on geo-thermal energy for power generation.

10. (*a*) Discuss the differences between Kaplan, Francis and Pelton turbines and state the types of power plants they are suitable for.

(*b*) At a particular hydro-electric power plant site the discharge of water is 400 m^3/sec and the head is 25 m. The turbine efficiency is 88%. The generator is directly coupled to the turbine having frequency of generation 50 cycles/sec and number of poles as 24. Calculate the least number of turbines required if (*i*) a Francis turbine is used with a specific speed of 300, and (*ii*) a Kaplan turbine with a specific speed of 750 is used.

11. (*a*) Draw a layout of a medium head hydro-electric plant using Francis turbines.

(*b*) A hydroplant operates under a mean head of 40 m. The reservoir has a catchment area of 480 square km. Find the capacity of the plant in kW if the average annual rainfall in the area is 1100 mm and 20% of the rainfall is lost due to evaporation etc. The loss of head in the penstock is estimated to be 10%. The turbine efficiency is 85% and the generator efficiency is 92%.

12. (*a*) Define hydrograph. How is the run-off measured in practice ?

(*b*) From the following table of the mean monthly discharge for 12 months of a river at a site, draw (*i*) the hydrograph and find the average monthly flow ; (*ii*) the power available at mean flow of water for head 90 m and overall efficiency of generation 90%. Take 30 days in a month.

Month	Q-$m^3 \times 10^6$
April	500
May	200
June	1500
July	2500
Aug.	3000
Sept.	2400
Oct.	2000
Nov.	1500
Dec.	1500
Jan.	1000
Feb.	800
Mar.	600

13. (*a*) Why is governing of hydraulic turbines necessary ? Explain the governing mechanism of a Kaplan turbine.

(*b*) Derive an expression for the specific speed of a hydraulic turbine and calculate it for a turbine operating under a head of 24 m and running at 400 r.p.m. The rate of discharge is 9 m^3/sec and turbine η is 90%.

14. (*a*) Sketch a layout of a hydraulic power plant suitable for high heads. Label the various parts and explain their functions.

(*b*) At a potential hydraulic plant site the average elevations of head water and tail water levels are 605 m and 520 m respectively. The average annual water flow was determined to be equal to that volume flowing through a rectangular channel 10 m wide and a depth of 0.12 m and an average velocity of 5 m/s. Find the annual electric energy in kWh that the site can produce with turbine efficiency of 85% and generator efficiency of 95%. Take the loss of head works equal to 3% of the available head.

15. (*a*) What is a flow duration curve ? Explain its utility.

(*b*) Define the specific speed of a hydraulic turbine. A hydro-electric power plant site is capable of developing 101250 h.p. If the turbine has to work under a head of 29.5 m and at a speed of 166.7 r.p.m., find out the number of turbine units required.

(*c*) Explain the governing method adopted for a large Pelton wheel giving functions of each component of the governor.

16. (*a*) How is the cost of electrical energy generated determined ? Explain the effect of load factor of an electric power station on the cost per kWh generated.

(*b*) Discuss the advantages of operating storage type hydro-electric plant in combination with steam plant.

17. (*a*) Sketch hydrograph, flow duration curve and mass duration curves. Discuss the utility of each.

(*b*) Draw a pumped storage scheme and discuss how this scheme results in overall economy in the case of inter-connected station.

(*c*) A hydro-electric scheme has a catchment area of 120 sq. km. The available run-off is 50% with annual rainfall of 100 cm. A head of 250 m is available on the average. Efficiency of the power plant is 70%. Find (*i*) average power produced, and (*ii*) capacity of the power plant.

18. (*a*) Show schematically the layout of a hydro-plant. What are the safety devices used in these plants ? Discuss briefly the function of each.

(*b*) The available quantity of water and head at a proposed site of hydro-electric power plant is 400 m^3/sec and 30 m respectively. Assuming the turbine efficiency of 90% and speed of 250 r.p.m., find the least number of turbines required if (*i*) Francis turbine with a specific speed of 300 is used, and (*ii*) Kaplan turbine with a specific speed of 800 is used.

19. (*a*) Explain the construction of flow duration curve and discuss its significance.

(*b*) What do you understand by 'pump storage power plant' ? What are the advantages and limitation of this plant ? Where should such plants be best applied ?

(*c*) Define specific speed as applied to water turbines. What information does specific speed give and how is it used in practice ?

20. (*a*) What different methods are used to measure the rainfall ? Explain any one of them.

(*b*) Define hydrograph and explain its importance in the design of storage type hydro electric power plants.

(*c*) A run-off rate of 400 m/s and head of 45 m is available at a site proposed for hydro-electric power plant. Assuming the turbine efficiency of 90% and speed of 250 r.p.m. find the least number of machines all of equal size required if (*i*) Francis turbine not greater than 200 specific speed or (*ii*) Kaplan turbine not greater than 600 specific speed is used.

21. (*a*) What different methods are used to find the average rainfall ? Discuss the relative merits. Explain the methods.

(*b*) A test is conducted on a model of $\frac{1}{4}$ size of prototype under the head of 36 m to find the performance of prototype. The head available for the prototype is 100 m and it has to run at 428 r.p.m. Find the power developed by the prototype. The H.P. developed by the model is 135 H.P. when the water supplied is 0.324 m^3/s. Assume the efficiency of the prototype 3% greater than the efficiency of the model. State the type of runner used.

22. Write short notes on the following (5 × 4) :

(*i*) Governing of water turbines ;

(*ii*) Circuit breakers ;

(*iii*) Magneto hydrodynamics (MHD) ;

(*iv*) Moderators in nuclear power plants.

23. (*a*) Explain the various methods used for calculating the average of rainfall depending upon the area of basin.

(*b*) What are the different factors to be considered while selecting the site for hydro-electric power plant ?

(*c*) A turbine is to run at 200 r.p.m. under the available head of 25 m. The flow rate available is 9 m^3/sec. If the turbine efficiency is 90%, calculate (*i*) the specific speed, (*ii*) power developed, and (*iii*) speed and power, if the head is reduced to 15 m.

24. (*a*) Describe the function of surge tank and penstock used in the storage type hydro-electric plant.

(*b*) Explain briefly with line sketch a typical high pressure intake head works for a hydro-electric power station.

(*c*) A model is to be designed to find the performance of a prototype Francis runner. The prototype turbine has to develop 50,000 hp under a head of 225 m. The available head and flow in the laboratory for model testing are 36 m and 0.17 m^3/sec. The prototype runner runs at 600 r.p.m. and assuming overall efficiency of 90%, calculate (*i*) suitable scale ratio for the model, (*ii*) power developed by the model, and (*iii*) the speed of the model runner.

25. (*a*) What are the factors to be taken into consideration for the selection of a hydro-electric plant ?

(*b*) Draw line sketch of a small medium head hydroplant showing dam, headworks, penstock and powerhouse.

(*c*) A hydro-electric station is to be designed for a catchment area of 102.5 sq. km, run-off 70 per cent and the average rain as 127 cm. The head available is 381 metres. What power in MW can be developed if the overall efficiency of the plant is 80 per cent ?

26. (*a*) What are the principal factors that make up the unit cost of power generation in a power plant ? Explain in brief how each affects the output cost.

(*b*) Compare steam and hydro plants as regards fixed and operating costs.

(*c*) The yearly duration curve of a certain plant can be considered as a straight line from 20000 to 3000 kW. To meet this load three turbo-generator units, two rated at 10000 kW each and one at 5000 kW, are installed. Determine installed capacity, capacity factor load factor and utilization factor.

27. (*a*) What are the advantages and disadvantages of a hydroelectric power plant over a thermal one ?

(*b*) What do you mean by 'specific speed' of a water turbine ? State its significance.

(*c*) Describe a method of governing a Pelton wheel with a neat sketch.

28. (*a*) Name the different types of hydraulic turbines used in hydel power stations. Also discuss briefly the suitability of each type for a particular range of net heads.

(*b*) Classify hydro plants and explain the use of each plant.

(*c*) Describe briefly the working of a pumped storage plant. Where can each type of plant be installed ?

29. (*a*) Explain the importance of hydrograph and flow duration curve on the selection of reservoir storage capacity. What do you understand by a 'pump storage plant' ?

(*b*) The table below provides data on the load requirement during 24-hour period at a certain location :

Time period	Load in mW
12 mid-night to 6 am	20
6 am to 10 am	100
10 am to 6 pm	160
6 pm to 8 pm	80
8 pm to 12 mid-night	40

If the load is shared by a combination of thermal and 'pump storage hydroplant' with the thermal plant carrying the base load lying somewhere between 80 MW, 100 MW, estimate the energy supplied to the thermal plant in MWh during 24 hours and the overall efficiency of the combined plant.

Assume $\eta_{thermal}$ at full load = 35%

η_{pump} = 80%

$\eta_{hydraulic\ turbine}$ = 90%.

30. (*a*) Enumerate the factors that you would consider while installing a hydropower plant.

(*b*) A turbine developing 7353 kW at a head of 27.4 with an overall efficiency of 80%, is to be supplied from a reservoir. The estimated run-off in m^3/month for 12 consecutive months of 30 days is given below :

10^7 × (9.64, 10.2, 8.64, 7.51, 6.8, 8.08, 11.34, 9.07, 8.64, 11.35, 9.92, 8.93)

Assuming that the reservoir is full at the beginning determine (*i*) the minimum capacity of the reservoir to assure the required demand, and (*ii*) the quantity that is wasted during the year.

31. Write notes on any two of the following :

(*i*) Surge tanks ; (*ii*) Storage and pondage ;

(*iii*) Electrostatic precipitators.

Nuclear Power Plant

7

7.1. General aspects of nuclear engineering—Atomic structure—Atomic mass unit—Isotopes— Radioactivity—Nuclear radiation—Binding energy—Radioactive decay—Nuclear reactions—Nuclear cross-sections—Fertile materials—Fission of nuclear fuel—Nuclear Fusion—Comparison of fission and fusion processes. **7.2. Nuclear power systems. 7.3. Nuclear reactors**—Introduction—Classification of nuclear reactors—Essential components of a nuclear reactor—Power of a nuclear reactor. **7.4. Main components of a nuclear power plant. 7.5. Description of reactors**—Pressurised water reactor (PWR)—Boiling water reactor (BWR)—CANDU (Canadian-Deuterium-Uranium) reactor—Gas-cooled reactor—Liquid metal cooled reactors—Breeder reactor. **7.6. Selection of materials for reactor components. 7.7. Metals for nuclear energy. 7.8. Advantages of nuclear power plants. 7.9. Nuclear-plant site selection. 7.10. Application of nuclear power plants. 7.11. Economics of nuclear power plants. 7.12. Safety measures for nuclear power plants. 7.13. Nuclear power plants in India. 7.14. Future of nuclear power. 7.15. Useful by-products of nuclear power generation and their uses**—*Worked Examples—Highlights—Theoretical Questions—Unsolved Examples—Competitive Examinations Questions.*

7.1. GENERAL ASPECTS OF NUCLEAR ENGINEERING

7.1.1. Atomic Structure

— **Atomic model.** An element is defined as a substance *which cannot be decomposed into other substances.* The *smallest particle* of an element which takes part in chemical reaction is known as an '*atom*'. The word atom is derived from Greek word 'Atom' which means indivisible and for a long time the atom was considered as such. *Dalton's atomic theory* states that (*i*) all the atoms of one element are precisely alike, have the same mass but differs from the atoms of other elements, (*ii*) the chemical combination consists of the union of a small fixed number of atoms of one element with a small fixed number of other elements.

Various atomic models proposed by scientists over the last few decades are : 1. Thompson's plum puddling model, 2. Rutherford's nuclear model, 3. Bohr's model, 4. Sommerfeld's model, 5. Vector model, 6. Wave-mechanical model.

— The complex structure of atom can be classified into *electrons* and *nucleus*. The nucleus consists of *protons* and *neutrons* both being referred as *nucleons*. *Protons* are *positively* charged and *neutrons* are *neutral*, thus making complete nucleus as positively charged.

— The *electrons* carry *negative* charge and circulate about the nucleus. As the positive charge on proton particle is equal to the negative charge on electron particle, and the *number of electrons is equal to the number of protons,* atom is a neutral element. Any addition of the number of electrons to the neutral atom will make it negatively charged. Similarly any subtraction of the electrons will make it positively charged. Such an atom is known as *ion* and the process of charging the atom is termed an *ionisation*.

— The nuclear power engineering is specially connected with *variation of nucleons in nucleus.* Protons and neutrons are the particles having the mass of about 1837 times and 1839 times the mass of an electron.

— The modern atomic theory tells that the atom has a diameter of about 10^{-7} mm. In a neutral atom the electrons are bound to the nucleus by the electrostatic forces, which follows the Coloumb's law of forces, *i.e.*, like charges repel and unlike charges attract each other. The function of electrostatic force is similar to the gravitational force.

— The atomic spectrum study has revealed that every electron in an atom is in one group of specific states of motion which is corresponding to its total energy. In an atom the electrons are spinning around the nucleus in orbits. These

orbits are called *shells*, which represent the energy levels for the electrons. *All the electrons having very nearly the same total energy are said to be in the same shell.* The shells have been named as *K*, *L*, *M*, *N* etc. Each shell consists of the specific maximum number of electrons. The *K* shell (inner shell) contains **2** electrons, *L* shell has **8** electrons, *M* shell is limited to **18** and the *N* shell possesses **32** electrons. In fact, the number of electrons in any orbit is equal to $2n^2$ where *n* is the serial number of the orbit taking first orbit nearest to the nucleus, *with the exception that the outermost orbit cannot have more than eight electrons* . In a given atom all orbits may not be complete. It is obvious from the study that *amplitude difference in energy between two shells is much more than the difference in between energy levels in one shell.* In a *shell less than the specified number of electrons may exist but not a large number.* The inner shell is filled up first and then the other successive shells are completed.

— The *chemical properties of the atom varies with composition of number of electrons in various shells and the state of energies within the shells determine the electrical characteristics of the atom.* For example, *Hydrogen* (H_2) consists of one electron in the *first shell*, *Helium* (He) has two electrons in the first shell, *Lithium* (Li) has two electrons in first shell and one is second shell, *Carbon* (C) consists of two electrons in first and four in second shell.

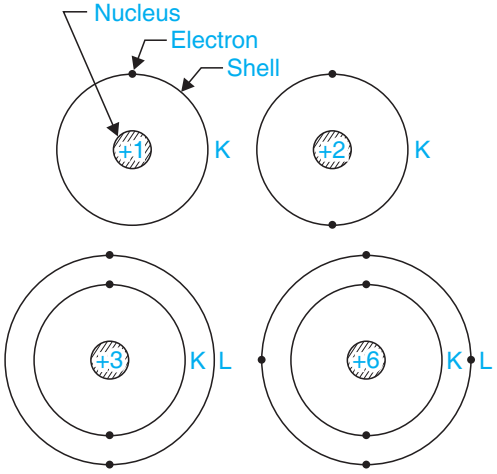


Fig. 7.1 (*a*). Atomic structure of H_2, He, Li and C.

— The electrons lying in the outermost shell are termed *valence electrons.* If the outermost shell is completely filled, the atom is stable and will not take any electron to fill up the gap. However, the incomplete outer shell will try to *snatch* the required number of electrons from the adjacent atom in a matter. The binding force between the electron and nucleus is the electrostatic force of attraction. *To emit one electron energy required is more than the electrostatic force of attraction. When the energy is supplied, the electron jumps from one discrete energy level to another permissible level. The process starts from outer shell.* The electron possesses the energy in two forms, *i.e.*, kinetic energy due to its motion and potential energy due to its position with respect to the nucleus. It is obvious that *electrons cannot exist in between the permissible orbits.*

— The charge of nucleus is represented by the *number of protons* present. This number is known as *atomic number* and designated by the letter *Z*. It also shows the position of atom in the periodic table. Hydrogen has only one number but natural uranium has ninety two. The atoms having *higher atomic number* have been developed artificially ranging from 93 to 102. These are einsteinium (Z = 99), Ferinium (Z = 100), and mendelevium (Z = 101). Platonium (Z = 94) is an important element to the nuclear power field.

The *mass number* (*A*) is the sum of total number of protons and neutrons in a nucleus. The number of electrons is represented by the letter *N*, *i.e.*, $N = (A - Z)$.

7.1.2. Atomic Mass Unit

The *mass of the atom is expressed in terms of the mass of the electron.* The unit of mass has been considered as $\frac{1}{16}$th of the mass of neutral oxygen atom which contains 8 protons and 8 neutrons. The atomic mass unit (a.m.u.) is equal to $\frac{1}{16}$ th the mass of oxygen neutral atom.

One a.m.u. = 1.66×10^{-24} g

$$\text{Mass of proton} = 1837 \text{ me} = \frac{1837 \times 9.1 \times 10^{-28}}{1.66 \times 10^{-24}}$$

$$= 1.00758 \text{ a.m.u.}$$

$$\text{Mass of neutron} = 1839 \text{ me} = \frac{1839 \times 9.1 \times 10^{-28}}{1.66 \times 10^{-24}}$$

$$= 1.00893 \text{ a.m.u.}$$

It has been concluded that the density of matter in a nucleus is enormous. It has been investigated that the *radius of nucleus is equal* to $1.57 \times 10^{-3} \times 3\sqrt{A}$, where *A* is the number of nucleons in nucleus.

The density of uranium by calculations comes to 1.65×10^{14} g/cm^3. It has been found by calculations that *natural substance has density millions of times lower than that of nuclear matter.*

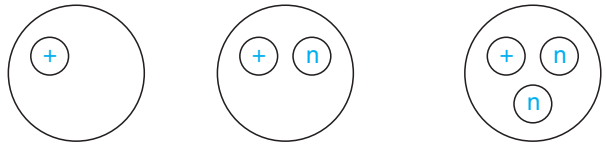
Electron volt. The energy is expressed in electron volt unit. An electron volt = *work done in moving an electron by a potential difference of one volt.* Or *it is the amount of energy acquired by any particle with one electronic charge, when it falls through a potential of one volt.*

One electron volt = 1.602×10^{-19} joule.

7.1.3. Isotopes

In any atom, the *number of electrons = number of protons.* This is independent of neutrons in the nucleus. *Atoms having different number of neutrons than the number of protons are known as 'Isotopes.'*

Example. Isotopes of hydrogen are shown in Fig. 7.1 (*b*).



H_1 – Hydrogen (No Neutron) | H_2 – Heavy hydrogen or Deuterium – D | H_3 – Heavy hydrogen or Tritium – T

Fig. 7.1 (*b*)

These isotopes have the *same chemical properties* and *have the same atomic number* and *occupy the same place in the periodic table.* But the *nuclear properties* of each of the isotopes are different *because of the different number of neutrons in the nucleus.*

The isotopes of oxygen vary from O_{14} to O_{19}. The change of number of neutrons in nucleus affect the mass of atom.

Example. Weight of heavy hydrogen is twice the weight of simple hydrogen. This means a volume of H_2O weighs less than the same volume of D_2O.

The isotopes can be represented with mass number (A) as subscript and atomic number (Z) as subscript like ${}_ZH^A$.

Example. Hydrogen isotopes are represented as ${}_1H^2$ (Deuterium), ${}_1H^3$ (Tritium) and Uranium isotopes as U^{234}, U^{235}, U^{238}.

— The isotopes are *not stable* and *disintegrate* at a certain rate. The isotope which disintegrates at a fixed rate is called *Radioactive isotope* or *Radio isotope*.

The instability of the nucleus can be either by the separation of parent nucleus into 2 or more nuclei or by the rearrangement of nucleons in the matter so that there is an emission of particles or energy in the form of rays or by rearrangement of electrons. During this transformation there is emission of particles at a very high velocity. This is known as *radiation.*

We must note that for any specific isotope, the rate of radiation from a unit mass and also the energy distribution are fixed and cannot be changed by any method. Thus, for any isotope, the quantity of radiation per unit time can be determined easily.

7.1.4. Radioactivity

Radioactivity was originally discovered by Becquerel in 1896. This phenomenon is *confined almost entirely to the heaviest element* from 83 to 106 in the periodic table.

The phenomenon of spontaneous emission of powerful radiations exhibited by heavy elements is called 'radioactivity'. Radioactivity is essentially a *nuclear phenomenon* and is a *drastic process* because the element changes its kind. It is *spontaneous* and an *irreversible self-disintegrating activity* because the element breaks itself up for good. Those elements which exhibit this activity are called *radioactive elements*. Examples are : *Uranium, polonium, radium, radon, ionium, thorium, actinium* and *mesothorium.*

The radioactive radiations emitted by the radioactive elements are found to consist of the following :

(*i*) Alpha (α) rays or α-particles

(*ii*) β rays or β-particles

(*iii*) γ-rays or photons.

The radioactivity may be *natural* or *artificial.*

Natural radioactivity. It is that *which is exhibited by elements as found in Nature.* It is always found in heavier elements in the periodic table.

Artificial or induced radioactivity. The modern techniques of artifical transmutation of elements have made it possible to produce radioactivity in many other elements much lighter than those that occur in Nature. Such type of radioactivity is known as artificial or induced radioactivity.

The general *properties* of radioactive radiations are :

1. These radiations are *highly penetrating, they affect photographic plates, ionise gases, cause scintillations on fluorescent screen, develop heat and produce chemical changes.*

2. As radiations are given out, *new elements are formed* in an irreversible process—the new elements themselves being usually radioactive.

3. The emission of radiations is *spontaneous* and is not affected by external agents.

4. The emission is *not instantaneous* but is prolonged *i.e.*, it is extented over a period of time otherwise it would not have been discovered at all.

5. Except for radioactivity, there is nothing abnormal about the radioactivity elements as regards their physical and chemical properties.

7.1.5. Nuclear Radiation

In nuclear power technology there are only *five* types of radiation of interest, but there many mechanisms by which these five are produced in reactor systems. The five types of radiation (with electrical charges indicated as + or – for positive or negative, respectively, and mass in atomic mass

units) are :

1. **Gamma rays** (or photons) : electromagnetic radiation.

2. **Neutrons** : uncharged particles, mass approximately 1.

3. **Protons** : + 1 charged particles, mass approximately 1.

4. **Alpha particles** : helium nuclei, charge + 2, mass 4.

5. **Beta particles** : electrons (charge – 1), positrons (charge + 1), mass very small.

1. Gamma rays

Prompt-fission gamma rays. These are produced as a result of the fissioning of a U^{235} (or other fissile-material) nucleus. The gamma rays are emitted within a fraction of a microsecond after fission takes place and are considered to be coincident with the fission process. Prompt-fission gamma rays carry off about 7 MeV/fission, with individual photon energies ranging from less than 0.5 MeV to greater than 1.5 MeV.

Fission-product-decay gamma rays. These are emitted from the fragments resulting from the fission process and their decay products. These radioactive fission products have half lives (the time it takes for one-half the atoms originally present to decay) from a fraction of a second to million of years. In most cases, they emit soft (low-energy) gamma rays and beta particles with energies lower than 1 MeV.

Capture gamma rays. These are emitted by nucleus of an atom instantaneously upon the capture of a neutron. The energy of these gamma rays is generally higher than those released by fission or decay. Many elements yield capture gamma rays in the 6 to 8 MeV range.

Activation-decay gamma rays. These are often omitted from the nucleus after a neutron-capture process, if the new nucleus formed is unstable. Most decays of this type are accomplished by electron emission accompanied by one or more gamma-rays photons. Each unstable (radioactive) isotope has a specific half-life and mode of decay which is an intrinsic property.

Inelastic-scattering gamma rays. These are emitted from a nucleus that has been excited to level above its ground state by interaction with an energetic neutron. These are emitted within an extremely short time after the interaction takes place, and the total energy carried off by these photons is less than or equal to the kinetic energy of the incident neutron.

2. Neutrons

Prompt-fission neutrons. These are produced as a result of the fissioning of a fissile material and, as in the case of prompt gamma rays, are considered to be emitted coincidentally with the fission process.

Delayed neutrons. These are emitted from several of the fission products with apparent half-lives of upto about 2 min. Although half-lives are usually ascribed to the production of delayed neutrons, they are actually emitted within less than a microsecond after the formation of a highly excited nucleus. The half-life actually describes the decay of a fission fragment to the highly excited fission product.

Photoneutrons. These are produced when a photon with energy greater than the binding energy of a neutron (the energy required to bind a neutron to the nucleus) interacts with a nucleus and ejects a neutron. This process is generally not important, since most isotopes have a high threshold for the reaction and a low probability of occurence above the threshold. Two isotopes used in some reactor systems which have low thresholds and a fairly significant probability of photoneutron interaction are hydrogen 2 (deuterium) and beryllium 9.

Activation neutrons. Neutron decay of an activated material occurs occasionally in cases other than delayed neutron decay of fission products. The only case which is of some interest in nuclear-reactor technology is the neutron decay of nitrogen 17, formed by fast-neutron irridiation of oxygen 17.

Reaction neutrons. These are the neutrons ejected from a nucleus by interaction with one of several particles. There are known cases of neutron emission resulting from a nucleus interacting with a neutron, proton, or alpha particle. Important use is made of this process in producing neutron sources for reactor start-up.

3. Protons

Protons are produced in a few radioactive-decay processes and more frequently by neutron-proton reactions in which an incident neutron causes a proton to be emitted from the nucleus.

4. Alpha particles

Alpha particles are produced by the decay of several fission products and a few activated materials as well as by a few neutron-alpha reactions in which an incident neutron interacts with and causes an alpha particle to be emitted from the nucleus.

5. Beta particles

Beta particles (electrons and positrons) are produced by several mechanisms, such as radioactive decay and pair production (in which a photon of high energy is converted into an electron-positron pair).

Effects of nuclear radiation on matter

Nuclear radiation, when it interacts with any material, deposits energy in the material and can have various effects. In chemical components the chemical form will be changed, in solids the crystalline structure may be altered, in any case heat will be generated. For charged particles and gamma rays the mechanisms of energy transfer is ionisation of the material traversed by the

radiation. Ionization is the production of electrically charged particles by stripping orbital electrons from the electrically neutral atoms. In the case of neutrons, the primary energy-transfer process is a kinetic-energy exchange caused by collision of neutrons with nuclei of the matter traversed.

7.1.6. Binding Energy

The nucleus of an atom is formed when the nucleons come closer to each other and this distance between the two nucleons is of the order of nearly 10^{-12} mm. At the *moment of combination there is a release of energy* and is known as *'binding energy'*. Further if it is required to separate out or to disintegrate two nucleons the equivalent amount of binding energy is to be supplied from the external source to overcome the force of attraction. The binding energy can also be defined as the *energy required to overcome the binding forces of nucleus.*

When two nuclear particles are combined to form a nucleus, it is observed that, there is a difference in the mass of the resultant nucleus and the sum of the masses of two parent nuclear particles. This decrement of mass is known as *'mass defect'*. The *amount of mass defect is directly proportional to the amount of energy released.*

The nuclear binding energy per nucleon increases with the increase of the number of nucleons in the nucleus. Example : The binding energy per nucleon for H^2 is 1.109 MeV and for He^4 it is $28.2 \div 4 \approx 7.05$ MeV. A curve representing the variation of nuclear binding energy per nucleon with the mass number is shown in Fig. 7.2. Here the average value of binding energy per nucleon has been considered. The curve indicates that the average binding energy per nucleon increases as the mass number increases initially with the peak value of about 8.8 MeV at nearly 60 mass number. The elements falling in this region are nickel and iron. As the mass number increases still further, the binding energy curve falls gradually to 7.6 MeV for U^{238}. For U^{235} from the Fig. 7.2 the binding energy per nucleon is 7.7 MeV. At the point where mass number is 117, binding energy per nucleon is nearly 8.6 MeV.

U^{235} nucleus is splitted into two approximately equal nuclei. The formation of two nuclei will release the energy of about 0.9 MeV per nucleon. There is a release of energy as the mass number decreases within the range of 60 to 250 mass number. This release of energy is corresponding to the increase of mass defect. In fission process, the U^{235} nuclei is splitted to two other nuclei and energy is liberated.

It is evident from the above discussion that the nuclear transformations of other nucleus is also possible such as U^{235}, U^{233} and Pu^{239} (these are the important fuels used in the production of nuclear power).

An atom with even number of protons of mass number is more stable because of the pairing of protons and neutrons. This type of atom also possesses *higher binding energy per nucleon* and is represented as *even type of atom.* In nuclear physics, the first even or odd represents the even or odd number of protons respectively and second one represents the even or odd mass number. This is obvious from the practical data that the U^{235} is fissionable with slow neutrons (neutrons having less energy) but U^{238} is fissionable only when the neutrons are having energy more than 1 MeV.

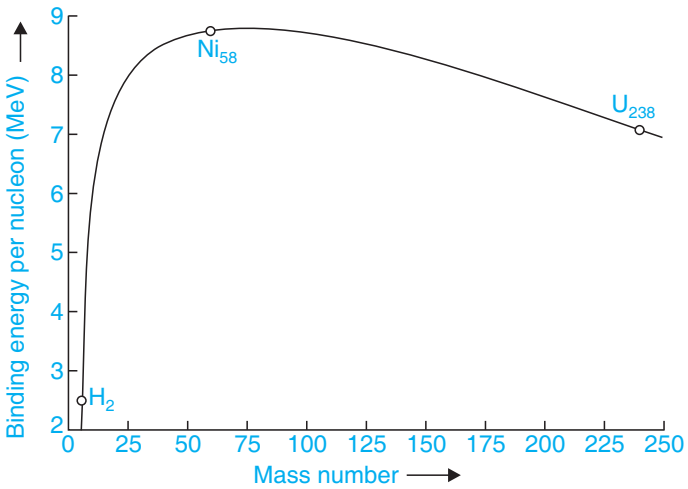


Fig. 7.2. Variation of average binding energy per nucleon with mass number.

7.1.7. Radioactive Decay

If has been observed that the emission of the particles in the form of alpha, beta or gamma radiations is not an instantaneous process. For various elements the decay time is different, which follows a certain *law*. Obviously the process is independent of the physical and chemical properties of the given isotope at a particular temperature and pressure.

The *law* states that the *small amount of disintegration of the isotope in a small period is directly proportional to the total number of radioactive nuclei and proportionality constant.*

If, N = Number of radioactive nuclei present at any time t,

N_0 = Initial number of such nuclei,

λ = Proportionality constant (also known as disintegration constant or the radioactive decay constant of the material),

Then the above law can be stated in the form of equation as follows :

$$\Delta N = -\lambda N \Delta t \qquad ...(7.1)$$

or

$$\frac{dN}{dt} = -\lambda N \qquad ...(7.2)$$

The *negative* sign represents that during disintegration the number of the nuclei is *decreasing.*

Integrating the above equation (7.2) after proper arrangement within the proper limits, we get

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t dt \qquad ...(7.3)$$

or $\log_e N - \log_e N_0 = -\lambda t$ or $\log_e \frac{N}{N_0} = -\lambda t$

or $$\frac{N}{N_0} = e^{-\lambda t} \quad \text{or} \quad N = N_0\, e^{-\lambda t} \qquad ...(7.4)$$

$$\frac{dN}{dt} = -\lambda N = -\lambda N_0\, e^{-\lambda t} \qquad ...(7.5)$$

The eqn. (7.5) represents that the *decay scheme follows the exponential law.*

Activity :

The *intensity of emitted radiation is termed activity.*

This is directly dependent on the rate of disintegration of the element.

If, A = activity at time t,
A_1 = initial activity,
k = detection coefficient,

Then, $$A = k\left(-\frac{dN}{dt}\right) = k\lambda N$$
$$= k\lambda N_0\, e^{-\lambda t} = A_1\, e^{-\lambda t} \qquad ...(7.6)$$

Half-life :

Half-life *represents the rate of decay of the radioactive isotopes.* The half-life is the *time required for half of the parent nuclei to decay or to disintegrate.*

Putting $N = \frac{N_0}{2}$ and $t = t_{1/2}$ in eqn. (7.6), we get

$$\frac{N_0}{2} = N_0\, e^{-\lambda t_{1/2}} \qquad \therefore \quad e^{-\lambda t_{1/2}} = 1/2$$

$$\therefore \quad \lambda t_{1/2} = \log_e 2 = 0.693 \quad \therefore \quad t_{1/2} = \frac{0.693}{\lambda} \qquad ...(7.7)$$

Here $t_{1/2}$ is the half-life of radioactive nuclei. After passing every half-life the number of nuclei is reduced to half and so is the activity. This process is repeated for the several half lives till the activity becomes negligible. The variation of half-life is from fraction of seconds to million of years.

Half-life of some of the metals is given below :

Metal	*Half-life*
Po-214	170 μ sec
I-137	25 sec
Carbon-14	5100 years
Th-232	1.4×10^{10} years
Uranium-238	4.525×10^{9} years

Average (mean) life :

This indicates the average of total time for which the radioactive nuclei has disintegrated for several half lives. Hence this is *greater than half-life.* This is obtained by taking the sum of the decay time of the radioactive nuclei and then it is divided by the initial number of nuclei.

If T is the time of average life, then

$$T = \frac{-\int_0^\infty t\, dN}{N_0} = \frac{\lambda N_0 \int_0^\infty t\, e^{-\lambda t}\, dt}{N_0} \qquad ...(7.8)$$

Now integrating by parts, we get

$$T = \left[-t\, e^{-\lambda t} - \frac{e^{-\lambda t}}{\lambda}\right]_0^\infty = \frac{1}{\lambda} \qquad ...(7.9)$$

But $$t_{1/2} = \frac{0.693}{\lambda}$$

From the above eqns. it is clear that mean life is 1.445 times greater than half-life.

Note. Number of disintegrations per second is the unit of radioactivity and is termed *curie*, as this phenomenon was first discovered by Curie.

7.1.8. Nuclear Reactions

During a nuclear reaction, the *change in the mass of the particle represents the release or an absorption of energy.* If the total mass of the particle after the reaction is reduced, the process releases the energy, consequently, the increase in the mass of the resultant particle, will cause the absorption of energy.

The equations of nuclear reactions are connected with the resettlement of protons and neutrons within the atom. The equations are much similar to chemical reactions. The energy variation is also of the order of MeV. In simple term the equation shows the *balance of neutron and proton.*

A nuclear reaction is written as follows :

(*i*) The bombarded nuclei or the target nuclei is written first from left hand side.

(*ii*) In the middle within brackets, first is the incident particle and second one the ejected.

(*iii*) On the right hand side, the resultant nucleus is placed.

A *neutron* is written as : ${}_0n^1$ because it has unit mass and it does not have any charge.

An *electron* is written as : ${}_{-1}e^0$ because its mass is negligible as compared to proton or neutron and its charge is equal but opposite to the charge of proton.

Some of the examples of reactions are given below :

(*i*) When ${}_{11}Na^{23}$ is bombarded with protons possessing high energy, it is converted to ${}_{12}Mg^{23}$

$${}_{11}Na^{23} + {}_1H^1 \longrightarrow {}_{12}Mg^{23} + {}_0n^1 + q \qquad ...(7.10)$$

(where q = release or absorption of energy in the reaction)

(*ii*) When ${}_{13}Al^{27}$ is bombarded with high energy protons it is transformed to ${}_{14}Si^{27}$.

$${}_{13}Al^{27} + {}_1H^1 \longrightarrow {}_{14}Si^{27} + {}_0n^1 + q \qquad ...(7.11)$$

(*iii*) When ${}_{13}Al^{27}$ is bombarded with deutrons, Al^{28} and proton may be produced.

$${}_{13}Al^{27} + {}_1H^2 \longrightarrow {}_{13}Al^{28} + {}_1H^1 \qquad ...(7.12)$$

The eqns. (7.10), (7.11) and (7.12) may be written in the equation form as given below :

$$Na^{23}(p,\ n)Mg^{23} \qquad ...(7.13)$$

$${}_{13}Al^{27}(p,\ n)Si^{27} \qquad ...(7.14)$$

$$Al^{27}(d,\ p)Al^{28} \qquad ...(7.15)$$

It is evident from the above mentioned reactions that the *nuclear reaction is followed by capturing a particle, resulting in a compound excited nucleus, which undergoes further transformation in a short period of time*.

The *transformation may adopt the following five main different paths :*

1. Elastic scattering. The neutron interacts with the nucleus and after transformation the compound nucleus emits a particle which is identical to the captured one. There is also no change in the resultant nucleus. The *total internal energy* of the bombarded nucleus and the restriking particle *will not change* at all. The process is known as *elastic scattering*. Elastic scattering is also termed as *elastic collision*. When the neutron strikes the nucleus, it imparts the part of initial kinetic energy and momentum to the nucleus which causes the displacement of the nucleus in the crystal lattice by a significant distance and can *change the structural properties of the material*.

In elastic scattering process the *kinetic energy of neutron is reduced and is beneficial to slow down the neutron is reactor*. In this transformation, *there is neither release nor absorption of energy but as a result of collision, redistribution of kinetic energy takes place*.

Example of elastic scattering. When a neutron strikes a light nucleus (*e.g.* hydrogen nucleus), the velocity of the neutron is very much reduced and the energy is transferred to the proton. Here most of the energy is transferred because both the particles are having nearly the *same masses*. It has been observed that in such a single collision, the loss of energy of the proton is nearly 70 to 75 per cent. In case the neutron impacts with the heavy nucleus, the energy loss in single collision is *less*. With carbon nucleus this loss amounts to nearly 12 to 17 per cent of the initial value. The reaction is written as $C^{12}(n, n)C^{12}$.

2. Inelastic scattering. The composition of the incident particle and ejected particle remains unchanged. When the particle interacts with the nuclei it loses its kinetic energy and the target nucleus is excited. The energy is released in the form of gamma emission. This transformation is known as *inelastic scattering* or collision. The process is limited to the condition that the neutron should have minimum energy sufficient to excite the target nucleus. The reaction is completed with the absorption or release of energy. The neutron energy loss is of the order of 10 to 20 per cent of the initial value.

When a fast moving neutron hits the U^{238} nucleus, the nucleus is excited and there is an emission of gamma quantum [U^{238} (n, $\eta\gamma$) U^{238}].

3. Capture. In this process the incident particle may be captured or absorbed by the nucleus and may raise the mass number by unity. The nucleus is excited and the energy is emitted in the form of gamma quantum. The *artificial radioactive materials are produced by this process*. In a reactor, Co-60 isotope is produced by bombarding the natural Co-59 with neutrons. The reaction has both the possibilities of producing the stable and unstable nucleus and may result in (n, γ) or (p, γ) reactions. This transformation may take place with elastic scattering. When a neutron interacts with light hydrogen, it forms heavy hydrogen, deuterium. The mass of deuterium is less than its components. This mass defect is corresponding to the release of gamma quantum.

4. In this reaction, the *impinging particle is trapped in the nucleus but the ejected particle is a different one. The composition of the resultant nucleus is also different from the parent nucleus*.

5. Fission. *When the nucleus is excited too much, it splits into two mostly equal masses*. This particular reaction is suited only to the *heavy nucleus* such as U^{233}, U^{235}, Pu^{239} etc. The transformation is known as *fission*. The produced two nuclei are lighter nuclei ; they have *more binding energies per nucleon and hence this reaction always releases the energy* (Fig. 7.2).

7.1.9. Nuclear Cross-Sections

Cross-sections (or attenuation coefficients) *are measures of the probability that a given reaction will take place between a nucleus or nuclei and incident radiation*.

Cross-sections are called either *microscopic* or *macroscopic*, depending on whether the reference is to a single nucleus or to the nuclei contained in a unit volume of material.

Microscopic cross-section

It is a measure of the probability that a given reaction will take place between a single nucleus and an incident particle. Microscopic cross-section is usually denoted by the symbol σ and is expressed in terms of the *effective area that a single nucleus presents for the specified reaction*. Since these cross-sections are usually quite small, in the range of 10^{-22} to 10^{-26} cm^2/nucleus it is general practice to express them in terms of a unit called the *barn*, which is 10^{-24} cm^2/nucleus.

Macroscopic cross-sections

These are the products of microscopic cross-sections and the atomic density in nuclei per cubic centimeter and are equivalent to the total cross-section, for a specific reaction of, all the nuclei in 1 cm^3 of material. Macroscopic cross-sections are denoted by the symbol Σ for *neutrons* and μ for *gamma rays* and have the units cm^{-1}.

Gamma ray cross-sections

Although there are a large number of interaction processes that take place between gamma rays and matter, the most commonly used are the energy-absorption cross-section (used to determine gamma heating and dose rates) and the total attenuation cross-section (used to determine material gamma-ray attenuation and for shielding design).

Neutron cross-sections

Neutrons undergo a large number of different interaction processes with matter, and, unlike gamma rays,

many of these individual interactions must be evaluated. Neutron cross-sections of general use are :

(*i*) Fission (*ii*) Gamma-ray production
(*iii*) Activation (*iv*) Elastic scattering
(*v*) Inelastic scattering
(*vi*) Reaction particle production
(*vii*) Total absorption (*viii*) Total attenuation.

Both neutron and gamma-ray cross-sections are *energy-dependent properties*. Plots of gamma-ray cross-section *vs* photon energy for all materials are, over the energy range of interest, *smooth curves*, whereas for neutron cross-sections the curves of many materials *show gross variations from a smooth curve*. The variations in neutron cross-sections show up as peaks and valleys on the cross- section plot ; these peaks are called *resonances*. When a material has a large number of resonance peaks over a portion of the energy range, this portion of the cross-section plot is called a *resonance region*. The *resonance region can have a significant effect on reactor design*, since the material U^{238} which is present in most fuels has a relatively wide resonance region which can cause extensive neutron absorption during the slowing down of neutrons to thermal energy.

The known cross-sections for materials potentially useful in reactor systems are used as primary criteria in materials selection. For example, high-neutron-absorption cross-section materials would not normally be used as materials of construction in the vicinity of a reactor core to prevent competition for the neutrons required to sustain the fission process ; and high activation cross-section materials would not be chosen, if they can be avoided, in a region exposed to a high neutron flux during operation, if that region is to be accessible after reactor shut-down.

7.1.10. Fertile Materials

It has been found that some materials are not fissionable by themselves but they *can be converted to the fissionable materials*, these are known as *fertile materials*.

Pu^{239} and U^{233} are not found in nature but U^{238} and Th^{232} can produce them by nuclear reactions. When U^{238} is bombarded with slow neutrons it produces ${}_{92}U^{239}$ with half-life of 23.5 days which is unstable and undergoes two beta disintegrations. The resultant Pu^{239} has half-life of 2.44×10^4 yrs and is a good alpha emitter.

$$ {}_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} + \gamma \qquad ...(7.16) $$

$$ {}_{92}U^{239} \xrightarrow{23.5 \text{ min.}} -{}_{-1}e^{0} + {}_{91}Np^{231} \qquad ...(7.17) $$

$$ {}_{93}Np^{239} \xrightarrow{2.3 \text{ days}} {}_{-1}e^{0} + {}_{94}Pu^{239} \qquad ...(7.18) $$

During conversion the above noted reactions will take place. The other isotopes of neptunium such as 2.1 day Np^{238} and plutonium can also be produced by the bombardment of heavy particles accelerated by the cyclotron.

The nuclear transformations to convert ${}_{90}Th^{232}$ to U^{233} are given below :

$$ {}_{90}Th^{232} + {}_{0}n^{1} \longrightarrow {}_{90}Th^{233} + \gamma \qquad ...(7.19) $$

$$ {}_{90}Th^{233} \xrightarrow{23.3 \text{ min.}} {}_{91}Pa^{233} + {}_{-1}e^{0} \qquad ...(7.20) $$

$$ {}_{91}Pu^{233} \xrightarrow{27.4 \text{ days}} {}_{92}U^{233} + {}_{-1}e^{0} \qquad ...(7.21) $$

U^{235} is the source of neutrons required to derive Pu^{239} and U^{233} from Th^{232} and U^{238} respectively. This process of conversion is performed in the *breeder reactors*.

Other fissionable materials : Th^{227}, Pa^{232}, U^{231}, Np^{238} and Pu^{241} are the other nuclides which are having high cross-sections for neutron thermal fission. Pu^{241} is the important nuclide which is used in plutonium fueled power reactors.

7.1.11. Fission of Nuclear Fuel

Fission is the *process that occurs when a neutron collides with the nucleus of certain of the heavy atoms, causing the original nucleus to split into two or more unequal fragments which carry off most of the energy of fission as kinetic energy*. This process is *accompanied by the emission of neutron and gamma rays*.

Fig. 7.3 is a representation of the fission of uranium 235. The *energy released as a result of fission is the basis for nuclear-power generation*. The release of about *2.5 neutrons/fission* makes it possible to produce *sustained fissioning*.

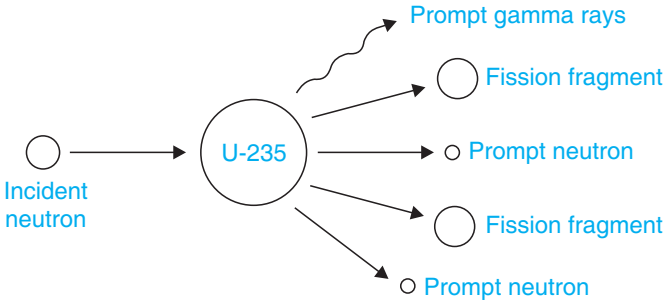


Fig. 7.3. Fission of uranium 235. Incident neutron, upon colliding with U^{235} nucleus, causes fission to take place, resulting in the production of fission fragments, prompt neutrons and prompt gamma rays.

The *fission fragments* that result from the fission process are *radioactive* and decay by emission of beta particles, gamma rays and to a lesser extent alpha particles and neutrons. The neutrons that are emitted after fission, by decay of some of the fission fragments, are called *delayed neutrons*. These are of the utmost importance, since *they permit the fission chain reaction to be easily controlled*.

The total detectable *energy released* owing to the fission of a single nucleus of uranium 235 is 193 MeV (milli electron volts), distributed as shown follows :

Distribution of Fission Energy

	MeV
Instantaneous energy release :	
Kinetic energy of fission fragments	168
Prompt-gamma-ray energy	7
Kinetic energy of prompt neutrons	5
Instantaneous total	180
Delayed energy release :	
Beta particle decay of fission products	7
Gamma-ray decay of fission products	6
Delayed total	13

As is shown above, the neutron emitted as a result of fission of a uranium 235 nucleus carry off 5 MeV of kinetic energy. Since on average there are about 2.5 neutrons emitted/U^{235} fission, the average neutron energy is 2 MeV. Actually fission neutrons are emitted with an energy speed of from nearly zero energy to approximately 16 MeV, the bulk of the them being in the 1- to 2-MeV energy region.

Note. Although not strictly a result of the fission process, there is an additional 5 to 8 MeV emitted per fission as a result of the capture of neutrons not used in the fission chain reaction. About 1 MeV of this total is emitted over a period of time owing to decay of activation products, and the remainder is emitted immediately upon neutron capture.

Most of the reactors in existence today or planned for the near future are called *thermal reactors*, since they depend on neutrons which are in or near thermal equilibrium with their surroundings to cause the bulk of fissions. *These reactors make use of the fact that the probability for fission is highest at low energy by slowing down the neutrons emitted as a result of fissioning to enhance fission captures in the fuel*. Loss of neutrons to non-fission-capture processes is lessened by minimising the quantity of non-fissile material in or near the reactor core. *The materials used to decelerate fast neutrons to thermal energy levels* are called **moderators.** Effective and efficient moderators must slow the fission neutrons, in the 1- to 2-MeV range to thermal energy at about 0.025 eV to less that 0.1 eV. This effect must be produced in a small volume and with very little absorption.

The Chain reaction

A chain reaction is that process in which the number of neutrons keeps on multiplying rapidly (in geometrical progression) during fission till whole of the fissionable material is disintegrated. The chain reaction will become self-sustaining or self propagating only if, for every neutron absorbed, at least one fission neutron becomes available for causing fission of another nucleus. This condition can be conveniently expressed in the form of *multiplication factor or reproduction factor* of the system which may be definded as

$$K = \frac{\text{No. of neutrons in any particular generation}}{\text{No. of neutrons in the preceding generation}}$$

If $K > 1$, chain reaction will continue and if $K < 1$, chain reaction cannot be maintained.

Fig. 7.4 shows schematically a chain reaction which when set off ultimately leads to a rapidly growing avalanche having the characteristic of an explosion. The rate of growth of the chain process is shown in Fig. 7.5.

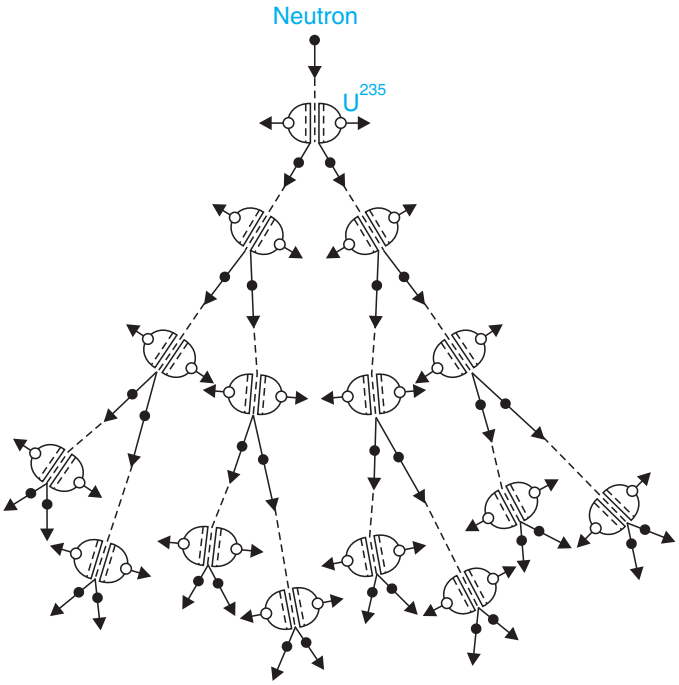


Fig. 7.4. Chain reaction.

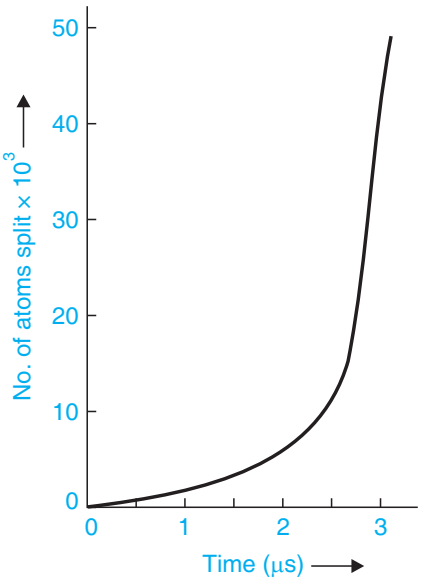


Fig. 7.5. The rate of growth of the chain process.

Requirements of fission process

The *requirements of fission process* may be summed up as follows :

1. The neutrons emitted in fission must have adequate energy to cause fission of another nuclei.

2. The produced number of neutrons must be able not only to sustain the fission process but also to increase the rate of fission. Certain loss of neutrons during the process is also to be accounted.

3. The process must be followed by the liberation of energy.

4. It must be possible to control the rate of energy liberation *i.e.*, the rate of fission by some means.

Since the chain reaction requires that one neutron from each fission cause another fission, it is worth noting that there are several processes competing for the neutrons produced. These processes are non-fission capture in the fuel material, capture in the fuel container (cladding), core structural materials, moderator and coolant, and leakage of neutrons from the core. *To permit a chain reaction to take place, it is necessary to design a system in which, after accounting for all neutron losses due to non-fission absorption and leakage, there is still at least one neutron remaining to produce another fission.*

The *minimum quantity of fuel required for any specific reactor system* is called the '*critical mass*' and the size associated with this mass is called the '*critical size*'. When nuclear fuel is assembled just to the point of a critical mass, the reactor is said to "*go critical*" *i.e.*, to reach the point of just sustaining a chain reaction. Natural uranium contains only about 0.7% of the fissile isotope U^{235}. Since U^{238} which makes up the balance absorbs neutrons, a nuclear reactor which will sustain a chain reaction with natural uranium requires a large critical mass (and size) and the use of moderator and materials of construction which have very low absorption cross-sections. To reduce the critical mass required and permit more flexibility in material and design choice, uranium fuel is frequently *enriched* in U^{235} content, thereby increasing the fraction of neutron captures that occur in U^{235} and cause fission.

7.1.12. Nuclear Fusion

'Nuclear Fusion' is the process of combining or fusing two lighter nuclei into a stable and heavier nuclide. In this case also, *large amount of energy is released* because mass of the product nucleus is *less* than the masses of the two nuclei which are fused.

Several reactions between nuclei of low mass numbers have been brought about by accelerating one or the other nucleus in a suitable manner. These are often fusion processes accompanied by release of energy. However, reactions involving artificially-accelerated particles cannot be regarded as of much significance for the utilisation of nuclear energy. To have practical value, fusion reactions must occur in such a manner as to make them *self-sustaining, i.e., more energy must be released than is consumed in initiating the reaction*.

It is thought the energy liberated in the sun and other stars of the main sequence type is due to the nuclear fusion reactions occurring at the very high stellar temperature of 30 million K. Such processes are called *thermonuclear reactions* because they are temperature-dependent.

7.1.13. Comparison of Fission and Fusion Processes

The comparison between '*Fission*' and '*Fusion*' processes is given below :

Fission	Fusion
1. When heavy unstable nucleon is bombarded with neutrons, the nucleus *splits* into fragments of equal mass and energy is released.	1. Some light elements *fuse together* with the release of energy.
2. About *one thousandth* of the mass is *converted into energy*.	2. It is possible to have *four thousandths* of mass *converted into energy*.
3. Nuclear reaction *residual problem is great*.	3. Residual problem is *much less*.
4. Amount of radioactive material in a fission reactor is *high*.	4. A possible advantage is that the total amount of radioactive material in a working fusion reactor is likely to be *very much less* than that in a fission reactor.
5. Because of higher radioactive material, *health hazards is high in case of accidents*.	5. Because of lesser radioactive material, *health hazards is much less*.
6. It is *possible to construct self-sustained fission reactors* and have positive energy release.	6. It is *extremely difficult to construct controlled fusion reactors*.
7. *Manageable temperatures* are obtained.	7. Needs *unmanageable temperatures* like 30 million degrees for fusion process to occur.
8. Raw fissionable material is *not available in plenty*.	8. Reserves of deuterium, the fusion element, *is available in great quantity*.

7.2. NUCLEAR POWER SYSTEMS

A nuclear-fueled power-producing system consists essentially of the following :

(*i*) *A controlled fission heat source.*

(*ii*) *A coolant system to remove and transfer the heat produced.*

(*iii*) *Equipment to convert the thermal energy contained in the hot coolant to electric power.*

Regardless of the type of fission heat source used, the basic mechanism is fission of nuclear fuel to produce thermal energy. This thermal energy is removed from the heat source (reactor core) by contacting the fuel with a coolant which can be used directly as the working fluid in the power- conversion cycle or indirectly to heat another fluid to be used as the working fluid.

In some cases an intermediate heat-transfer loop is inserted between the reactor coolant and the working fluid, to increase isolation of the radioactive reactor coolant from the conventional power-producing equipment. The working fluid is then used to drive a turbo-generator set to produce electrical power.

Though several other methods are feasible for direct conversion of fission energy to electric power (*i.e.*, thermoelectric, thermionic, photoelectric, etc.), these methods are not at present suitable for the production of large quantities of power.

Schematic representations of nuclear power systems using the direct, indirect, and indirect with intermediate heat-transfer approaches are shown in Fig. 7.6.

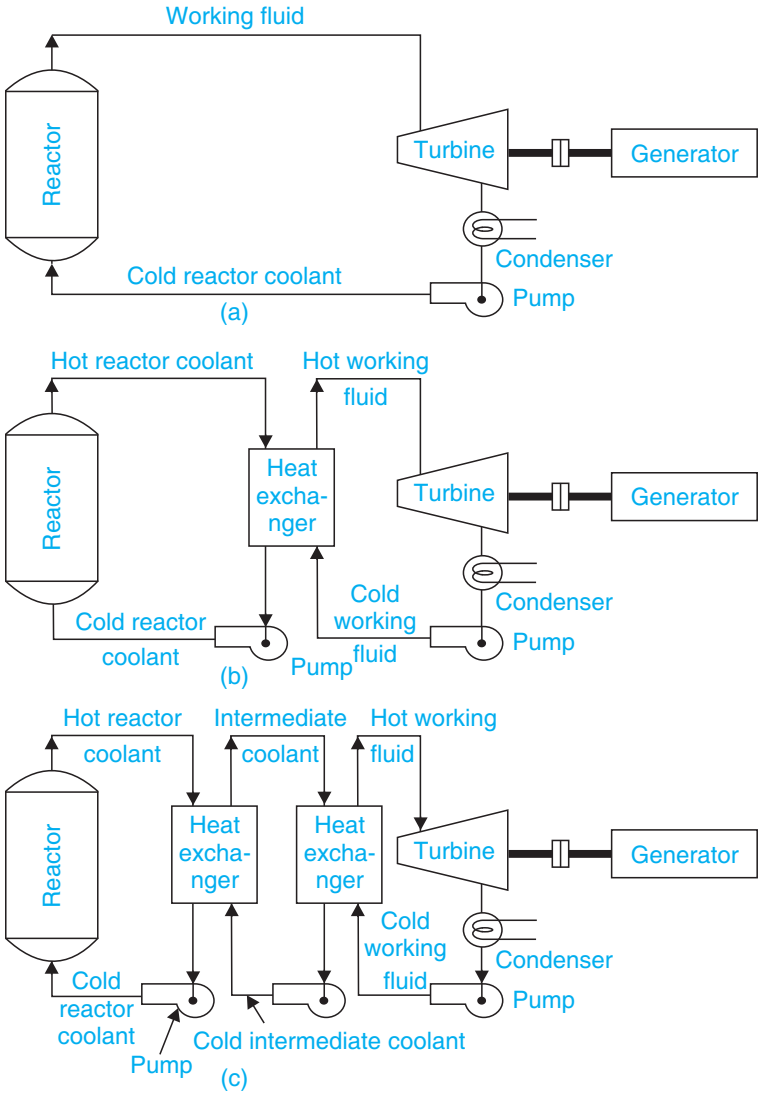


Fig. 7.6. Schematics of nuclear power systems. (*a*) Direct cycle, reactor coolant used as the working fluid ; (*b*) Indirect cycle, reactor coolant transfers heat to separate working fluid ; (*c*) Indirect cycle with intermediate loop, reactor coolant transfers heat through intermediate heat-transfer loop to working fluid.

Nuclear power systems differ in a number of respects from fossil-fuel systems. Some of the more important *considerations* that differentiate nuclear-fueled plants from fossil-fueled plants are listed below :

1. Nuclear fuel is charged to a power plant infrequently and has a relatively long life, usually measured in months or years, as compared with the continuous fuel-feed requirements for fossil-fueled plants.

2. Burned nuclear fuel is radioactive ; it requires remote handling and special processing and disposal.

3. Major portions of a nuclear plant are radioactive during and after operation, requiring special precautions for maintenance of much of the plant.

4. Special system designs are required to prevent radioactivity release during normal operation or due to accidents.

5. Control and instrumentation requirements are strongly influenced by safety requirements and are related to reactor stability, load-following requirements, and the capability of a reactor to increase power output with no additional fuel input.

6. Nuclear fuel is highly processed material generally used in a precise fabricated form, as opposed to fossil fuels, which are essentially raw materials used with only minimal rough processing.

7. The use of nuclear fuel does not require combustion air, thus obviating thermal stack losses and related problems.

These considerations give rise to the general requirements, complexities, and problems of nuclear systems.

7.3. NUCLEAR REACTORS

7.3.1. Introduction

Definition. *A nuclear reactor is an apparatus in which nuclear fission is produced in the form of a controlled self-sustaining chain reaction*. In other words, it is a controlled chain-reacting system supplying nuclear energy. It may be looked upon as a sort of nuclear furnace which burns fuels like U^{235}, U^{233} or Pu^{239} and, in turn, *produces many useful products like heat, neutrons and radioisotopes*.

Mechanism of heat production. Most of the energy is imparted to the two fission fragments into which the nucleus divides causing them to move at high speed. However, because they have taken birth in a dense mass of metal, they are rapidly slowed down and brought to rest by colliding with other atoms of the metal. In so doing, their energy is converted into heat in much the same way as energy given up by a slowing motor can be converted into heat in the brake lining. In this way, the mass of uranium metal gets heated up.

7.3.2. Classification of Nuclear Reactors

Nuclear reactors are **classified** according to the *chain reacting system, use, coolants, fuel material* etc.

1. Neutron energies at which the fission occurs

(*i*) Fast fission is caused by high energy neutrons	*Fast reactors*
(*ii*) Intermediate or epithermal	*Intermediate reactors*
(*iii*) Low energy *i.e.*, thermal	*Slow reactors*

On the basis of the energy of the neutrons to cause fission the reactors have been divided into three groups—*fast, intermediate and thermal*. (*a*) In ***fast reactors*** the high velocity neutrons produced by fission are *utilised directly* to cause fission of the fuel in the reactor. The velocity of the neutrons is *not reduced deliberately*. (*b*) If in a reactor the fission process is maintained due to the slow neutrons capture, the reactor is known as ***slow reactor***. The minimum velocity to which neutrons *are slowed down* before the fission is equal to the thermal velocity which the slow neutrons may acquire in a state of thermal equilibrium with the medium. This velocity is of the order of 2150 m/s at room temperature which is equivalent to $\frac{1}{40}$ eV or neutron energy. The neutrons associated with the energy of this order are known as *thermal neutrons* and the reactor as *thermal reactors*. With the *moderator the neutrons are slowed down.* The *main advantage is that the probability of reaction increases*. (*c*) If the velocity of neutrons is kept between both the above noted limits, the reactors are termed as '***intermediate reactors***'.

2. Fuel-moderator assembly

(*i*) Homogeneous reactors

(*ii*) Heterogeneous reactors.

In '*homogeneous reactor*' *the fuel and moderator are mixed to form a homogeneous material, i.e.*, uranium fuel salt forms a homogeneous solution in water which is a moderator or fine particles of uranium and carbon gives a mechanical mixture.

In '*heterogeneous reactor*' the fuel is used in the form of rods, plates, lamps or wires and the moderator surrounds the each fuel element in the reactor core.

3. Fuel state

(*i*) Solid (*ii*) Liquid

(*iii*) Gas

The nuclear fuel is available in three states—solid, liquid and gas. In reactors the fuel is mostly used in solid state or in the form of solution dissolved in water. The *liquid metal reactors are in practical use*.

4. Fuel material

(*i*) Natural uranium with U^{235} contents (occurs in nature)

(*ii*) Enriched uranium with more than 0.71 of U^{235}

(*iii*) Pu^{239}, Pu^{241} or Pu^{239} (man made)

(*iv*) U^{-233} (man made)

Considering the necessary requirement of fission process and its availability economically the fuels used in reactors are *uranium, plutonium* and *thorium*. U^{235} is easily available in natural uranium (*i.e.*, 0.7%) and its content increases upto 90% in enriched uranium.

5. Moderator

(*i*) Water (H_2O)
(*ii*) Heavy water (D_2O)
(*iii*) Graphite
(*iv*) Beryllium or beryllium oxide
(*v*) Hydrocarbons or hydrides.

A moderator's function is to *absorbs the part of the kinetic energy of the neutrons.* The neutrons collide directly with the moderator and thus slowed down. No ideal moderator is available in nature or has been produced artificially. The light weight nuclei materials are not suited at all as a moderator because they do not possess the property of absorption of neutrons.

Light water, heavy water and *graphite* are the *most common moderators* used in reactors.

6. Principal product

(*i*) Research features to produce neutrons — *Research reactors*
(*ii*) Power reactor to produce heat — *Power reactors*
(*iii*) Breeder reactors to produce fissionable materials — *Breeder reactors*
(*iv*) Production reactors to produce isotopes — *Production reactors*

Research reactors. These are designed to produce the high neutron flux for research work and these neutrons are used to determine the neutron properties of interaction with the nuclei and the effect of bombardment of neutrons on the materials. The reactors are operated at high neutron flux and low power level otherwise the cooling will be a problem. The unit is cooled constantly during operation. The by-products are heat and fission products which are removed during operation.

Power reactors. In these reactors the energy is produced in heat form which is carried away to the heat exchanger by circulating the coolant through the reactor and heat exchanger. In the heat exchanger the coolant converts the water into steam to run the turbine. The by-products are fission products, neutrons and other radiation particles.

These reactors are useful to produce *huge amount of power* and are *widely used in power plant stations.* In such reactors *consumption is very low.*

Breeder reactors. A breeder reactor *converts fertile materials into fissionable materials* such as U^{238} and Th^{232} to Pu^{239} and U^{233} respectively *besides the power production*. It is worth noting that the amount of fissionable material produced is *more* than its consumption of fissionable material. By-products are the same as those of power reactors.

Production reactors. The output of such reactors is radioactive materials which are used as sources of radiation and tracers in research in all areas of science. By-products are the same as those of power reactors.

7. Coolant

(*i*) Air, carbon or helium cooled reactors
(*ii*) Water or other liquid cooled reactors
(*iii*) Liquid metal cooled reactors.

In *gas-cooled reactors* the amount of gas required to extract the heat is too much and therefore these reactors are expensive. Gases have poor heat carrying capacity. CO_2 and He have been used in the early reactors. *Mostly water is used as a coolant.*

Liquid metal cooled reactors are also suitable as the metal is having high boiling point and low steam pressure. These are the power reactors.

8. Construction of core

(*i*) Cubical (*ii*) Cylindrical
(*iii*) Octagonal (*iv*) Spherical
(*v*) Slab (*vi*) Annulus.

The proper shape to the core is given on the practical consideration and can have cubical, cylindrical or ring type construction.

7.3.3. Essential Components of a Nuclear Reactor

The essential components of a nuclear reactor are as follows :

1. Reactor core
2. Reflector
3. Control mechanism
4. Moderator
5. Coolants
6. Measuring instruments
7. Shielding.

1. Reactor core :

The reactor core is that part of a nuclear power plant where fission chain reaction is made to occur and where *fission energy is liberated in the form of heat for operating power conversion equipment.* The *core* of the reactor consists of an assemblage of fuel elements, control rods, coolant and moderator. Reactor cores generally have a shape approximating to a right circular cylinder with diameters ranging from 0.5 m to 15 m. The pressure vessels which houses the reactor core is also considered a part of the core (Fig. 7.7). The fuel elements are made of plates or rods of uranium metal. These plates or rods are usually clod in a thin sheath of stainless steel, zirconium or aluminium to provide corrosion resistance, retention of radioactivity and in some cases, structural support. Enough space is provided between individual plates or rods to allow free passage of the coolant.

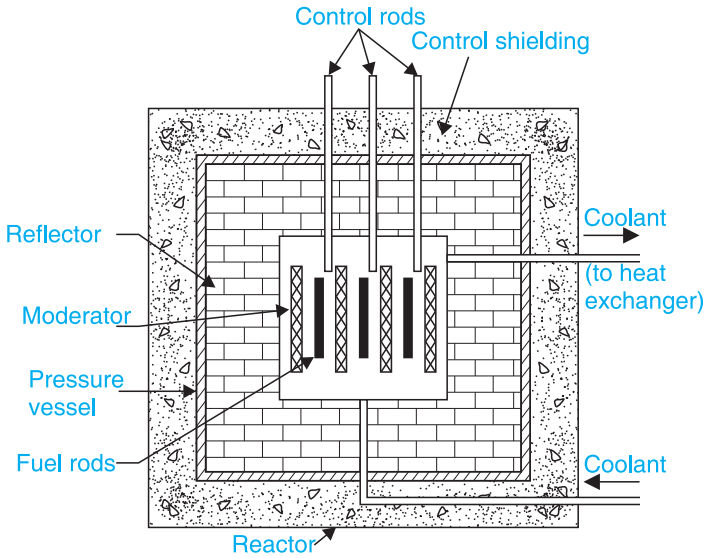


Fig. 7.7. Nuclear reactor.

2. Reflector :

A reflector is usually placed round the core to reflect back some of the neutrons that leak out from the surface of the core. It is generally made of the same material as the moderator.

3. Control mechanism :

It is an essential part of a reactor and serves the following purposes :

(*i*) For starting the reactor *i.e.*, to bring the reactor up to its *normal operating level*.

(*ii*) For maintaining at *that level i.e.*, keep power production at a steady state.

(*iii*) For shutting the reactor down under normal or emergency conditions.

The control system is also necessary to prevent the chain reaction from becoming violent and consequently damaging the reactor. The effective multiplication factor of the reactor is always kept *greater than unity* in order that the number of neutrons keeps on increasing in successive generations. As the number of neutrons and hence the neutron flux density increases, the temperature also increases. Unless the growth is checked at some point, the reactor is likely to be damaged as a result of too rapid liberation of energy.

Note. The *control system* works on the simple *principle of absorbing the excess neutrons* with the help of control rods either made of boron steel or cadmium strips. Both these materials have very large cross-section for thermal neutrons *i.e.*, they are very good absorbers of slow neutrons and also have the advantage of not becoming radioactive due to neutron capture. By pushing these rods deeper into the central core, any amount of excess neutrons can be absorbed. Once the reactor has reached pre-determined power level, these control rods serve to keep the value of $K = 1$ so that there is no further increase in the number of neutrons from one generation to another. If, at some stage, it is desired to increase the neutron flux density and hence the power level, the rods are *partially pulled out* thereby allowing K to *exceed unity*. For shutting down the reactor, the control rods are inserted to a considerable depth so that K becomes *less than unity* and the chain-reaction can no longer be maintained. To start up the reactor, all that is necessary is to carefully withdraw the control rods and then adjust them till required output level is attained. Movement of control rods can be manual or made automatic with the help of carefully designed *servomechanism*.

4. Moderator :

In a nuclear reactor the function of a moderator is :

(*i*) *To slow down the neutrons from the high velocities* and hence high energy level, which they have on being released from the fission process. Neutrons are slowed down most effectively in scattering collisions with nuclei of the light elements, such as hydrogen, graphite, beryllium etc.

(*ii*) *To slow down the neutrons but not absorb them*

The *desirable properties of a moderator* in a reactor are :

1. High slowing down power.
2. Low parasite capture.
3. Non-corrosiveness (or corrosiveness resistance).
4. Machinability (if solid).
5. High melting point for solids and low melting point for liquids.
6. Chemical and radiation stability.
7. High thermal conductivity.
8. Abundance in pure form.

H_2O, D_2O (heavy water), He (gas), Be and C (graphite) are the commonly used moderators.

As a moderator D_2O is the best material available (moderating ratio of D_2O is 12000 as compared to 72 for H_2O and 170 for carbon) because (*i*) it has excellent neutron slowing properties, (*ii*) it has very small cross-section for neutron capture, (*iii*) it can be used as a coolant as well. Its *disadvantages* are : (*i*) it has low boiling point so that it *necessitates pressurisation,* (*ii*) it is *very expensive*. But, the advantages of D_2O as moderator or moderator coolant outweigh its high cost.

5. Coolants :

The function of a coolant is to remove the intense heat produced in the reactor and to bring out for being utilised.

The desirable characteristics for a reactor coolant are :

1. Low parasite capture.
2. Low melting point.
3. High boiling point.
4. Chemical and radiation stability.
5. Low viscosity.
6. Non-toxicity.
7. Non-corrosiveness.
8. Minimum induced activity (short half lives, low energy emission).
9. High specific heat (reduces pumping power and thermal stresses).
10. High density (reduces pumping power and physical plant size).

Commonly used coolants : Santiwax R (organic, Hg, He, CO_2)

The most widely-used gaseous coolant is CO_2 particularly in large-power reactors. It is (*i*) cheap, (*ii*) does not attack metals at reasonable temperatures, and (*iii*) has small cross-section for neutron capture.

Some possible reactor cooling systems :

Some possible reactor cooling systems are illustrated schematically in Figs. 7.8, 7.9 and 7.10.

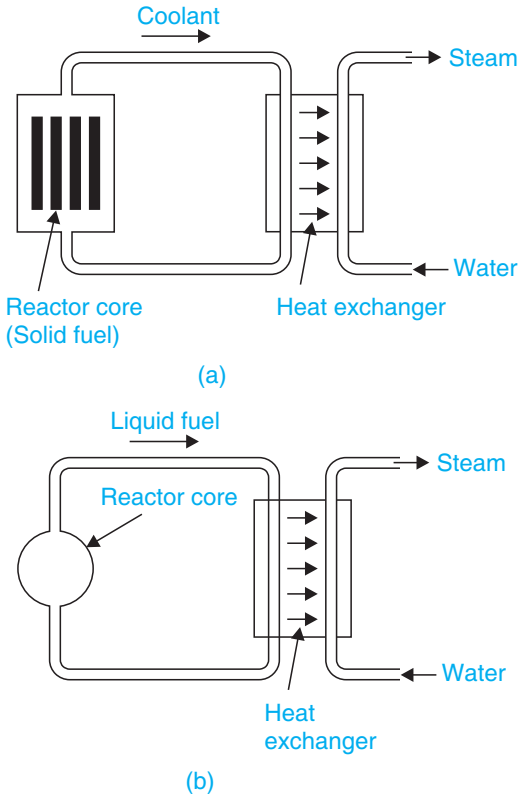


Fig. 7.8. Cooling systems : (*a*) Indirect cooling ; (*b*) Direct cooling.

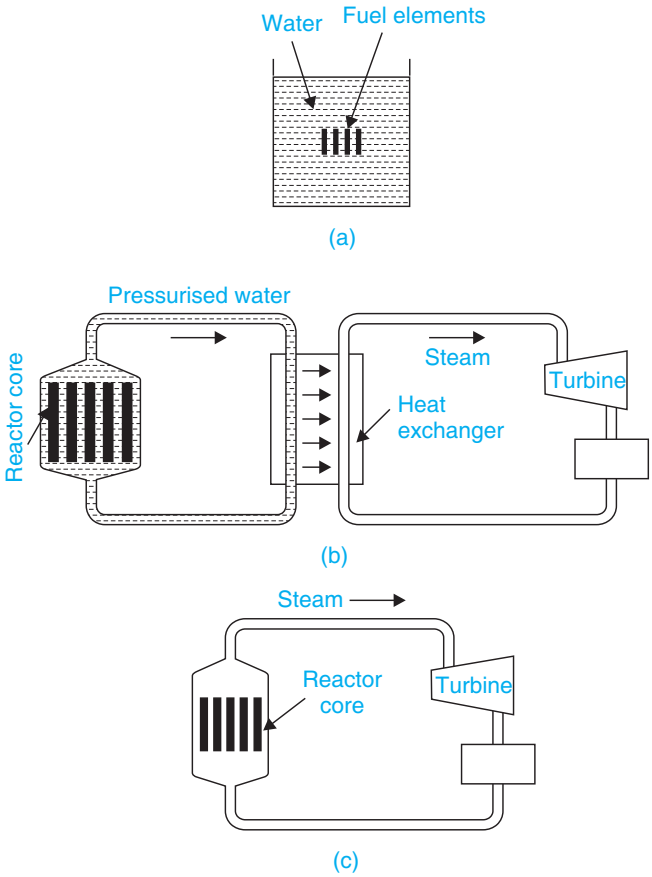


Fig. 7.9. Water cooled reactors : (*a*) Swimming-pool reactor ; (*b*) Pressurised-water reactor ; (*c*) Boiling water reactor.

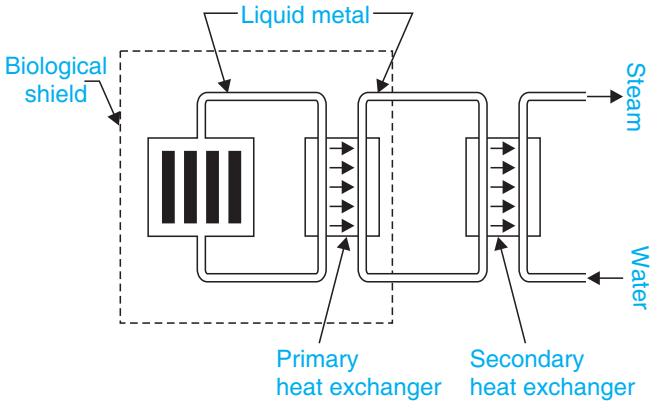


Fig. 7.10. Liquid-metal-cooled reactor.

6. Measuring instruments :

Main instrument required is for the purpose of measuring thermal neutron flux which determines the power developed by the reactor.

7. Shielding :

Shielding is necessary in order to :

(*i*) protect the walls of the reactor vessel from radiation damage, and also to

(*ii*) protect operating personnel from exposure to radiation.

The first known as *thermal shield* is provided through the *steel lining*, while the other called *external* or *biological* shield is generally made of *thick concrete surrounding the reactor installation*.

Among the nuclear radiations produced in a reactor the alpha and beta particles, thermal (slow) neutrons, fast neutrons and gamma rays are harmful ones and must be shielded against. Of these only the fast neutrons and gamma rays present some serious difficulty in designing the reactor shielding, since alpha and beta particles can be stopped by a fraction of an inch of a solid substance, while thermal neutrons can be automatically guarded against with a shield thick enough to provide protection against fast neutrons and gamma rays.

The effectiveness of a nuclear shield against gamma rays approximately depends upon its mass. A heavy material like lead will be a more effective shield per unit weight, than a light element such as carbon. On the other hand, light elements, particularly hydrogen are much more effective per unit weight than heavy elements for fast neutron shielding. Concrete is a material that offers a compromise between these two extreme characteristics of shielding material for *both gamma rays and fast neutrons*. It is a material which has *low cost* and is *easily available*.

The actual design of the shield, however, involves the following considerations :

(*i*) The total amount of radiation produced in the reactor.

(*ii*) The amount of radiation that can be permitted to leak through the shield.

(*iii*) The shielding properties of material.

7.3.4. Power of a Nuclear Reactor

The fission rate of a reactor *i.e.*, total number of nuclei undergoing fission per second in a reactor is

$$= nC\sigma NV = \phi_{nu}\, \sigma NV$$

where, n = Average neutron density *i.e.*, number per m^3,

C = Average speed in m/s,

$\phi_{nu} = nC$ = Average neutron flux,

N = Number of fissile nuclei /m^3,

σ = Fission cross-section in m^2, and

V = Volume of the nuclear fuel.

Since 3.1×10^{10} fission per second generate a power of one watt, the power P of a nuclear reactor is given by

$$P = \frac{nC\sigma NV}{3.1 \times 10^{10}} \text{ watt}$$

$$= 3.2 \times 10^{-11}\, nC\sigma\, NV \text{ watt}$$

$$= 3.2 \times 10^{-11}\, \phi_{nu}\, \sigma\, NV \text{ watt}$$

Now, NV = Total number of fissile nuclei in the reactor fuel

$$= m \times 6.02 \times 10^{26}/235$$

where m is the mass of the U^{235} fuel. It is known that fission cross-section σ of U^{235} for thermal neutrons is 582 barns = 582×10^{-28} m^2.

$$\therefore\ P = \frac{3.2 \times 10^{-11} \times \phi_{nu} \times 582 \times 10^{-28} \times m \times 6.02 \times 10^{26}}{235}$$

$$= 4.77 \times 10^{-12}\, m\, \phi_{nu} \text{ watt}$$

$$\simeq 4.8 \times 10^{-12}\, mnC \text{ watt}.$$

7.4. MAIN COMPONENTS OF A NUCLEAR POWER PLANT

Fig. 7.11 shows schematically a nuclear power plant.

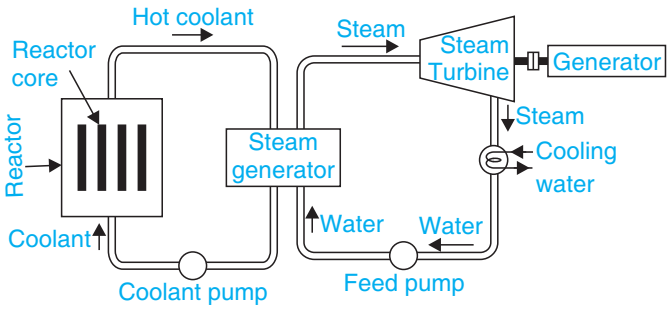


Fig. 7.11. Nuclear power plant.

The main components of a nuclear power plant are :

1. Nuclear reactor
2. Heat exchanger (steam generator)
3. Steam turbine
4. Condenser
5. Electric generator.

In a nuclear power plant the reactor performs the same function as that of the furnace of steam power plant (*i.e.*, produces heat). The heat liberated in the reactor as a result of the nuclear fission of the fuel is taken up by the coolant circulating through the reactor core. Hot coolant leaves the reactor at the top and then flows through the tubes of steam generator and passes on it heat to the feed water. The steam so produced expands in the steam turbine, producing work and thereafter is condensed in the condenser. The steam turbine in turn runs an electric generator thereby producing electrical energy. In order to maintain the flow of coolant, condensate and feed water pumps are provided as shown in Fig. 7.11.

7.5. DESCRIPTION OF REACTORS

7.5.1. Pressurised Water Reactor (PWR)

A pressurised water reactor, in its simplest form, is a light water cooled and moderated thermal reactor having an

unusual core design, using both natural and highly enriched fuel. The principal parts of the reactor are :

1. Pressure vessel
2. Reactor thermal shield
3. Fuel elements
4. Control rods
5. Reactor containment
6. Reactor pressuriser.

The components of the secondary system of pressurised water plant are similar to those in a normal steam station.

Refer to Fig. 7.12. In PWR, there are two circuits of water, one *primary circuit* which passes through the fuel core and is *radioactive*. This primary circuit then produces steam in a *secondary circuit* which consists of heat exchanger or the boiler and the turbine. As such the steam in the turbine is *not radioactive* and need not be shielded. The *pressure* in the primary circuit should be *high* so that the boiling of water takes place at high pressure. A *pressuring tank* keeps the water at about 100 kgf/cm^2 *so that is will not boil*. Electric heating coils in the pressuriser boil some of the water to form steam that collects in the dome. As more steam is forced into the dome by boiling, its pressure rises and pressurises the entire circuit. The pressure may be reduced by providing cooling coils or spraying water on the steam.

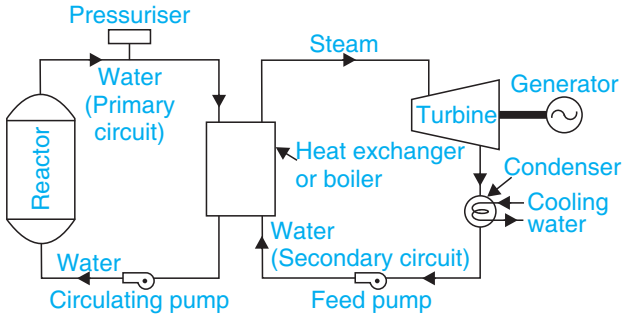


Fig. 7.12. Pressurised water reactor.

Water acts both as coolant as well as moderator. Either heavy water or the light water may be used for the above purpose.

A pressurised water reactor *can produce only saturated steam*. By providing a separate furnace, the steam formed from the reactor could be super-heated.

Advantages of PWR :

1. Water used in reactor (as coolant, moderator and reflector) is cheap and easily available.
2. The reactor is compact and power density is high.
3. Fission products remain contained in the reactor and are not circulated.
4. A small number of control rods is required.
5. There is a complete freedom to inspect and maintain the turbine, feed heaters and condenser during operation.
6. This reactor allows to reduce the fuel cost extracting more energy per unit weight of fuel as it is ideally suited to the utilisation of fuel designed for higher burn-ups.

Disadvantages :

1. Capital cost is high as high primary circuit requires strong pressure vessel.
2. In the secondary circuit the thermodynamic efficiency of this plant is quite low.
3. Fuel suffers radiation damage and, therefore its reprocessing is difficult.
4. Severe corrosion problems.
5. It is imperative to shut down the reactor for fuel charging which requires a couple of month's time.
6. Low volume ratio of moderator to fuel makes fuel element design and insertion of control rods difficult.
7. Fuel element fabrication is expensive.

7.5.2. Boiling Water Reactor (BWR)

In a boiling water reactor *enriched fuel* is used. As compared to PWR, the arrangement of BWR plant is simple. The plant can be safely operated using natural convection within the core or forced circulation as shown in Fig. 7.13. For the safe operation of the reactor the pressure in the forced circulation must be maintained constant irrespective of the load. In case of *part load operation of the turbine some steam is by-passed*.

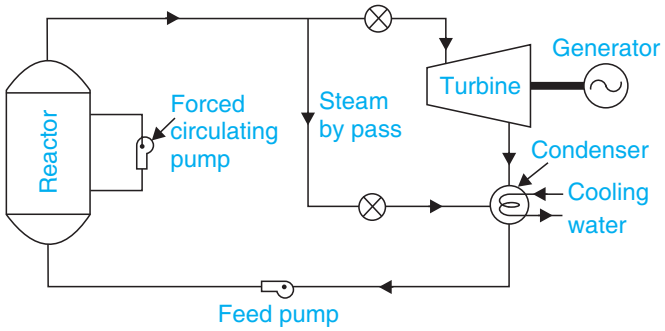


Fig. 7.13. Boiling water reactor.

Advantages of BWR :

1. Heat exchanger circuit is eliminated and consequently there is gain in thermal efficiency and gain in cost.
2. There is use of a lower pressure vessel for the reactor which further reduces cost and simplifies containment problems.
3. The metal temperature remains low for given output conditions.

4. The cycle for BWR is more efficient than PWR for given containment pressure, the outlet temperature of steam is appreciably higher in BWR.
5. The pressure inside the pressure vessel is not high so a thicker vessel is not required.

Disadvantages :

1. Possibility of radioactive contamination in the turbine mechanism, should there be any failure of fuel elements.
2. More elaborate safety precautions needed which are costly.
3. Wastage of steam resulting in lowering of thermal efficiency on part load operation.
4. Boiling limits power density ; only 3 to 5% by mass can be converted to steam per pass through the boiler.
5. The possibility of "burn out" of fuel is more in this reactor than PWR as boiling of water on the surface of the fuel is allowed.

7.5.3. CANDU (Canadian-Deuterium-Uranium) Reactor

CANDU is a thermal nuclear power reactor in which *heavy water* (99.8% deuterium oxide D_2O) *is the moderator and coolant as well as the neutron reflector.* This reactor was developed in Canada and is being extensively used in this company. A few CANDU reactors are operating or under construction in some other countries as well.

In this type of reactor the *natural uranium* (0.7% U^{235}) *is used as fuel and heavy water as moderator.* There reactors are more economical to those countries which do not produce enriched uranium, as the *enrichment of uranium is very costly.*

CANDU (heavy water) reactor, differs basically from light-water reactors (LWRS) in that in the latter the *same water serves as both moderator and coolant*, whereas in the *CANDU reactor the moderator and coolant are kept separate.* Consequently unlike the pressure vessel of a LWR, the CANDU reactor vessel, which contains the relatively cool heavy water moderator, *does not have to withstand a high pressure. Only the heavy water coolant circuit has to be pressurised to inhibit boiling in the reactor core.*

Description of CANDU reactor

Fig. 7.14 shows the schematic arrangement of a CANDU reactor.

Reactor vessel and core. The reactor vessel is a steel cylinder with a horizontal axis ; the length and diameter of a typical cylinder being 6 m and 8 m respectively. The vessel is penetrated by some 380 horizontal channels called *pressure tubes* because they are designed to withstand a high internal pressure. The channels contain the fuel elements and the pressurised coolant flows along the channels and around the fuel elements to remove the heat generated by fission. Coolant flows in the opposite directions in adjacent channels.

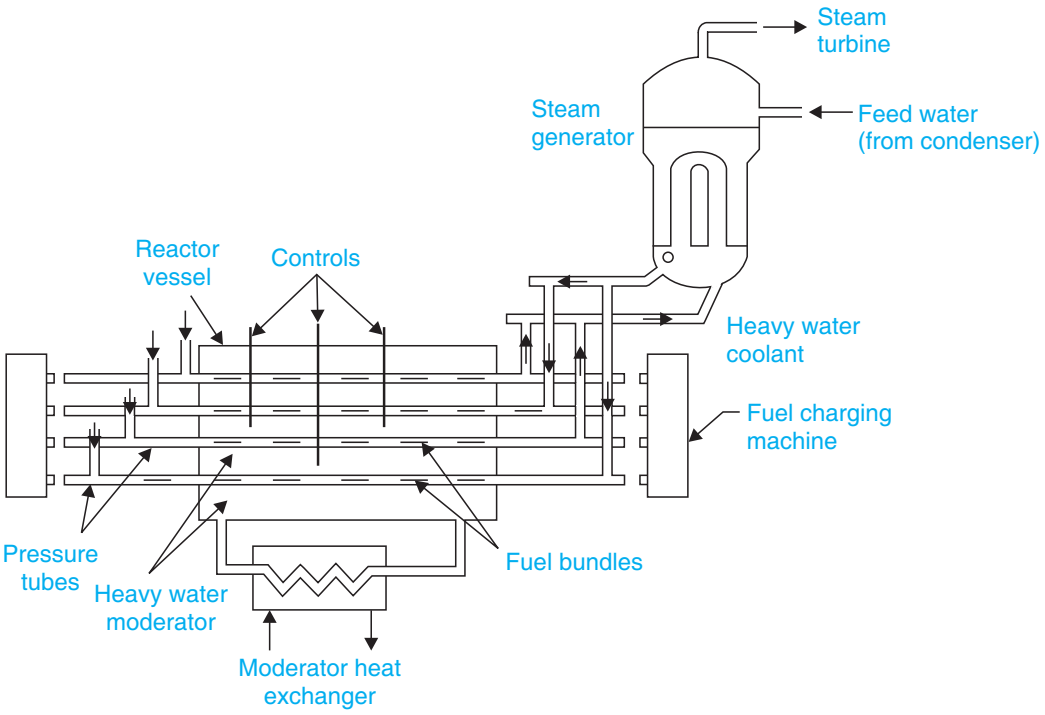


Fig. 7.14. CANDU reactor.

The high pressure (10 MPa) and high temperature (370°C) coolant leaving the reactor core enters the steam generator. About 5% of fission heat is generated by fast neutrons escaping into the moderator, and this is removed by circulation through a separate heat exchanger.

Fuel. In a CANDU reactor the fuel is *normal* (*i.e.*, unenriched) *uranium oxide* as small cylinder pellets. The pellets are packed in a corrosion resistance zirconium alloy tube, nearly 0.5 long and 1.3 cm diameter, to form a fuel rod. The relatively short rods are combined in bundles of 37 rods, and 12 bundles are placed end to end in each pressure tube. The total mass of fuel in the core is about 97,000 kg. The CANDU reactor is *unusual* in *that refueling is conducted while the reactor is operating.*

Control and protection system

There are the various types of vertical control system incorporated in the CANDU reactor :

— A number of strong neutron absorber *rods of cadmium* which are used mainly for *reactor shut-down* and *start-up*.

— In addition to above there are other *less strongly*, absorbing rods to *control power variations* during reactor operation and *to produce an approximately uniform heat* (power) distribution throughout the core.

In an emergency situation, the shut-down rods would immediately drop into the core, followed, if necessary by the injection of a gadolinium nitrate solution into the moderator.

Steam system. Steam system is discussed below :

— The respective ends of the pressure tubes are all connected into inlet and outlet headers.

— The high temperature coolant leaving the reactor passes out the outlet header to a steam generator of the conventional inverted U-tube and is then pumped back into the reactor by way of the inlet header.

— Steam is generated at a temperature of about 265°C.

There are two coolant outlet (and two inlet) headers, one at each end of the reactor vessel, corresponding to the opposite directions of coolant flow through the core. Each inlet (and outlet) header is connected to a separate steam generator and pump loop. A single pressurizer (of the type used in pressurised water reactors) maintains an essentially constant coolant system pressure.

The reactor vessel and the steam generator system are enclosed by a *concrete containment structure*. A water spray in the containment would condense the steam and reduce the pressure that would result from a large break in the coolant circuit.

Advantages of CANDU reactor :

1. Heavy water is used as moderator, which has higher multiplication factor and low fuel consumption.
2. Enriched fuel is not required.
3. The cost of the vessel is less as it has not to withstand a high pressure.
4. Less time is needed (as compared to PWR and BWR) to construct the reactor.
5. The moderator can be kept at low temperature which increases its effectiveness in slowing down neutrons.

Disadvantages :

1. It requires a very high standard of design, manufacture and maintenance.
2. The cost of heavy water is very high.
3. There are leakage problems.
4. The size of the reactor is extremely large as power density is low as compared with PWR and BWR.

7.5.4. Gas-Cooled Reactor

In such a type of reactor, the coolant used can be air, hydrogen, helium or carbon dioxide. Generally inert gases are used such as helium and carbon dioxide. The moderator used is graphite. The problem of corrosion is reduced much in such reactors. This type of reactor is more safe specially in case of accidents and the failure of circulating pumps. The thickness of gas cooled reactor shield is much reduced as compared to the other type of reactor.

There are two principal types of gas cooled reactors developed for centre station service and these are :

(*i*) The gas cooled, graphite moderator reactor (GCGM)

(*ii*) The high temperature gas cooled reactor (HTGC).

Both types are graphite moderated. The former (GCGM) uses natural uranium fuel while the latter (HTGC) employs highly enriched uranium carbide mixed with thorium carbide and clad with graphite.

The *coolant pressure* and *temperature* in *GCGM* are about 7 bar 336°C respectively, for *HTGC*, there figures are 15 to 30 bar and 700°C to 800°C.

Arrangement of high temperature, gas cooled reactor is shown in Fig. 7.15.

Advantages of gas-cooled reactor :

1. The processing of the fuel is simpler.
2. No corrosion problem.
3. As a result of low parasitic absorption it gives better neutron economy.
4. Graphite remains stable under irradiation at high temperatures.

5. The use of carbon dioxide as coolant completely eliminates the possibility of explosion in the reactor which is always present in water-cooled plants.
6. The uranium carbide and graphite are able to resist high temperatures, and, therefore, the problem of limiting the fuel element temperature is not as serious as in other reactors.

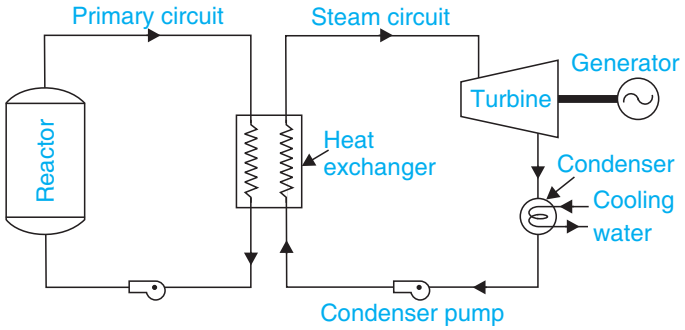


Fig. 7.15. Gas-cooled reactor.

Disadvantages :

1. Fuel loading is more elaborate and costly.
2. Power density is very low (due to low heat transfer coefficient), therefore, large vessel is required.
3. Since the critical mass is high therefore, large amount of fuel loading is initially required.
4. If helium is used in stead of carbon dioxide, the leakage of gas is a major problem.
5. More power is required for coolant circulation (as compared with water-cooled reactors).
6. The control is more complicated due to low negative coefficient as helium does not absorb neutrons.

7.5.5. Liquid Metal Cooled Reactors

Sodium-graphite reactor (SGR) is one of the typical *liquid metal reactors.* In this reactor *sodium works as a coolant* and *graphite works as moderator.*

Sodium boils at 880°C under atmospheric pressure and freezes at 95°C. Hence *sodium* is first *melted* by electric heating system and be pressurised to about 7 bar. The liquid sodium is then circulated by the circulation pump. The reactor will have *two coolant circuits or loops* :

(*i*) The *primary circuit* has *liquid sodium* which circulates through the fuel core and gets heated by the fissioning of the fuel. This liquid sodium gets cooled in the intermediate heat exchanger and goes back to the reactor vessel.

(*ii*) The *secondary circuit* has an *alloy* of *sodium and potassium in liquid form*. This coolant takes heat from the intermediate heat exchanger and gets heat from liquid sodium of primary circuit. The liquid sodium-potassium then passes through a boiler which is once through type having tubes only. The steam generated from this boiler will be superheated. Feed water from the condenser enters the boiler, the heated sodium-potassium passing through the tubes gives it heat to the water thus converting it into steam. The sodium-potassium liquid in the second circuit is then pumped back to the intermediate heat exchanger thus making it a closed circuit.

The reactor vessel, primary loop and the intermediate heat exchanger is to be shielded for radio-activity. The liquid metal be handled under the cover of an inert gas, such as helium, to prevent contact with air while charging or draining the primary or secondary circuit/loop.

The arrangement of a sodium-graphite reactor (SGR) is shown in Fig. 7.16.

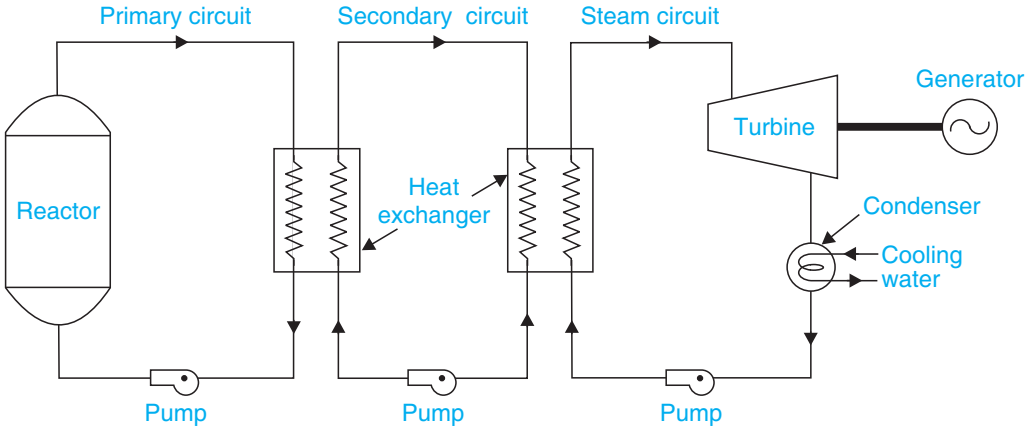


Fig. 7.16. Liquid metal cooled reactor.

Advantages of SGR :

1. The sodium as a coolant need not be pressurised.
2. High thermal efficiency at low cost.
3. The low cost graphite moderator can be used as it can retain its mechanical strength and purity at high temperatures.
4. Excellent heat removal.
5. High conversion ratio.
6. Superheating of steam is possible.
7. The size of the reactor is comparatively small.
8. The neutron absorption cross-section of sodium is low and, therefore, it is best suited to thermal reactor with slightly enriched fuel.

Disadvantages :

1. Sodium reacts violently with water and actively with air.
2. Thermal stresses are a problem.
3. Intermediate system is necessary to separate active sodium from water.
4. Heat exchanger must be leak proof.
5. It is necessary to shield the primary and secondary cooling systems with concrete blocks as sodium becomes highly radioactive.
6. The leak of sodium is very dangerous as compared with other coolants.

7.5.6. Breeder Reactor

In its simplest form a *fast breeder reactor* is a small vessel in which necessary amount of *enriched plutonium* is kept *without using moderator*. A fissible material, which absorbs neutrons, surrounds the vessel. The reactor core is cooled by liquid metal. Necessary *neutron shielding* is provided by the use of *light water, oil* or *graphite*. Additional shielding is also provided for gamma rays. (It is worth noting that when U^{235} is fissioned, it produces heat and additional neutrons. If some U^{238} is kept in the same reactor, part of the additional neutrons available, after reaction with U^{235}, convert U^{238} into fissible plutonium).

Fig. 7.17 shows a schematic diagram of a breeder reactor.

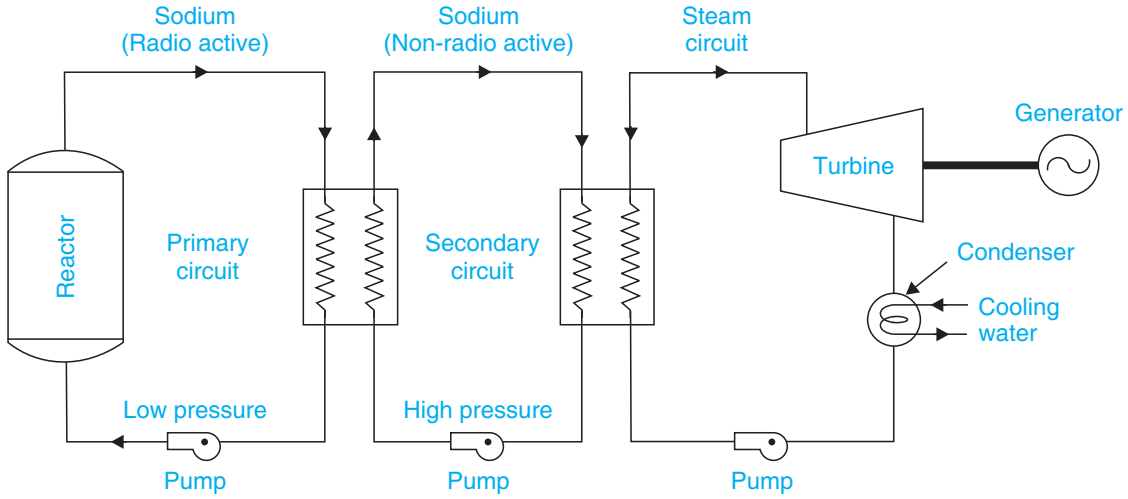


Fig. 7.17. Breeder reactor.

Advantages of a breeder reactor :

1. The moderator is not required.
2. High breeding is possible.
3. Small core is sufficient (since it gives high power density than any other reactor).
4. The parasite absorption of fuel is achievable.
5. High burn-up of fuel is achievable.
6. Absorption of neutrons is low.

Disadvantages :

1. Requires highly enriched (15 per cent) fuel.
2. It is necessary to provide safety against *melt-down*.
3. Neutron flux is high at the centre of the core.
4. The specific power of the reactor is low.
5. There is a major problem of handling sodium as it becomes hot and radioactive.

7.6. SELECTION OF MATERIALS FOR REACTOR COMPONENTS

Some of the factors governing the selection of materials for the various reactor components are considered below :

1. Structural material :

The structural units implied are :

(*i*) The cladding material for fuel elements.

(*ii*) Fuel element assemblies.

(*iii*) Containers for coolants, ducts, etc., in the core.

(*iv*) Any general structure in the reaction zone.

Obviously the *purely mechanical properties must be adequate at the normal working temperature*, and the *material must be capable of the necessary fabrication and working*.

In case where liquids are involved, corrosion or erosion problems may be present. These may be especially troublesome in aqueous homogeneous reactors or in reactors employing liquid metals.

From the standpoint of the nuclear physics the *basic requirement is low neutron absorption cross-section.* Since absorption cross-sections are less at high than at low neutron energy levels, a material which is entirely unsuitable at thermal energies may be acceptable in fast reactors. In addition to the effect on the neutron economy of the system, structural materials may become dangerous to handle due to induced radioactivity.

Some *structural materials* are discussed below :

Aluminium. In a very pure state it is being extensively used as a *cladding material for fuel elements.*

Magnesium. It is *more costly* and is *difficult to work.*

Beryllium. It offers advantages in that it would *serve* also as a *moderator* but it is again *costly* and *difficult to work.*

Zirconium. It is a comparatively new material commercially, but offers considerable promise. It is *extremely corrosion resistant at low temperatures,* but less so above 400°C. Its mechanical properties are also impaired above this temperature. In the intermediate cross-section range *titanium* has a very good strength/weight ratio from 100 to 450°C and is corrosion resistant to aqueous solutions of high temperatures.

Alloys. *Silicon steels* may be used in some fast reactors, but considerable care is needed in their heat treatment.

A number of nickel alloys are of interest and offer considerable resistance to attack by fused salts and alkali hydroxide.

Silicon, of absorption cross-section 0.1 barn and tin, absorption cross-section 0.6 barn, might prove useful for alloying with other material.

2. Reactor coolants :

Gaseous coolants. There coolants have much to recommend them from the standpoint of *general radiation* and *thermal stability* and *ease of handling.* Gases are poor, however, from the standpoint of heat transfer and at high temperatures some of them, for example *oxygen* and *hydrogen,* may attack other materials present in the core. *Air* has been used in some research reactors operating on open cycle with discharge to the atmosphere at a high level to minimise the effect of Ar. *Helium* is attractive but is expensive. *Gases involve high pumping cost.*

Water. Water has *better thermal properties* than gases and the pumping power is roughly $\frac{1}{10}$ th that for gases operated at ten atmospheres pressure. Its moderating properties may be usefully utilised when used as a coolant. It has a *fairly large absorption cross-section,* and *undergoes decomposition by radiation.* It is *subjected to induced radioactivity*, and it has a *corrosive action on metals,* and a *low boiling point. Degasification may be necessary*.

For efficient power production high pressure operation is necessary. This necessitates the use of a pressure vessel to enclose the reactor. Boiling water reactors (BWR) in which the coolant serves also as a moderator show promise.

Heavy water has a lower absorption cross-section than natural water and its use leads to economy in fissile material. If it were cheaper it would be attractive for use in boiling water type reactor.

Liquid metals are of special interest in relation to reactors operating at high thermal flux. Their main disadvantage is in *difficulty of handling,* and in their *corrosive properties.* Their *heat transfer properties are better than those* of *water*, but their volumetric heat capacity is not as good, so that the pumping power may be greater or less than that of water. ***Sodium*** is the most favoured at present, for *if free from oxygen it does not attack stainless steel, nickel and nickel alloys, beryllium or graphite at temperatures below 600°C*.

3. Moderators and reflectors :

Possible materials for use as moderator and reflectors are :

(*i*) Ordinary and heavy water

(*ii*) Beryllium

(*iii*) Beryllia

(*iv*) Graphite.

Ordinary water has *excellent slowing down properties for neutrons,* but unfortunately, neutron capture is also high. This means that enriched uranium fuel is required in ordinary water moderated reactors, but the small migration length still permits a reactor of relatively small size. Some of *disadvantages* of water are (*i*) *attendant corrosion problems,* (*ii*) *its relatively low boiling point,* and (*iii*) decomposition by nuclear radiations, resulting in the liberation of oxygen and hydrogen which may require to be recombined in ancillary plant. The low boiling point requires the use of a pressure vessel when high temperatures are involved.

Heavy water is an *excellent moderator* and *has a high moderating ratio compared with the other materials.*

Beryllium. The nuclear properties of beryllium are *eminently suitable, but it is expensive, brittle and difficult to fabricate and is corroded by water.*

Graphite. It has been used *most extensively as a reactor moderator* despite the fact that its moderating properties are not as good as heavy water or beryllium. However, (*i*) it is *reasonably cheap,* even when the necessary high degree of purity is achieved, (*ii*) it has *good mechanical properties* and *thermal stability*, and (*iii*) is a *good conductor of heat.*

Its chief *disadvantages* are the possibility of reaction with air at high temperatures and its relatively low mechanical strength.

4. Fuel :

The proportion of the fissile material in the fuel is of considerable importance in determining the *critical size* of the reactor. This is because the ratio of fissile to non-fissile material in the fuel determines the neutron economy at the source. The following table gives the average number of neutrons liberated per neutron absorbed in the fuel.

Neutron type	U^{235}	Pu^{239}	Natural uranium
Thermal	2.11	1.95	1.32
Fast	2	2	1

5. Shielding and radiation protection :

Protection of personnel is achieved partly by the use of remote control and, in some cases, the provision of a pressure vessel to contain the fission products which might result from an accident. However, shielding of the reactor itself is invariably required.

A biological shield must slow down the fast neutrons leaving the core of the reactor, must capture the slowed down neutrons and must absorb all gamma and similar radiation produced. It must be borne in mind that neutron capture in the shield itself may give rise to further gamma radiation. A combination of light (moderating or slowing down) and heavy elements is the best. The latter reduces the energy of very fast neutrons by inelastic scattering. The incorporation of a good neutron absorber (*e.g.* boron 10) is beneficial. *Cadmium* is not particularly suitable since it emits high energy photons, with energies of the order 7.5 MeV. The *heavy elements* may be *metallic iron* or *lead*, or *iron oxide* or *barytes.* The *light element* is usually *hydrogen in the form of water,* often combined in concrete, but in research reactors in particular, possibly as water. A *homogeneous arrangement of heavy and light elements* is best, for example, the *use of a laminated construction or the use of iron concrete.* The latter consists of iron mixed in barytes concrete, or alternatively limonite (iron ore) is used partially to replace barytes in the mix.

Thermal shield. Every absorption in a shield is roughly exponential. Thus 90% of the radiation is absorbed in the first 10% of the thickness. This results in considerable liberation of heat. For this reason that part of the shield nearest to the core is usually of *iron* in thickness 5 to 10 cm which may be ***air-cooled.*** *This part of the shield is referred to as the* ***'thermal shield'.***

Summary of Materials for Nuclear Power Reactors

Structural :
(*i*) Aluminium (*ii*) Stainless steel
(*iii*) Nickel alloys (*iv*) Zirconium
(*v*) Magnesium

Fuel :
(*i*) Uranium (*ii*) Uranium ceramics
(*iii*) Thorium (*iv*) Thorium oxide

Coolant :
(*i*) Water (*ii*) Liquid metals
(*iii*) Sodium, potassium (*iv*) Mercury
(*v*) Lead bismuth (*vi*) Gases
(*vii*) Helium (*viii*) Nitrogen
(*ix*) Carbon dioxide

Control :
(*i*) Boron steel (*ii*) Cadmium
(*iii*) Samarium oxide (*iv*) Gadolinium oxide

Mederator reflector :
(*i*) Water (*ii*) Heavy water
(*iii*) Beryllium (*iv*) Beryllium oxide
(*v*) Graphite (*vi*) Metal hydrides

Shielding :
(*i*) Water (*ii*) Cement and concrete
(*iii*) Iron (*iv*) Lead
(*v*) Tantalum (*vi*) Bismuth
(*vii*) Boron.

7.7. METALS FOR NUCLEAR ENERGY

Several metals such as *uranium, thorium and plutonium* are used for nuclear energy. The most important among them is Uranium. These metals are discussed below :

1. Uranium :

Occurrence :

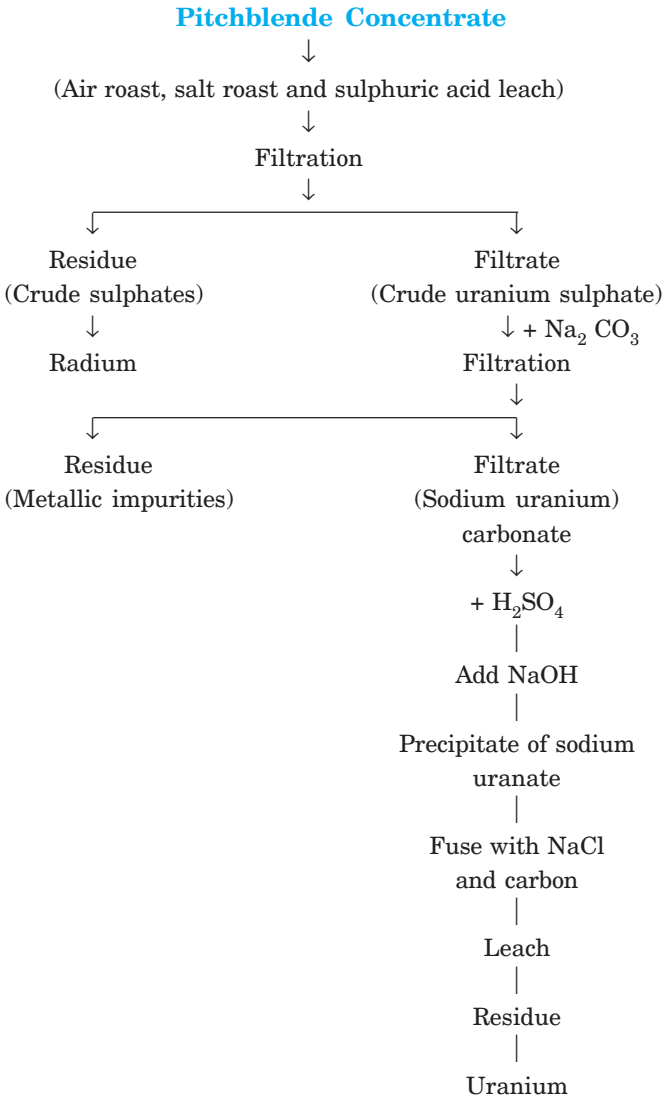
The following are the important ores :

(*i*) Uranite UO_2 (contains Th, rare earths)

(*ii*) Pitchblende UO_{2+x}

(*iii*) Carnotite $K_2 (UO_2)_2(VO_4)_{2x} . H_2O$.

The flow sheet for recovery of Uranium from Pitchblende is given below :



Extraction of Uranium :

The uranium can be produced by numerous processing treatments. In general, one of the two leaching treatments is used at the initial step in chemical concentration. One of those is the *acid leaching* and the other *carbonate leaching*. The choice depends upon the nature of the ore. The concentrate is treated chemically to give a uranyl nitrate solution than can be further purified by solvent extraction. The impurities remain in the acqueous phase while uranium is extracted from organic phase. The pure uranium is then stripped from organic phase and recovered as nitrate crystals or precipitated from the solution. The largest tonnage of uranium metal of good quality have been prepared from UF_4 by reduction with calcium or magnesium.

Mechanical properties :

	Annealed	Cold-drawn
Hardness (BHN)	92	112

Oxidation and corrosion resistance. Uranium is not chemically stable in air ; it reacts slowly in cold water and more rapidly in hot water.

Special properties. Uranium is the element having the largest number and atomic weight that is native in earth's crust ; hence it is a logical material for making heavier atoms by adding neutrons to the nucleus of uranium in atomic energy piles, and these by acquiring energy and radio active elements by fusion of relatively unstable transuranic elements which form.

Fabricating characteristics

(*i*) Pure uranium is malleable and very ductile however, small amounts of aluminium and iron embrittle it.

(*ii*) It dissolves oxygen and hydrogen readily ; consequently it is usually vacuum-annealed between cold-working operations.

(*iii*) Above 1400°C it is worked as a body-centered cubic metal.

(*iv*) It acquires distinct directional properties on cold working.

(*v*) The metal may be welded by resistance welding or inert gas arc welding processes.

(*vi*) Uranium is usually processed by powder metallurgical methods, or melted with inert arc process or high frequency furnaces using beryllia or thoria crucibles.

2. Thorium :

Thorium is one of the many metals which have become available as engineering materials as a result of the programme of the Atomic Energy Commission. The metal is difficult to prepare in the pure state because of its high melting pointing, 1690°C and its chemical reactivity with both gases and refractories. Once obtained, the silvery white metal is soft and ductile.

How to produce thorium ?

Metallic thorium can be produced by the reduction of the oxide or halides with alkali and alkaline-earth metals, by thermal decomposition of thorium iodide, and by the electrolysis of thorium compounds in fused salts. Marden and other produced powdered metal by reduction of thoria with calcium. This powdered metal is pressed and sintered into solid bars of good ductility and purity. Methods similar to those used for uranium are used to obtain thorium and the metal is now available in tonne quantities.

Physical constants of thorium. The principal physical constants are given below :

Density, g/cm^3	
(*a*) Theoretical	11.71
(*b*) Typical casting	11.63
Melting point	1690 ± 10°C
Boiling point	3000°C

Electrical resistivity, ohm-cm (20°C)	18×10^{-6}
Crystallography :	
(*a*) Structure	Face-centered cube
(*b*) Atomic diameter	3.59
(*c*) Transformation temperature	1400°C ± 25

Mechanical properties. Thorium is a soft material having a 75 to 80 VPN (Vickers Pyramid Number) and an annealed strength of 2600 kg/cm^2 nearly. The mechanical properties of thorium are grossly affected by small amounts of impurities. Carbon in particular tends to increase the hardness and strength of high-purity iodide metal. Poisson's ratio averages 0.265 in both tension and compression. The metal work hardens rapidly. In impact thorium exhibits a transition from brittle to ductile behaviour in temperature range (100 to 200°C).

Corrosion and oxidation resistance. Thorium is stable in air if the oxide content of the metal is low. The metal becomes covered with a stable oxide film which prevents further attack. It is stable in water and acqueous alkali solutions but is attacked by sulphuric or hydrochloric acids, halogen gases, and fused alkali.

Fine thorium powder may burn spontaneously ; wire or solid metal deoxidizes slowly in air. On heating in air, it will ignite and burn with great brilliancy.

Special properties. All thorium is *radio active* ; it is a potential source of *nuclear fuel.* It has good electron emission, and hence it is used in filaments and electric arc electrodes.

Fabricating characteristics. Thorium is very malleable metal and is ductile after some cold work, being much like lead. It may be rolled and swaged easily, and it can be cold-drawn after annealing and some swaging to work-harden it sufficiently, for the wire has a very low tensile strength in the annealed state. By cladding with copper or iron, it may be drawn to extremely fine wire.

Thorium is easy to machine and shape and may be welded by resistance-welding or inert arc welding methods.

Health hazards. Thorium like uranium, is an alpha emitter and the parent element of radio active thorium series. Highly radio active products may be released in grinding the ores and during the reduction and casting of the primary metal. The processed metal has a relatively low activity level and is handled without protective clothing or shielding. Competent medical authorities should be consulted regarding the handling of and tolerances for thorium.

3. Plutonium :

(*i*) It is very reactive.

(*ii*) It is easily oxidised.

(*iii*) It is highly toxic.

(*iv*) Its low temperature phases are very complex. In general it exists in six allotropic forms.

7.8. ADVANTAGES OF NUCLEAR POWER PLANTS

Some of the *major advantages* of nuclear power plants are :

1. A nuclear power plant *needs less space* as compared to other conventional power plant of equal size.
2. Nuclear power plants are well suited to meet large power demands. They give better performance at high load factors (80 to 90%).
3. Since the fuel consumption is very small as compared to conventional type of power plants, therefore, there is *saving in cost of the fuel transportation.*
4. The nuclear power plants, besides producing large amount of power, *produce valuable fissible material* which is produced when the fuel is renewed.
5. The operation of a nuclear power plant is *more reliable.*
6. Nuclear power plants are not affected by adverse weather conditions.
7. Bigger capacity of a nuclear power plant is an additional advantage.
8. The expenditure on metal structures piping, storage mechanisms is much lower for a nuclear power plant than a coal burning power plant.

Disadvantages/Limitations

1. The *capital cost* of a nuclear power station is always *high*.
2. The *danger of radioactivity* always persists in the nuclear stations (inspite of utmost precautions and care).
3. These plants *cannot be operated at varying load efficiently*.
4. The *maintenance cost is always high* (due to lack of standardisation and high salaries of the trained personnel in this field of specialisation).
5. The disposal of fission products is a big problem.
6. Working conditions in nuclear power station are always detrimental to the health of the workers.

Comparative Ratings of 10 MW Nuclear and Coal-burning Power Plant

S. No.	Ratings	Nuclear plant	Coal-burning plant
1.	Weight of machines and mechanisms, *tons*	700	2700
2.	Weight of metal structures, *tons*	900	1250
3.	Weight of pipes and fittings, *tons*	200	300
4.	Weight of masonary/graphite assembly, *tons*	500	1500
5.	Weight of fuel storage mechanism, *tons*	–	2500
6.	Weight of rolling stock, *tons*	–	300
7.	Volume of plain and reinforced concrete work, *cum*	9000	4000
8.	Capacity of buildings (without turbine room and electrical facilities), *cum*	50000	75000
9.	Area of construction site, *hectares*	5	15
10.	Internal power consumption, *kW*	5000	8000

7.9. NUCLEAR-PLANT SITE SELECTION

Nuclear power plants *must meet all the economic and technical and most of the legal criteria* that apply to the siting of conventional fossil-fuel-fired power plants. *In addition, the importance of site characteristics in the assessment of public safety results in greater concern in siting nuclear plants than with any other type of industrial facility*. Of particular concern are the population distribution with respect to the site and the natural factors which could affect the transport of radioactive material to the public, under normal operating conditions and in the highly unlikely event of an accident which could release radioactive material to the environment.

The various factors to be considered while selecting the site for a nuclear power plant are enumerated and described in detail below :

1. Proximity to load centre
2. Population distribution
3. Land use
4. Meteorology
5. Geology
6. Seismology
7. Hydrology.

1. Proximity to load center :

Electrical power can be transmitted over considerable distances by power-transmission lines, but, because of the capital cost of the lines and rights-of-way and transmission losses, an economic penalty is incurred which increases with increasing distance between the generating station and the load center. It is apparent, therefore, that *the closer the power-plant site can be located to the load center* (while meeting other requirements such as reasonable land cost, adequate cooling water, local zone restrictions, accessibility for fuel shipment, etc.), *the lower can be the cost of power delivered to the consumer*. Although nuclear plants should be built close to their load centers, regulatory bodies have been very cautious, despite the unparalleled nuclear plant safety record. Most plants built to date have not been in or near heavily populated areas.

2. Population distribution :

Since power reactors must be located reasonably close to load centers, the *population distribution around the site is a necessary consideration* in the evaluation of a nuclear power-plant site. The distances, the site meteorological conditions and the amount of radioactive material which could be released from the plant during a major accident are used to evaluate the suitability of the site from the standpoint of safety to the public. In addition to the permanent population surrounding a site, it is also necessary to consider part-time peaks in population, such as during the day or on weekends in recreational areas, and seasonal variation in population, particularly in resort areas. Consideration also should be given to estimates of future increases or changes in population distribution.

To permit placing nuclear plants in desirable locations, it is necessary to provide effective engineered safeguard features to offset, at least in part, the present requirement for large distances from population centers. The trade-off between distance requirements and engineered safeguards is qualitative, and there are no established rules or principles by which such a trade-off can be factored into the evaluation of possible sites for a nuclear power plant. Such a trade-off can, at present, be based only on engineering judgement and on precedents established in the siting of other nuclear plants having different degrees of safeguards and located at various distances from population centers.

3. Land use :

The use to which the land surrounding a nuclear-plant site is being put, even though it may not be densely populated, *may have an effect on the suitability of the site for a nuclear plant*. For example, if land is used for agriculture, ingestion of food which has been contaminated by fallout after an accident might conceivably result in a

greater radiation dose to the public than might be received from direct exposure to radioactive materials transported downwind from the plants. Of similar concern, but possible as a result of normal operation, is the chance that certain marine life, stationary shellfish in particular, can concentrate the small quantities of radioactivity normally released into the cooling water discharged from the plant. Over a long period of time, the concentration of radioactivity conceivable could build up to levels approaching maximum permissible concentrations.

4. Meteorology :

Because the atmosphere is the principal means by which radioactivity released from a nuclear plant might be transported to the public, *site meteorological conditions* are considered in selecting a nuclear plant site. Meteorology is of concern both for normal discharges of gaseous radioactive wastes and for the much less likely releases of larger quantities of airborne radioactive material which might result from an accident. A number of meteorological variables are normally evaluated for the site to determine appropriate atmospheric dilution factors. Among these variables are : *wind-direction frequencies, in conjunction with the population distribution ; wind velocities and the frequencies of each velocity increment ; frequency and duration of calms ; atmospheric lapse rate ; frequency and duration of inversion conditions*. Atmospheric dilution is increased, and thus the meteorological conditions are more favourable, the more unstable the atmosphere and the greater the wind velocity.

Other meteorological conditions of concern are the following : *precipitation,* since it may significantly increase deposition of radioactive materials from the atmosphere, *i.e.*, "rain-out" ; possible effects of topography on the local meteorology ; *seasonal variations in meteorological conditions* ; and *the frequency and severity of storms*, particularly tornadoes and hurricanes, which could severely damage the plant. Meteorological information collected at the plant site provides the greatest assurance that it is representative of actual site conditions, provided that sufficiently accurate instrumentation is used and the data are collected over a long enough period of time to be statistically valid. Usually the only meteorological information available during selection and evaluation of a site is data collected at the locations in the same general area, over a long period of time.

At sites where meteorological conditions are particularly favourable or unfavourable, *more careful consideration would be given to meteorological characteristics*.

5. Geology :

Investigation of the site geology is necessary to determine the *bearing capacity of the soil* and the types of foundations which must be used for the major portions of the plant. Test borings are usually made for this purpose, just as for any other large structures. Of particular concern for nuclear plants, because of the implications for public safety, is the possibility of *sudden earth movement* which could severely damage the plant. Earth slides due to soil instability, subsidence due to consolidation of subsurface materials or to removal of oil or water from subsurface formations, and ground displacements during earthquakes along geologic faults traversing the site—each receives very careful consideration.

If the possibility exists for releasing radioactive liquids from the plant, the ion-exchange and filtering characteristics of the surrounding soil may be important. *If the soil could reliably retain any radioactivity released and prevent it from entering water sources or otherwise coming in contact with persons or animals, the site would be that* much more favourable.

6. Seismology :

Seismology is of particular concern is areas of *high seismic activity* because of the possibility that the forces which can be produced by earthquakes could be sufficient to damage the reactor system and rupture the containment structure. Careful consideration is given to the general seismic history of the area, including a description of all earthquakes which have been observed at the site, their magnitude or intensity, and the frequency spectrum for which structures should be analyzed. *The proximity of the site to known active faults must be determined, and any significant faulting at or near the plant site must be evaluated*. Conservative earthquake design factors, usually substantially greater than those required by the Uniform Building Code, are used for critical equipment and structures in areas of high seismic activity.

In coastal areas the possibility of tsunamis may have to be considered. These earthquake-generated sea waves may travel long distances very rapidly and, under certain shore conditions, can build up to substantial heights. Standard seismic design is generally adequate to meet the design criteria based on the factors described above, and with the conservative design factors ordinarily used, reactor systems are adequate for even worse conditions than could be realistically expected to occur.

7. Hydrology :

An important consideration is selecting a site for any power plant is the *local hydrology*. Present-day type of nuclear plants *require substantially greater quantities of cooling water* than do modern fossil steam plants because of their higher turbine heat rates. In areas of limited water supply, cooling towers can be used but at some cost penalty. *An additional consideration for nuclear plants is that there be sufficient water flow for the discharge of low-level radioactive liquid wastes*. This usually imposes no limitation because of the small quantities of wastes to be discharged and because it is possible to dilute or clean up the wastes to nearly any required concentration. *If necessary, it is possible to collect and ship these wastes off site*.

Another area of concern is the *possibility of flooding*, which could cause damage to the plant and equipment and cause plant shutdown. Seismic sea waves and hurricanes may increase the possibility of flooding at coastal sites. Seiches (Periodic surface oscillations) could result in flooding adjacent to large, enclosed bodies of water. *The flooding history of the site must be determined to permit adequate site evaluation and plant design*.

The characteristics of the ground water and the level of the water table at the site must be evaluated to ensure that contamination of local water sources by the discharge of liquid radioactive wastes does not occur. It there is any possibility of significant discharge of radioactive contamination to ground water, the absorption characteristics of the soil and the drainage characteristics of the ground water, including its depth and estimated direction of flow, and the characteristics of wells in the area may have to be determined as part of the site evaluation.

7.10. APPLICATION OF NUCLEAR POWER PLANTS

A nuclear power station is ideally suited under the following situations :

(*i*) In an area with *potential for industrial development*, but *limited conventional power resources*, nuclear power generation appears as an only alternative.

(*ii*) If the existing power grid is to be firmed up or additional power demand is to be met while all available hydro power resource have been exploited, and coal is scarce or expensive to transport, a nuclear power station may be used with advantage.

7.11. ECONOMICS OF NUCLEAR POWER PLANTS

Typically, all costs of nuclear power plants are broken down into the following categories :

1. *Capital costs (total).*
2. *Fuel costs (per year).*
3. *Other operating and maintenance costs (per year).*

With a knowledge of these total and annual costs, and a knowledge of the pertinent factors relating to production, anticipated plant life, and the costs of invested money, unit costs may be determined for any time period desired.

Although such unit costs may be determined on a single plant basis, it should be noted that the addition of any new plant will normally provide excess capacity in the system under study. Thus, *a more valuable analysis involves the inclusion of the additional costs incurred by the new plant in the total system cost pattern and the redetermination of total system costs*. Simplified analysis requires the assumption of an immediate load availability to the new plant at the expense of load availability to the older existing plants. *Although more complicated, a system analysis using the lowest system incremental loading cost will provide a more accurate picture of real annual unit costs for the various alternatives considered*.

1. Capital costs :

Capital costs are those costs which *occur only once* and are usually limited to the costs of procurement and construction of the facilities prior to the time of commercial operation. These are normally "*capitalized*" ; *i.e.*, *they are treated as an investment which is depreciated over the useful life of the plant rather than being treated as an annual or other shorter-term operating cost*.

Determination of those costs which may be allowed within the capital-cost structure often depends on review by the appropriate public-utility commission or other regulatory body and on corporate accounting policies. Allocation of the capital-cost items over the life of the plant is normally accomplished by applying factors, or percentage rates, *which will account for depreciation, return on investment, and taxes applied to income and property value*. The product of the total of these factors and the allowable capital costs gives the annual fixed charge per year for the capitalized investment. Within this structure, several different depreciation methods are used, such as *sinking fund, straight-line depreciation*, etc., depending upon the accounting structure already in existence.

2. Fuel costs :

Fuel cycle. An understanding of *nuclear-fuel costs* requires an understanding of the *nuclear-fuel cycle*, since the fuel-management programmes are significantly different from those used for fossil-fueled plants.

Fig. 7.18 shows the basic fuel cycle. The word "*cycle*" is intentionally used, for, unlike fossil fuels, a single pass through the reactor does not consume all the nuclear fuel. Further, a valuable new fuel, plutonium, is generated during power production.

Fuel costs are affected by the number of functional services which must be performed on the uranium fuel to prepare if for use, the additional services which must be performed to recover the "ash" value of the spent fuel, and the variation in the design data for each batch of fuel employed.

The calculation of nuclear-fuel costs using various data is particularly complex if a high degree of sophistication is desired, such as in the evaluation of competitive fixed-price bids or in the determination of minimum incremental operating costs between two or more plants. However, for project scoping purposes and general

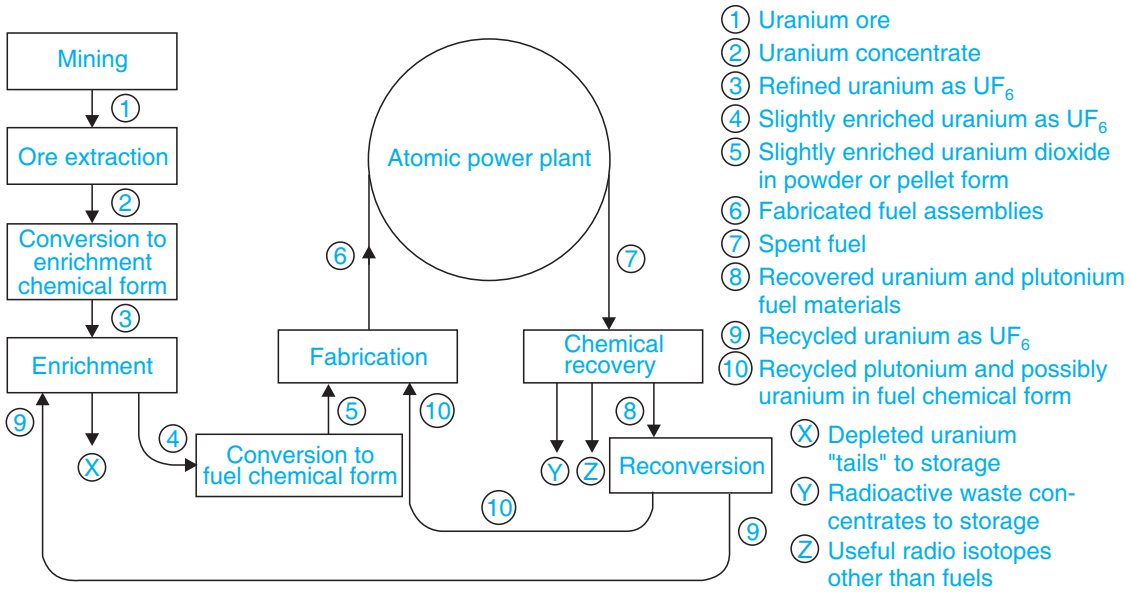


Fig. 7.18. Nuclear fuel cycle (based on water-cooled reactors).

familiarization with the principles involved, the following simplified method may be used to determine *equilibrium fuel-cycle costs* :

1. Determine the initial uranium-procurement unit cost in rupees per kilogram of uranium. This cost will vary with the price of uranium yellow cake, the cost of converting it to uranium hexafluoride, and the cost of toll enrichment. This latter item is, in turn, dependent upon the enrichment required (which determines the amount of separative work required) and the unit cost of separative work.

2. Determine the fabrication unit cost, in terms of rupees per kilogram, of combined uranium.

3. Determine the spent-fuel-element shipping, reprocessing, and reconversion costs in terms of rupees per kilogram of contained uranium.

4. Determine the credit available for the recovered uranium and plutonium.

5. Determine the indirect costs, *i.e.*, return on investment and provision for applicable taxes, by determining the average investment level throughout the procurement period, energy-production period, and spent-fuel recovery period and multiplying by the appropriate interest of fixed-charge rates.

6. Sum items 1 through 5 to give the total unit costs, in terms of rupees per kilogram of uranium.

7. Determine the unit energy production, based upon the average fuel energy production (usually given in terms of megawatt-days thermal per metric ton of uranium) and the thermal efficiency of the plant.

8. Divide item 6 by item 7 to give the unit costs.

The results of such simplified calculations are likely to be somewhat low, since they *do not recognize the various minor material losses*. However, they are also not likely accurately to reflect the true investment costs, since the *investment value is a complex value varying with energy production*.

The complications inherent in a complete fuel-cycle cost, coupled with the need to compute costs over an extended period involving changing cost patterns and also over the several fuel loadings required to reach an equilibrium fuel-flow requirement, have led to the development of computerized calculational methods.

3. Operations and maintenance costs :

Operating and maintenance costs categories fall in the following groups :

(*i*) Labour

(*ii*) Materials, supplies and services

(*iii*) Insurance

(*iv*) Fuel management

(*v*) Working capital.

(*i*) The *plant staff* required is relatively independent of plant size, typically running 60 to 70 men, including all supervision, technical assistance, operations, maintenance and miscellaneous supporting services. The costs for this staff may vary substantially, being highly dependent upon the local labour market and the labour costs.

(*ii*) *Materials, supplies, and services* are also relatively insensitive to plant size, although certain items

are directly proportional to the thermal power level and the frequency and extent of power-level changes.

(*iii*) *Insurance costs* may be divided into two component parts, *property insurance* and *liability insurance*. Property insurance is normally a direct function of the capital value.

(*iv*) *Fuel-management services* may be provided either by contracting for external services or by adding staff to that already discussed. This cost is also essentially independent of plant size.

Total Energy Costs. The total unit cost of energy delivered at the bus bar is the sum of all of the preceding cost components which are related to the energy-production period divided by the energy produced during the same period. If escalation is disregarded, technological improvements and lower fuel costs will tend to reduce this value.

— From economical considerations, the Nuclear Power Plant are designed for 75% of the base load. Fig. 7.19 shows the comparison of cost of production of power by thermal plants with the cost of production by nuclear plants.

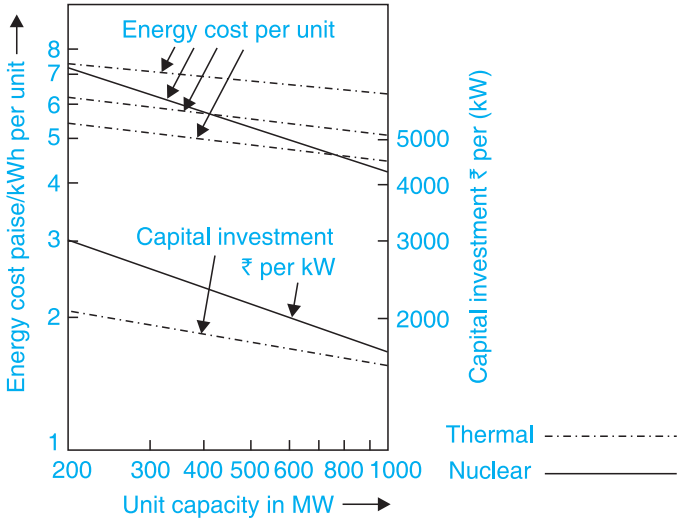


Fig. 7.19. Comparison of costs between nuclear and thermal power plants.

As can be seen, at low installed capacities, both the capital investment and the energy cost per unit are less for thermal power plants. But when the installed capacity reaches 1000 MW, both the plants become comparable. Further, the increased cost of coal production and also the far flung coal mines will eventually make the nuclear power a cheaper one.

In spite of the inevitability of our option to go nuclear for power production, the hazards are enormous and we shall have to be extremely careful in designing, constructing and operating the nuclear power plants. The disaster in Russia and elsewhere cannot be ignored easily.

7.12. SAFETY MEASURES FOR NUCLEAR POWER PLANTS

In case of nuclear power plants the three main sources of radioactive contamination of the air are : (*i*) Fission of nuclei of nuclear fuels, (*ii*) The effect of neutron fluxes on the heat carries in the primary cooling system and on the ambient air, (*iii*) Damage of shells of fuel elements.

The above, mentioned contamination of air can cause health hazard to workers and community and negative effect on surrounding forests. This calls for safety measures for a nuclear power plant, some of them are listed below :

1. A nuclear power plant should be constructed away from human habitation. An *exclusion zone* of 106 km radius around the plant should be provided where no public habitation is permitted.

2. The materials to be used for the construction of a nuclear power plant should be of required standards.

3. Waste water from nuclear power plant should be purified.

4. The nuclear power plant must be provided with such a safety system which should safely shut down the plant as and when necessity arises.

Narora Atomic Power Project (NAPP) design entails the following significant design improvements : (*i*) An integral reactor vessel and end shield assemblies, (*ii*) Two independent shut down systems, (*iii*) Total double containment with suppression pool.

5. There must be periodic checks to ensure that radioactivity does not exceed the permissible value is the environment.

6. While disposing off the wastes from the nuclear plants it should be ensured that there is no pollution of water of river or sea where these wastes are disposed.

7.13. NUCLEAR POWER PLANTS IN INDIA

The various nuclear power plants situated in India are as follows :

1. Tarapur power plant
2. Rana-Partap Sagar power plant
3. Kalpakkam power plant
4. Narora power plant
5. Kakrapar power plant.

The particulars of these plants are given in tabular form below :

Particulars	Power plants				
	Tarapur	Rana-Partap Sagar	Kalpakkam	Narora	Kakrapar
1. Location	Maharashtra (65 miles north Mumbai)	Near Kota in Rajasthan	Near Chennai in Tamil Nadu state	U.P	Surat district, Gujarat
2. Capacity	380 MW	400 MW (2 × 200 MW)	470 MW (2 × 235 MW)	2 × 235 MW (under construction) 40 bar at 250°C	4 × 235 MW (proposed)
3. Steam pressure and temperature	35 bar at 240°C	40 bar at 250°C	–	–	–

7.14. FUTURE OF NUCLEAR POWER

India has hydro-power potential, and some coal reserves ; unfortunately these are not very well distributed throughout the country. Moreover, most of the economically feasible hydropower schemes have already been developed. The quality of Indian coal is not very good, and the reserves are concentrated in one or two parts of the country. These reserves are also being depleted at a fast rate, the railways consuming a large quantity. On the other hand, India has *adequate deposits of fissionable material-thorium*, which can eventually be used for generation of power. Therefore, development of nuclear power, to supply the growing electricity demand of the country is quite logical and necessary. Thus the future of nuclear power is quite bright. The following three factors, however, need discussion :

(*i*) *Cost of power generation*. Although cost of power generation in a nuclear power plant is comparatively more, yet with research in the nuclear technology the cost is bound to come down to a value comparable with that for conventional plant.

(*ii*) *Availability of nuclear fuel*. The problem of availability of large amount of nuclear fuel can be overcome to a great extent by switching over to breeder reactor in which fissionable fuel is produced at the same time they are consuming it.

(*iii*) *Safety of the nuclear plants*. If the nuclear plants are designed in such a way that they do not explode like a nuclear bomb they can give a safe operation, since they contain only a small amount of fissionable material (as compared to 90% fissionable fuel in the atomic bomb core).

7.15. USEFUL BY-PRODUCTS OF NUCLEAR POWER GENERATION AND THEIR USES

The Nuclear plants supply many by-products like isotopes which have many useful applications in our day-to-day life.

The fission products consist of Beta and Gamma emiting radioactive isotopes with different half-lives. Only a very small percentage of nucleon waste is used for industrial purposes. 90% of the nucleon wastes have short half-lives and decay in a few years. It is the remaining 10% who have centuries as half-lives which pose disposal problems.

Industrial isotopes must satisfy the following two conditions :

(1) Yield of the isotope should be quite high.

(2) The half-life should neither be too short nor too long.

Some of the Isotopes and their characteristics are shown below :

Isotopes	%Yield	Half-life	Type of Radiation	
			Beta MeV	Gamma MeV
Cesium—137	6.22	33 years	0.5, 1.2	None
Barium—137	6.22	2.6 mins.	None	0.658
Strontium—90	5.3	28 years	0.605	None
Cerium—144	5.28	285 days	0.351	None
Praseodymium—144	5.28	17.3 minutes	3.02	0.2
Zirconium—95	6.39	65 days	0.391, 1.0	0.915
Niobium—95	6.39	35 days	0.15	0.76
Technetium—99	6.19	2.1 × 10 years	0.295	None
Promethium—147	2.61	2.5 years	0.219	None

The radioactive isotopes are widely used in *Biology, Medicine, Agriculture and Industries*.

Industrial Applications :

(1) *Position location* : Buried pipelines can be traced by using portable geiger Counters.

(2) *Flow patterns* in pipes can be detected by injecting radioactive isotopes into the flow. The radiation will be different for laminar and turbulent flows.

(3) *Leakage detection* can be done by injecting isotopes into fluid in pipes. The reactivity will be different at leakage points.

(4) *Ground water path* is detected by mixing short lived radioactive material with water (to avoid contamination).

(5) *Thickness gauges.*

(6) *Liquid level gauges.*

(7) *Radiography (Flaw detection).*

X-rays, which are having a high penetrating power are made to pass through castings, welds etc. and on the other side, the photographic plate receives the radiation. The attenuation (reduced intensity) is a function of the thickness of the test material and its density. Thus the film is exposed to varying intensities of radiation which help in detecting internal flaws of welds and castings.

Co^{60} is a good source of Gamma rays and is cheaper than X-ray tube and has a longer life. But this needs constant heavy shielding whereas X-ray tube needs shielding only during operation.

(8) *Density and content gauges :*

The Through Gauge is used for this purpose. If the reactivity is a function of density of the material and thus the density of the content can be measured. This method is used in cigarette packing line and a relay arrangement is made to reject the faulty cigarettes.

(9) *Application in chemistry :*

Substances deteriorate when exposed to radiation and the destroyed molecules are rejoined chemically to yield new materials. This technique has been exploited in the fields of polymerization, oxidation and halogenation processes.

In polymerization process, used in the manufacturing of synthetic rubber and plastics, the elements react at high temperature and pressures. But by irradiating the ingredients by Gamma radiation, the process can be carried out at 202°C and atmospheric pressure. This has helped in revolutionizing the polythene industry.

(10) *Sterilization of foods and drugs :*

Bacteria are produced in food-stuffs and vegetables and cause fermentation. Heating process can help in sterilization (complete destruction of Bacteria) and pasteurization (90% destruction of Bacteria). But this heating process cannot be done for fruits, vegetables and drugs. For these items, irradiation is the process adopted to kill the bacteria. In this process, the materials are kept in an air-tight container and are subjected to Gamma Radiation. After irradiation, these materials can be stored at room temperature for longer durations.

(11) *Direct electrical power generation :*

Direct electrical power generation can be done in devices called atomic battery.

(12) *Tracer applications :*

In this method, small dozes of isotopes of small half-lives are injected into reactants and then traced. This helps to trace the elements and their functions in the reactions. Determining the role of sulphur in the vulcanization is one such example.

In circuit breakers, the transfer of small amount of materials between the contact points can be detected by this methods. Similarly, flows in the bonding of two materials and the flaws can be detected, as in the case of bonding between asphalt and stone.

WORKED EXAMPLES

Example 7.1. *Calculate the following :*

(*i*) *The fission rate of* U^{235} *for producing a power of one watt.*

(*ii*) *The energy released in the complete fissioning of 1 kg of* U^{235}.

Assume that 200 MeV are released per fission of the uranium nucleus.

Solution. (*i*) Energy released per fission of U^{235} nuclide

$$= 200 \text{ MeV} = 200 \times 1.6 \times 10^{-13} \text{ J}$$

$$= 3.2 \times 10^{-11} \text{ J or W-s}$$

Hence, *fission rate for producing one watt of power*

$$= \frac{1}{3.2 \times 10^{-11}} = \mathbf{3.1 \times 10^{10}\ fission/second.} \quad \textbf{(Ans.)}$$

(*ii*) One kg-atom of U^{235} *i.e.*, a mass of 235 kg of U^{235} contains 6.02×10^{26} atoms (nuclides). Hence, energy released by 1 kg-atom of U^{235} is

$$= 200 \times 6.02 \times 10^{26} \text{ MeV}$$

$\therefore$ *Energy released per kg of* U^{235} *is*

$$= \frac{200 \times 6.02 \times 10^{26}}{235} \text{ MeV}$$

$$= \frac{200 \times 6.02 \times 10^{26} \times 1.6 \times 10^{-13}}{235} \text{ J}$$

$$= \mathbf{8.2 \times 10^{13} \text{ J.}} \quad \textbf{(Ans.)}$$

Example 7.2. *A nuclear reactor consumes 10 kg of U^{235} per day. Calculate its power output if the average energy released per U-235 fission is 200 MeV.*

Solution. Quantity of U^{235} consumed per day = 10 kg

Average energy released per U^{235} fission = 200 MeV

Number of atoms in 235 kg of U^{235}

$= 6.02 \times 10^{26}$ (Avogadro's number)

Hence, number of atoms contained in 10 kg of U^{235}

$$= \frac{6.02 \times 10^{26}}{235} \times 10 = 2.56 \times 10^{25}$$

Fission energy produced by these atoms

$= 200 \times 2.56 \times 10^{25}$ MeV

$= 200 \times 2.56 \times 10^{25} \times 1.6 \times 10^{-13}$ J

$= 819.2 \times 10^{12}$ J

Time taken to consume 10 kg of U^{235}

= one day = 24×3600 seconds

$$\therefore \quad \textit{Power produced} = \frac{819.2 \times 10^{12}}{24 \times 3600}$$

$$= \mathbf{9.48 \times 10^{9} \text{ W.}} \quad \textbf{(Ans.)}$$

Example 7.3. *During a 10-hour run from one station to another, a railway engine develops an average power of 1200 kW. If the engine is driven by an atomic power plant of 20% efficiency, how much U^{235} would be consumed on the run ? Each U^{235} atom on fission releases 180 MeV of energy.*

Solution. Duration of the run between two stations = 10 hour

Average power developed by the railway engine = 1200 kW

Efficiency of the atomic power plant, $\eta = 20\%$

Energy released by each atom of U^{235} = 180 MeV

Mass of U^{235} consumed, m :

Energy consumed by the engine for the run

$= 1200 \times 10 = 12000$ kWh

Since 1 kWh = 36×10^5 J

$\therefore$ Energy consumed

$= 12000 \times 36 \times 10^5 = 432 \times 10^8$ J

Since the efficiency of atomic power plant is only 20%, energy required to produce it

$$= \frac{432 \times 10^8}{\eta} = \frac{432 \times 10^8}{0.2} = 216 \times 10^9 \text{ J}$$

Energy produced per disintegration of U^{235} atom is

$= 180 \text{ MeV} = 180 \times 1.6 \times 10^{-13}$ J

Hence number of U^{235} atoms which must disintegrate for producing 216×10^9 J is

$$= \frac{216 \times 10^9}{180 \times 1.6 \times 10^{-13}} = 7.5 \times 10^{21}$$

Now, 6.02×10^{26} atoms are contained in 235 kg of U^{235}.

Hence, the mass which contains 7.5×10^{21} atoms is

$$m = \frac{235 \times 7.5 \times 10^{21}}{6.02 \times 10^{26}} = 2.928 \times 10^{-3} \text{ kg}$$

$$= \mathbf{2.928 \text{ gm.}} \quad \textbf{(Ans.)}$$

Example 7.4. *A power of 6 MW is being developed in a nuclear reactor.*

(i) How many atoms of U^{235} undergo fission per second ?

(ii) How many kg of U^{235} would be used in 1000 hours.

Assume that on an average 200 MeV is released per fission.

Solution. Power being developed in the reactor = 6 MW = 6×10^6 W

Average energy released per fission = 200 MeV

(i) Number of atoms which undergo fission :

The fission rate for producing 1 watt = 3.1×10^{10} fissions/second (Refer to Example 7.1)

Hence, fission rate for 6×10^6 W is

$= 3.1 \times 10^{10} \times 6 \times 10^6 = \mathbf{18.6 \times 10^{16}}$. **(Ans.)**

(ii) Mass of U^{235} consumed :

Number of atoms (or nuclides) which would undergo fission in 1000 hours

$= 18.6 \times 10^{16} \times (1000 \times 3600) = 6.696 \times 10^{23}$

Now, 1 kg-atom of U^{235} *i.e.*, 235 kg of U^{235} contains 6.02×10^{26} nuclides, hence

Mass of U^{235} *consumed*

$$= \frac{235 \times 6.696 \times 10^{23}}{6.02 \times 10^{26}} = \mathbf{0.2614 \text{ kg.}} \quad \textbf{(Ans.)}$$

Example 7.5. *200 MW of electrical power (average) is required for a city. If this is to be supplied by a nuclear reactor of efficiency 20 per cent, using U^{235} as the nuclear fuel, calculate the amount of fuel required for one day's operation.*

Assume that energy released per fission of U^{235} nuclide = 200 MeV.

Solution. Average electrical power required by a city = 200 MW = 200×10^6 W

Efficiency of the nuclear reactor, $\eta = 20\%$.

Amount of fuel required for one day's operation :

Energy consumed by the city in one day

$= 200 \times 10^6 \times 24 \times 3600 = 1728 \times 10^{10}$ J

Since efficiency is 20%, energy required to be produced by the nuclear reactor is

$$= \frac{1728 \times 10^{10}}{0.2} = 864 \times 10^{11} \text{ J}$$

Energy released/atom

$$= 200 \times 1.6 \times 10^{-13} = 32 \times 10^{-12} \text{ J}$$

$\therefore$ Number of atoms to be fissioned

$$= \frac{864 \times 10^{11}}{32 \times 10^{-12}} = 27 \times 10^{23}$$

Now, 6.02×10^{26} atoms are contained in 235 kg of U^{235}, hence 27×10^{23} atoms are contained in a mass

$$m = \frac{235 \times 27 \times 10^{23}}{6.02 \times 10^{26}} = \mathbf{1.054\ kg.}\ \textbf{(Ans.)}$$

Example 7.6. *A city requires 1500 MWh of electric energy per day. It is to be supplied by a reactor which converts nuclear energy into electric energy with an efficiency of 20 per cent. If reactor used nuclear fuel of U^{235}, calculate the mass of U^{235} needed for one day's operation.*

Solution. Amount of electric energy required per day = 1500 MWh

Efficiency of the nuclear plant = 20%.

Mass of U^{235} needed :

$$\text{Nuclear energy input} = \frac{\text{Electrical output}}{\text{Efficiency}}$$

$$= \frac{1500}{0.2} = 7500 \text{ MWh}$$

Now, 1 kWh $= 36 \times 10^8$ J

$\therefore$ Nuclear energy input per day

$$= 7500 \times 36 \times 10^8 = 2.7 \times 10^{13} \text{ J}$$

Now, energy released per fission of U^{235} nuclide

$$= 200 \times 1.6 \times 10^{-13} \text{ J} = 3.2 \times 10^{-11} \text{ J}$$

$\therefore$ Number of U^{235} nuclides required per day

$$= \frac{2.7 \times 10^{13}}{3.2 \times 10^{-11}} = 0.844 \times 10^{24}$$

Since, 235 kg of U^{235} contains 6.02×10^{26} number of atoms, the mass of U^{235} required for 0.844×10^{24} atoms is

$$= \frac{235 \times 0.844 \times 10^{24}}{6.02 \times 10^{26}} = 0.329 \text{ kg}$$

Hence mass of U^{235} needed for one day's operation **= 0.329 kg.** **(Ans.)**

Example 7.7. *The motors of an atomic ice-breaker deliver 30000 kW. Calculate the fuel consumption of reactor per day if its efficiency is 22%. Average fission energy release of U^{235} nuclide is 200 MeV.*

What would be the daily amount of 29300 kJ/kg coal needed to obtain the same power if the efficiency now is 78%.

Solution. Electric power delivered by atomic ice-breaker = 30000 kW

Efficiency of the nuclear reactor = 22%

Average fission energy release of U^{235} = 200 MeV.

Calorific value of coal = 29300 kJ/kg

Efficiency = 78%

(*i*) Fuel consumption of the reactor :

Power output $= 30000 \times 1000 = 3 \times 10^7$ W or J/s

Daily output $= 3 \times 10^7 \times 24 \times 3600$

$= 25.92 \times 10^{11}$ J

Since efficiency is = 22%, the daily energy input

$$= \frac{25.92 \times 10^{11}}{0.22} = 11.78 \times 10^{12} \text{ J}$$

Now, as seen from Ex. 7.1, 1 kg of U^{235} provides 8.2×10^{13} J of energy,

$$\therefore \quad \textit{Daily fuel consumption} = \frac{11.78 \times 10^{12}}{8.2 \times 10^{13}}$$

$$= \mathbf{0.1436\ kg.}\ \textbf{(Ans.)}$$

(*ii*) Coal required per day :

With an efficiency of 78%, daily energy input is

$$= \frac{25.92 \times 10^{11}}{0.78} = 33.23 \times 10^{11} \text{ J or } 33.23 \times 10^8 \text{ kJ}$$

$$\therefore \quad \textit{Coal required per day} = \frac{33.23 \times 10^8}{29300 \times 1000}$$

$$= \mathbf{113.4\ tonnes.}\ \textbf{(Ans.)}$$

Example 7.8. *What is the energy equivalence of 1 atomic mass unit ?*

Solution. 1 atomic mass unit (a.m.u.) $= 1.66 \times 10^{-24}$ g

Using Einstein's equation

$$E = mC^2$$

where, E = energy ; m = mass ; C = velocity of light ($= 3 \times 10^8$ m/s)

Substituting the values, we get:

$$E = (1.66 \times 10^{-24}) \times (3 \times 10^8 \times 10^2)^2$$

$$= 1.494 \times 10^{-3} \text{ ergs}$$

Now, 1 erg $= 0.625 \times 10^6$ MeV

$\therefore$ $E = 1.494 \times 10^{-3} \times 0.625 \times 10^6 = 933.75$ MeV

Hence energy equivalence of 1 a.m.u.

$$= \mathbf{933.75\ MeV.}\ \textbf{(Ans.)}$$

Example 7.9. *Calculate the total binding energy and the binding energy per nucleon for the $_8O^{16}$ isotope.*

Solution. The atomic weight of $_8O^{16}$, by definition, is 16.000 a.m.u.

The predicted mass of $_8O^{16}$ is given as under :

Mass of 8 protons $= 1.00759 \times 8 = 8.06072$ a.m.u.

Mass of 8 neutrons $= 1.00898 \times 8 = 8.07184$ a.m.u.

Mass of 8 electrons $= 0.00055 \times 8 = 0.00440$ a.m.u.

Total $= 16.13696$ a.m.u.

Isotopic mass $= 16.00000$ a.m.u.

$\therefore$ Mass defect $= 16.13696 - 16.00000$

$= 0.13696$ a.m.u.

But energy equivalent of 1 a.m.u. = 933.75 MeV

$\therefore$ *Total binding energy* $= 933.75 \times 0.13696$

$$= \mathbf{127.88\ MeV.}\ \textbf{(Ans.)}$$

Binding energy per nucleon

$$= \frac{127.88}{16} = \textbf{7.99 MeV.} \quad \textbf{(Ans.)}$$

Example 7.10. *The half-life of Radon gas is 3.83 days. What is its radioactive decay constant ?*

What percentage of the radon atoms originally present will decay in a period of 45 days.

Solution. Let $t_{1/2}$ = Half-life of radioactive nuclei,

N = Number of radioactive nuclei present at any time t,

N_0 = Initial number of such nuclei, and

λ = Proportionality constant (also known as *radioactive decay constant*).

From eqn. (7.7), the half-life is given as

$$t_{1/2} = \frac{0.693}{\lambda}$$

But $t_{1/2} = 3.83$ days ...(given)

$\therefore$ Radioactive decay constant,

$$\lambda = \frac{0.693}{3.83} = 0.181 \text{ day}^{-1}$$

From eqn. (7.4),

$$N = N_0 e^{-\lambda t}$$

Here $t = 45$ days

$\therefore$ $N = N_0 \times e^{-(0.181 \times 45)} = 0.00029\ N_0$

%age of radon atoms those will decay in a period of 45 days

$$= \frac{N_0 - N}{N_0} \times 100 = \frac{N_0 - 0.00029\ N_0}{N_0} \times 100$$

$= \textbf{99.971\%.}$ **(Ans.)**

Example 7.11. *A U^{235} nucleus is bombarded by a neutron, resulting in its fission into Barium 137 and Krypton 97 nuclei. Write the complete nuclear equation and find the amount of energy liberated in the reaction.*

Solution. The nuclear reaction can be written as :

$$_{92}U^{235} + {}_0n^1 \longrightarrow {}_{56}Ba^{137} + {}_{36}Kr^{97} + x$$

In a nuclear reaction, since the atomic numbers and mass numbers must balance on both sides of the equation therefore, the above equation is balanced with the addition of a particle or particles having combined Z = 0 and A = 2 to the products. Thus

$$x = 2\,{}_0n^1$$

$\therefore$ The complete nuclear equation becomes as :

$$_{92}U^{235} + {}_0n^1 = {}_{56}Ba^{137} + {}_{36}Kr^{97} + 2\ {}_0n^1$$

Mass before the reaction

= Mass of $_{92}U^{235}$ + mass of $_0n^1$

= 235.116 + 1.00898 = 236.125 a.m.u.

Mass after the reaction = Mass of Ba^{137} + mass of Kr^{97} + mass of two $_0n^1$

= 136.9514 + 96.9520 + 2 × 1.00898

= 235.9214 a.m.u.

Thus, *there is decrease in the mass after the reaction, so energy will be liberated.*

The mass defect = 236.125 – 235.9214

= 0.2036 a.m.u.

$\therefore$ *Energy released* = 0.2036 × 933.75

$= \textbf{190.11 MeV.}$ **(Ans.)**

HIGHLIGHTS

1. Those pairs of atoms which have the same atomic number and hence similar chemical properties but different atomic mass number are called isotopes.
2. Those atoms which have the same mass number but different atomic numbers are called *isobars*. Obviously, these atoms belong to different chemical elements.
3. Those pairs of atoms (nuclides) which have the same atomic number and atomic mass number but have different *radioactive properties* are called isomers and their existence is referred to as nuclear isomerism.
4. Those atoms whose nuclei have the same number of neutrons are called isotones.
5. The phenomenon of spontaneous emission of powerful radiations exhibited by heavy elements is called radioactivity. The radioactivity may be natural or artificial.
6. The five types of nuclear radiations are :
   (*i*) Gamma rays (or photons) : electromagnetic radiation.
   (*ii*) Neutrons : uncharged particles, mass approximately 1.
   (*iii*) Protons : + 1 charged particles, mass approximately 1.
   (*iv*) Alpha particles : helium nuclei, charge + 2, mass 4.
   (*v*) Beta particles : electrons (charge – 1), positrons (charge + 1), mass very small.
7. *Half life* represents the rate of decay of the radioactive isotopes. The half life is the time required for half of the parent nuclei to decay or to disintegrate.
8. *Nuclear cross-sections* (or attenuation co-efficients) are measures of the probability that a given reaction will take place between a nucleus or nuclei and incident rediation.
9. It has been found that some materials are not fissionable by themselves but they can be converted to the fissionable materials, these are known as *fertile materials*.
10. Fission is the process that occurs when a neutron collides with the nucleus of certain of the heavy atoms, causing the original nucleus to split into two or more unequal fragments which carry off most of the energy of fission as kinetic energy. This process is accompanied by the emission of neutrons and gamma rays.

11. A *chain reaction* is that process in which the number of neutrons keeps on multiplying rapidly (in geometrical progression) during fission till whole the fissionable material is disintegrated. The multiplication or reproduction factor (K) is given by :

$$K = \frac{\text{No. of neutrons in any particular generation}}{\text{No. of neutrons in the preceding generation}}$$

If $K > 1$, chain reaction will continue and if $K < 1$, chain reaction cannot be maintained.

12. *Nuclear fusion* is the process of combining or fusing two lighter nuclei into a stable and heavier nuclide. In this case large amount of energy is released because mass of the product nucleus is less than the masses of the two nuclei which are fused.

13. A *nuclear reactor* is an apparatus in which nuclear fission is produced is the form of a controlled self-sustaining chain reaction.

14. Essential components of a nuclear reactor are :
(*i*) Reactor core (*ii*) Reflector
(*iii*) Control mechanism (*iv*) Moderator
(*v*) Coolants (*vi*) Measuring instruments
(*vii*) Shielding.

15. The main components of a nuclear power plant are :
(*i*) Nuclear reactor
(*ii*) Heat exchanger (steam generator)
(*iii*) Steam turbine
(*iv*) Condenser
(*v*) Electric generator.

16. Some important reactors are :
(*i*) Pressurised water reactor (PWR)
(*ii*) Boiling water reactor (BWR)
(*iii*) Gas cooled reactor
(*iv*) Liquid metal cooled reactor
(*v*) Breeder reactor.

17. Following factors should be considered while selecting the site for a nuclear power plant :
(*i*) Proximity to load centre
(*ii*) Population distribution
(*iii*) Land use (*iv*) Meteorology
(*v*) Geology (*vi*) Seismology
(*vii*) Hydrology.

18. Typically, all costs of nuclear power plants are broken down into the following categories :
(*i*) Capital costs (total) (*ii*) Fuel costs (per year)
(*iii*) Other operating and maintenance cost (per year).

THEORETICAL QUESTIONS

1. Explain the following terms :
(*i*) Atomic model (*ii*) Atomic mass unit
(*iii*) Isotopes (*iv*) Isobars
(*v*) Isomers (*vi*) Isotones.
2. What do you mean by the term 'Radioactivity' ?
3. What is the difference between 'Artificial radioactivity' and 'Natural radioactivity' ?
4. Name five types of radiation of interest, in nuclear power technology.
5. Explain briefly the following :
(*i*) Prompt-fission gamma rays
(*ii*) Fission-product-decay gamma rays
(*iii*) Capture gamma rays
(*iv*) Activation gamma rays
(*v*) Inelastic scattering gamma rays.
6. Explain briefly the following types of neutrons :
(*i*) Prompt-fission neutrons
(*ii*) Delayed neutrons
(*iii*) Photoneutrons
(*iv*) Activation neutrons
(*v*) Reaction neutrons.
7. What do you mean by 'Binding Energy' ? What are the total binding energy and binding energy per nucleon for the ${}_6C^{12}$ nucleus ?
8. Explain briefly the following terms relating radioactive decay :
(*i*) Activity (*ii*) Half life
(*iii*) Average (mean) life.
9. What do you mean by the following :
(*i*) Elastic scattering (*ii*) Inelastic scattering
(*iii*) Capture (*iv*) Fission.
10. Write a short note on 'Fertile materials'.
11. What do you mean by 'Fission of nuclear fuel' ?
12. What is a chain reaction ?
13. What are the requirement of fission process?
14. How are the following defined ?
(*i*) Critical mass (*ii*) Critical size.
15. What is 'nuclear fusion' ? How does it differ from '*nuclear fission*' ?
16. What is a nuclear reactor ?
17. How are nuclear reactors classified ?
18. Enumerate and explain essential components of a nuclear reactor.
19. Explain with help of neat diagram the construction and working of a nuclear power plant.
20. What is a moderator ? Name common moderators and discuss their advantages and limitations.
21. Give the functions and materials for the following :
(*i*) Reflector (*ii*) Control rods
(*iii*) Biological shield.
22. Describe with the help of a neat sketch the construction working of a Pressurised Water Reactor (PWR). What are its advantages and disadvantages ?
23. What is 'Boiling Water Reactor' (BWR) ? How does it differ from 'Pressurised Water Reactor' (PWR) ?
24. Give the construction and working of a 'Gas cooled reactor'. What are its advantages and disadvantages ?
25. What is a 'Liquid Metal cooled Reactor' ? Explain briefly a typical liquid metal reactor.
26. Describe a breeder reactor. What are its advantages and disadvantages ?
27. What factors must be considered while selecting materials for the various reactor components ?

28. List the advantages and disadvantages/limitations of nuclear power plants.
29. Discuss the various factors which must be considered while selecting a site for a nuclear power plant.
30. Give the application of nuclear power plants.
31. What do you mean by 'Economics of nuclear power plants' ?
32. List down some safety measures for nuclear power plants.
33. What is the future of nuclear power ?

UNSOLVED EXAMPLES

1. A nuclear reactor is developing a power of 3 MW. How many atoms of U^{235} undergo fission per second ? How many kg of U^{235} would be used in 1000 hours of operation assuming that on an average 200 MeV is released per fission. [**Ans.** 9.3×10^6 ; 0.132 kg]
2. A city requires 100 MW of electric power on an average. If this is to be supplied by a nuclear reactor of efficiency 20 per cent, using U^{235} as the nuclear fuel, calculate the amount of fuel required for one day's operation. Given that energy released per fission of U^{235} nuclide = 200 MeV. [**Ans.** 0.53 kg]
3. Mumbai requires 3000 MWh of electric energy per day. It is to be supplied by a reactor which converts nuclear energy into electric energy with an efficiency of 20 per cent. If reactor uses nuclear fuel of U^{235}, calculate the mass of U^{235} needed for one day's operation. [**Ans.** 0.66 kg]
4. The motors of an atomic ice breaker deliver 32824 kW. Calculate the fuel consumption of reactor per day if its efficiency is 20 per cent. Average fission energy release of U^{235} nuclide is 200 MeV. What would be the daily amount of 7000 kcal/kg coal needed to obtain the same power if the efficiency now is 80%. [**Ans.** 0.173 kg ; 12100 tonnes]

COMPETITIVE EXAMINATIONS QUESTIONS

1. (*a*) With the help of a sketch show all the important parts of a nuclear reactor, describing briefly the functions of each part.
   Under what circumstances would a nuclear power station be recommended for installation ?
   (*b*) Give a brief comparison, between a nuclear and a conventional thermal power station, in respect of (*i*) capital cost, (*ii*) fuel cost, and (*iii*) operating and overhead cost, as a percentage of the total cost given by the sum of (*i*), (*ii*), and (*iii*).
2. (*a*) What are the principal parts of a nuclear reactor ? Explain each part in brief.
   (*b*) Why are nuclear power stations not so popular and successful in this country ?
3. (*a*) "The source of future power generation will be only nuclear fuel". Write your comments.
   (*b*) Explain the working of a reactor in a nuclear power station.
4. (*a*) Why is shielding of a reactor necessary ? What do you understand by thermal shielding ?
   (*b*) Explain the working of a reactor in a nuclear power station.
5. (*a*) Explain the generation of nuclear energy in a nuclear power plant.
   (*b*) Describe a boiling water reactor with diagram.
6. (*a*) What are the principal parts of a nuclear reactor ? Explain each part in brief.
   (*b*) Explain the working of a steam surface condenser.
7. (*a*) What do you understand by the following terms :
   (*i*) binding energy, (*ii*) half life,
   (*iii*) isotope, and (*iv*) moderator.
   (*b*) Discuss the boiling water reactor with the help of a neat sketch and write down its chief characteristics.
8. (*a*) How are nuclear power plants classified ? Explain how fission reaction takes place and how the chain reaction is controlled.
   (*b*) Discuss briefly boiling water reactor plant.
9. (*a*) Describe in brief giving neat sketch, the working of a pressurised water reactor plant.
   (*b*) Draw a line diagram of a diesel power plant and describe briefly the cooling system and the lubrication system.
10. (*a*) What is a moderator in nuclear reactor ? Explain the desirable properties of good moderator.
    (*b*) Draw a neat diagram of CANDU type reactor and explain its working principle and give its advantages over the other types.
11. (*a*) Draw a neat diagram of nuclear reactor and explain the functions of different components.
    (*b*) Explain the working principle of a closed cycle gas turbine plant.
12. (*a*) Draw a neat diagram of nuclear reactor and explain the functions of different components.
    (*b*) Explain the working principle of a closed cycle gas turbine plant.
13. (*a*) How are nuclear reactors classified ? Explain with neat sketch the working of a pressurised water reactor.
    (*b*) What different methods are used to thermal efficiency of the open cycle gas turbine plant ? Explain *any one* of them.
14. (*a*) Using neat sketches explain the construction and working of an air preheater.
    (*b*) Explain the layout of *any one* type of nuclear power plant system used in India.
    (*c*) Clearly bring out the differences in the constructional features of steam turbines of 500 MW rating used in conventional coal fired steam power plant and PWR plant.
15. (*a*) Explain the following terms with reference to a nuclear reactor :
    (*i*) Moderator (*ii*) Coolant
    (*iii*) Control rods (*iv*) Reflector.
    (*b*) Give the layout of a fast breeder reactor power plant and explain its salient features.
    (*c*) Give a brief account of nuclear waste disposal.

Combined Operation of Different Power Plants

8

8.1. General aspects. 8.2. Advantages of combined operation of plants. 8.3. Load division between power stations. 8.4. Hydro-electric (storage type) plant in combination with steam plant. 8.5. Run-of-river plant in combination with steam plant. 8.6. Pump storage plant in combination with steam or nuclear power plant. 8.7. Co-ordination of hydro-electric and gas turbine stations. 8.8. Co-ordination of different types of power plants—*Worked Examples—Theoretical Questions—Unsolved Examples.*

8.1. GENERAL ASPECTS

The leading aim of the national economy is to make available maximum amount of generating capacity with the available funds and ensure power generation at the cheapest rate possible. Since a large investment is required in power supply industry, therefore, once generating facilities are created it is desirable to utilise them in optimum manner. It is also of paramount importance that most economic generating scheme should be selected to supply power at lowest cost before huge amount of money is invested. When the generating facilities are established it is a wiser step to think of having integrated operation of neighbouring power systems so that maximum energy generation takes place from power stations like *thermal* and *nuclear* and maximum energy and capacity are utilised from the *hydro-electric* power stations. This is possible only if we have close combined operation of different power systems which if operated individually cannot be utilized to the maximum advantage. This leads to conclusion that if maximum benefit is to be yielded then power systems of different states should be interconnected. It is beyond doubt that the rapid pace of interconnection between the power systems can greatly improve the *continuity, security* and *integrity of power supply* provided it is associated with sound mechanism for monitoring and control.

8.2. ADVANTAGES OF COMBINED OPERATION OF PLANTS

If several power stations (such as hydro, thermal, nuclear etc.) work together to meet the demand of the consumers then the system is known as '*Interconnected system*'. Such a combined system claims the following **advantages** over a single power plant/station :

1. Greater reliability of supply to the consumers.
2. When one of the stations fails to operate the consumers can be fed from the other station, thus avoiding complete shut down.
3. The overall cost of energy per unit of an interconnected system is less.
4. There is a more effective use of transmission line facilities at higher voltage.
5. Less capital investment required.
6. Less expenses on supervision, operation and maintenance.
7. The interconnection of different power plants reduces the amount of generating capacity required to be installed as compared to that which would be required without inter-connection.
8. In an interconnected system the spinning reserve required is reduced.

8.3. LOAD DIVISION BETWEEN POWER STATIONS

Under the situation when the load curve has a very high peak value, it is usually supplied for two or more power stations/services by interconnection. In that case, total load as shown on load duration curve may be divided into following two parts :

(*i*) The base load (*ii*) The peak load.

Base load is supplied by one power station and the other power station takes care of the *peak load*. In such

cases the *load is economically apportioned to various systems in order to achieve the overall economy.*

In such cases it is not very necessary to interconnect the two systems of the *same type*. For example, if the base load is supplied by the steam power station, then it is not very necessary that the peak load may also be supplied by the steam power station. A hydro-electric power station can very well be adopted for supplying the peak load. Similarly, a hydro-electric station can be used for supplying the base load and in that case the peak load can be supplied by steam power station or a diesel engine station or any other suitable unit. However the selection of the power stations for supplying the base load or peak load is made on the basis of the requirements and ability of the various power stations/services to meet those requirements.

Requirements of a plant supplying the 'Base load' :

1. Minimum operation cost.
2. Continuous supply of the load.
3. Capital cost of the plant should be minimum.
4. Requirement of plant maintenance should be minimum.
5. Plant should be such that it can be easily located near the load centre.
6. The number of operators required should be minimum.
7. The spare parts etc. should be readily available.

Taking into view the above requirements, let us now consider various types of plants for their suitability to meet the base load.

Hydro-electric stations. (*i*) In these plants the *operating cost is minimum* as practically *no fuel* is required for the purpose of power generation, and as such there is no problem of procurement of the fuel.

(*ii*) *Maintenance cost is lower* than that of other plants.

(*iii*) *Initial cost of the plant is very high and sometimes prohibitive.*

(*iv*) These plants cannot be necessarily located near the load centre as the same can be located at the site suitable for it.

(*v*) In this case there is more or less dependence on availability of water, which in turn depends on the natural phenomenon of rain.

Steam power stations. (*i*) The capital investment in this case as compared to hydro-electric stations is less but with the modern trend of using higher pressures for the purpose, the cost of such stations has increased considerably. But this increased cost has resulted in lower operating costs so much so that even it may compete with that of hydro-electric power stations.

(*ii*) These plants can be easily located near the load centre, as such the cost of transmission lines and the losses occurring can be minimised which results in economical operation.

(*iii*) Maintenance requirement is slightly higher.

Diesel power stations. Due to limited generation capacity of diesel power station it is not much suitable as a base load plant.

Nuclear power station. (*i*) Initial cost is high although operating cost is comparable with that of steam power station.

(*ii*) Due to limited availability of the fuel these plants are not much favoured.

(*iii*) Whenever these plants are constructed they are invariably used as *base load* as otherwise also such plants suit to constant load conditions as economy in operation is such plants can be achieved only, when these are used as base load plants.

Requirements of a plant supplying the 'Peak load' :

1. Low operating cost.
2. Minimum capital cost.
3. The plant should be capable of being started from cold conditions within minimum time.
4. In case of emergency the plant should have the capacity to withstand the peak load for sometime.
5. It must have quick response to the change in load.

In view of the above requirements let us consider various plants for their suitability to meet the peak load.

Hydro-electric stations. A hydro-electric station *can* be considered for this purpose :

(*i*) It can be easily started from cold conditions as no warming up period is required.

(*ii*) High initial cost is the major disadvantage.

(*iii*) However, in this case, there is no requirement of fuel, so whenever the output of hydro-electric station is to be utilised, it can be used as a *peak station also.*

(*iv*) Particularly in case where the quantity of water available for the purpose of power generation is limited, such stations are used for meeting the peak load in case of a interconnected system.

Nuclear power stations. They do not find their use as peak load plants.

Diesel power stations. (*i*) These plants *can be used for meeting peak load* as they can be easily started from cold conditions and the initial cost in this case is also not high.

(*ii*) In this case the additional advantage is that the number of auxiliaries required is also limited as a result of which the maintenance work required is also less.

(*iii*) These plants have got good overload capacity (minimum being 10 per cent as per Indian Standard Specifications).

(*iv*) Thermal efficiency of diesel engines being high, the operating cost is also less as compared to that of a steam power station of equivalent capacity.

Analysis of Load Sharing between Base Load and Peak Load Stations :

The suitability of a plant not only depends on the above mentioned factor but also on local conditions for a particular application. However, if the combination of two plants/services is to be used, in that case the next problem is division of load between the plants. It is not desirable to transfer all the loads to one plant and also depending upon the operating characteristics of the various plants the load between the plants should be so decided that overall economy is achieved. This load division can be easily manipulated by viewing the load duration curve of the plants as follows :

Fig. 8.1 shows a load duration curve.

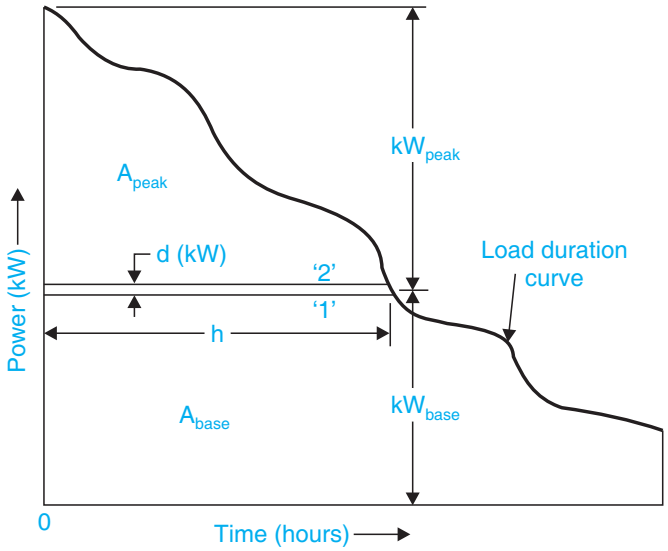


Fig. 8.1. Load duration curve of the plants.

Let A_{peak} = Area of curve for *peak load* plant,
A_{base} = Area of curve for *base load* plant,
kW_{peak} = Load for peak load plant,
kW_{base} = Load for base load plant,
C = Total operating cost of the combination, and
h = Hours per year.

Let the *base load* be supplied by a plant having the annual cost equation as

$$(₹)_1 = a_1 + b_1 \text{ kW} + c_1 \text{ kWh} \qquad ...(8.1)$$

For the plant supplying the *peak load* let the equation be

$$(₹)_2 = a_2 + b_2 \text{ kW} + c_2 \text{ kWh} \qquad ...(8.2)$$

Since the base load plant is operated most of the time, therefore, normally a plant having $c_1 < c_2$ is used for meeting the base load.

Let $b_1 > b_2$.

Let the load between the two plants (Fig. 8.1) be divided by arbitrary line drawn on the load duration curve represented by '1'. Under these conditions let kW_{base} be the kW for base load plant and let kW_{peak} be the load for peak load plant.

In this case the total operating cost of the combination is given as :

$$C_1 = a_1 + a_2 + b_1 \text{ kW}_{base} + b_2 \text{ kW}_{peak} + c_1 A_{base} + c_2 A_{peak} \qquad ...(8.3)$$

Now, if the base power is extended by the amount of d (kW) to line '2', the total operating cost of the combination will modify as follows :

$$C_2 = a_1 + a_2 + b_1 (\text{kW}_{base} + d \text{ kW}) + b_2 (\text{kW}_{peak} - d \text{ kW}) + (A_{base} + d \text{ kW} \times h) c_1 + (A_{peak} - d \text{ kW} \times h) c_2 \qquad ...(8.4)$$

The change in cost,

$$C_2 - C_1 = (b_1 - b_2) d \text{ kW} + (c_1 - c_2) d \text{ kW} \times h \qquad ...(8.5)$$

The optimum condition requirements are that above change must be zero, *i.e.*,

$$h = \frac{b_1 - b_2}{c_2 - c_1} \qquad ...(8.6)$$

Thus it is possible to divide the load between the plants due to which overall economy in operation is effected.

The method described above for distributing the load among the two power plants in an interconnected system can be used for any type of plants as (*i*) Thermal and diesel, (*ii*) Thermal and hydro, (*iii*) Nuclear and hydro and so on.

8.4. HYDRO-ELECTRIC (STORAGE TYPE) PLANT IN COMBINATION WITH STEAM PLANT

Hydro-plants can take up the load quickly and follow the peak variation much better than thermal plants. There is a great reliability in hydro-plants and it is still more in a combined system. In a combined system of hydro and thermal, water storage increases the application of more hydro-power in normal or heavy run-off years, while steam plant can help during the time of drought. *When the run-off is sufficient* (particularly in monsoon) the *hydro-plant is used as base load and thermal plant works as peak load plant. Thermal plant is used as base load plant during the drought period and hydro-plant works as peak load plant.* Fig. 8.2 (*a*), (*b*) shows their uses as base load or as peak load plant.

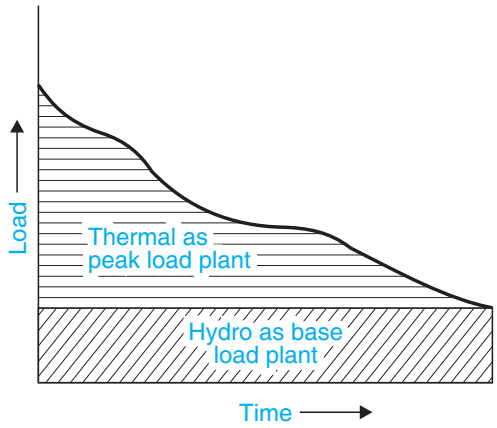


Fig. 8.2 (*a*). Hydro-plant used as base load plant during normal run-off in an interconnected system.

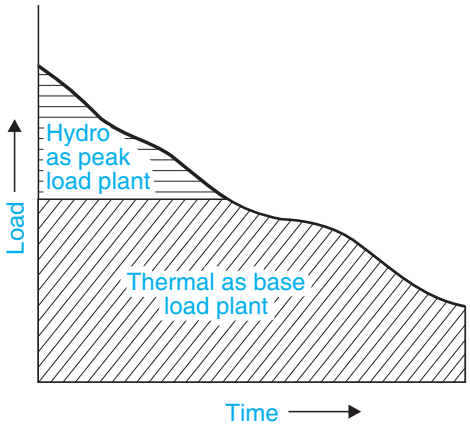


Fig. 8.2 (*b*). Hydro-plant used as peak load during drought period in an interconnected system.

Thermal plants can be used at any portion of the load duration curve but it is more expensive to use peak load station at low load factors.

Following cases will be discussed :

1. Predominant hydro.
2. Predominant thermal.
3. Hydro and thermal equally predominant.

Predominant Hydro :

Some of the hydro-plants, such as run-off river plants, are used as base load plants whereas some others are used as peak load plants. *When the hydro-plants carry the major demand throughout the year then the thermal plants are used in a combined system to improve the hydro-power efficiency during the periods when there is low run-off.*

Predominant Thermal :

To develop hydro-plants to operate even at comparatively low annual load factors is always advantageous. This is due to the fact the cost of storage water forms a major portion of the capital investment which is independent of annual load factor and capital cost is less for low than for a high load factor. Thus, *in a predominantly thermal station,* it is *preferable to develop hydro-power at the lowest practical load factor.*

Hydro and Thermal Equally Predominant :

The economic balance between hydro and thermal power in an interconnected system at any time depends upon the *nature of load curve, run-off and its seasonal variation, cost of fuel, availability of condensing water* etc. There is an optimum ratio of hydro-power to total peak demand which gives minimum cost for power supply. This is particularly true for the areas where the cost of hydro-power development is high and fuel cost is low. In areas where fuel is cheap and cost of hydro-power development is not high, the economic power ratio lies between 0.25 to 0.4. In areas where fuel is costly and favourable hydro-power plant sites are abundant the ratio will be higher to the tune of 0.8–0.9.

The combined system of hydro and thermal plants is being adopted all the world over, and is particularly useful to developing countries like India where economy is desirable at every stage of development.

8.5. RUN-OF-RIVER PLANT IN COMBINATION WITH STEAM PLANT

Since during the year the supply of water is not regular in *run-of-river plants*, therefore,these plants cannot meet with variable load requirements. Further as the variation of run-off during the year does not match the variation of power demand during the year, therefore, it becomes necessary to combine such a hydro-plant with steam plant to supply the load according to requirement with maximum reliability. *The run-of-river plant can be used as base load plant during rainy season and thermal plant takes up peak load. During dry season ; the thermal stations can be used as base load plant and run-of-river plant may work as peak load plant.*

8.6. PUMP STORAGE PLANT IN COMBINATION WITH STEAM OR NUCLEAR POWER PLANT

Whenever old and inefficient thermal stations are available they are generally used to take up peak loads. If suitable plants are not available to take load it is desirable to develop pumped storage plant for the purpose. In an interconnected system a pumped storage plant is useful in supplying sudden peak loads of short duration (a few hours in the year). Such a plant (pumped storage) possesses the following advantages when used in interconnected system :

(*i*) Thermal plants are loaded more economically.

(*ii*) The wastage of off-peak energy of thermal plants is reduced.

(*iii*) A pumped storage plant stores the energy using off-peak energy of thermal plant and the same is supplied when demand arises.

A combined system of a pumped storage plant and nuclear power plant is proposed at Ramganga power station in Uttar Pradesh. A parallel development of nuclear power station (400 MW capacity) near the hydro-site could provide cheap pumping energy to pump storage plant during off peak hours. This arrangement will enable the nuclear station to operate at high capacity factor and thereby make it competitive as compared to the conventional thermal station in that region where the coal prices are relatively high.

8.7. CO-ORDINATION OF HYDRO-ELECTRIC AND GAS TURBINE STATIONS

The working of gas turbine plants at peak load points is most economical under the following conditions :

(*i*) When the amount of energy supplied at peak load is small part of the total energy.

(*ii*) The load factor is less than 15%.

The following points are worth noting :

— The normal capacity of the gas turbine varies from 10 MW to 25 MW.

— The capital cost of a gas turbine plant is quite less (₹ 1000 to 1200/kW) compared with steam plant (₹ 1600 to 2000/kW).

— The thermal efficiency of gas turbine plant (25 per cent) is less than that of a steam plant (32 per cent).

— The high working cost of a gas turbine is compensated by *lower fixed charges and lower operating and maintenance charges*.

When used as a peak load plant, the gas turbine plant claims the following advantages over steam plant :

1. A gas turbine plant occupies less space comparatively.
2. Heavy foundations are not required.
3. The construction and installation can be carried out in a smaller period.
4. The cooling water requirement is much less comparatively.
5. Less number of operators are required.
6. The response of gas turbine plant is quick.

8.8. CO-ORDINATION OF DIFFERENT TYPES OF POWER PLANTS

In a particular region if different types of power plants are available it becomes necessary to co-ordinate them and use them with maximum economy. The problem of co-ordination of different types of power plants (*e.g.* hydro, thermal, nuclear, gas turbine and diesel plants) for best possible working and economy is very complicated as the *factors* to be considered for economical co-ordination are large in number ; some of these factors are listed below :

(*i*) Initial capital cost

(*ii*) Fuel cost

(*iii*) Operation and maintenance cost

(*iv*) Availability of fuel

(*v*) The economics of base load and peak load operation

(*vi*) The working characteristics of the plants

(*vii*) The transmission liability

(*viii*) The cost of incremental power.

The best co-ordination, several times, depends on the *nature of load duration curve* and availability of fuels and resources in the country.

Fig. 8.3 shows an annual load curve showing loads allocated to different plants.

The local conditions may change the sequence depending upon the availability of fuels and resources.

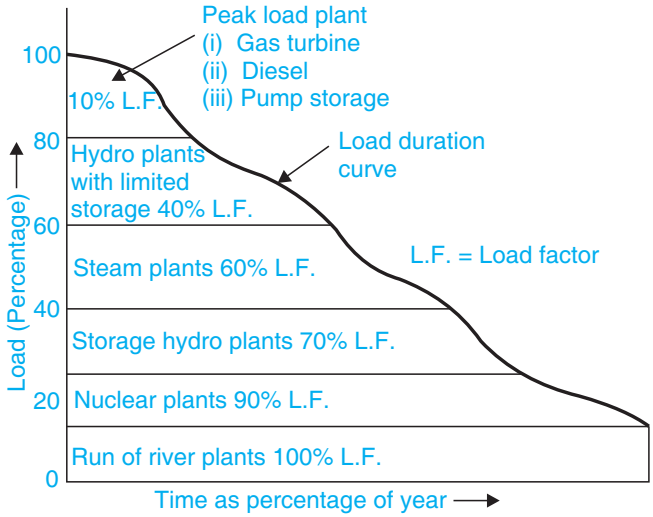


Fig. 8.3. Annual load duration curve showing loads allocated to different plants.

WORKED EXAMPLES

Example 8.1. *The estimated total annual operating costs and capital charges for two proposed power stations are given by the following expressions :*

Annual cost for station A

$= ₹(6,00,000 + 3.0\ kW + 0.015\ kWh)$

Annual cost for station B

$= ₹(7,50,000 + 5.0\ kW + 0.014\ kWh)$

where kW represents the capacity of the station and kWh represents the total annual output.

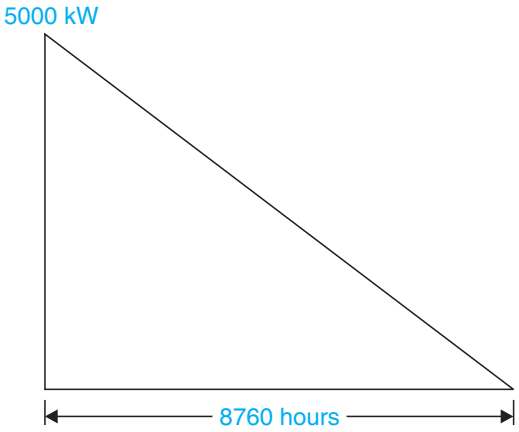


Fig. 8.4

The stations are to be used for supplying a load having a load duration curve as shown in Fig. 8.4. The ordinate of a point on this curve represents a certain load on the station and the abscissa represents the number of hours per year during which the load is equal to or exceeds this amount.

Which station should be used to supply the base load, what should be its installed capacity and for how many hours in a year should it be in operation to give the minimum total cost per unit generated ?

Calculate the total cost per unit generated under these conditions.

Solution. Let us consider the cost equations of the two stations. *Since the operating cost of station B is less than that of A, so station B may be selected for supplying the base load.*

Hours (h) for which the base load point is to be operated can be calculated as follows :

$$h = \frac{5-3}{0.015-0.014} = \frac{2}{0.001} = 2000 \text{ hours.}$$

Hence the base load point is to be operated for 2000 hours and the peak load point plant for the remaining period. From the load duration curve, the capacity of the base load plant can be computed as follows.

Refer to Fig. 8.5.

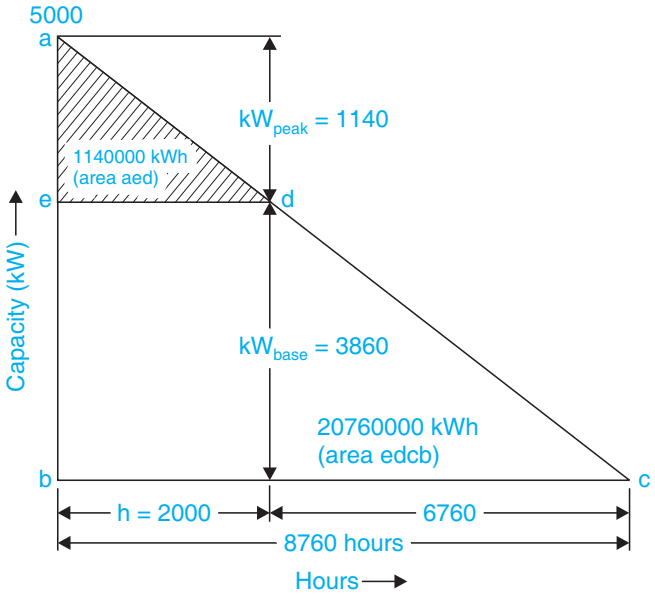


Fig. 8.5

$$\frac{kW_{base}}{6760} = \frac{5000}{8760}$$

$$\therefore \quad kW_{base} = \frac{5000 \times 6760}{8760} \simeq 3860 \text{ kW}$$

$$\therefore \quad kW_{peak} = 5000 - 3860 = 1140 \text{ kW}$$

Cost of generation

Total kWh supplied by peak load plant

$$= \frac{1140 \times 2000}{2} = 1140000 \text{ kWh}$$

Total kWh supplied by base load plant

$$= \frac{5000 \times 8760}{2} - 1140000$$

$$= 20760000 \text{ kWh}$$

Cost of generation per annum for *base load plant*

$= ₹(750000 + 5 \times 3860 + 0.014 \times 20760000)$

$= ₹(750000 + 19300 + 290640)$

$= ₹\ 1059940.$

Cost of generation per annum for *peak load plant*

$= ₹(600000 + 3 \times 1140 + 0.015 \times 1140000)$

$= ₹(600000 + 3420 + 17100) = ₹\ 620520$

Total cost $= 1059940 + 620520 = 1680460$

$$\textit{Cost of generation per unit} = \frac{\text{Total cost}}{\text{Total kWh supplied}}$$

$$= \frac{1680460}{\left(\frac{5000 \times 8760}{2}\right)} = \frac{1680460}{21900000}$$

= ₹ 0.0767 or 7.67 p. **(Ans.)**

Example 8.2. *In a system the load duration curve is a straight line, the maximum and minimum loads being 120 MW and 24 MW respectively. The costs of the base load and peak load plants, which supply the load, are given below :*

Base load plant : ₹ 240 / kW-year + 6 p / kWh

Peak load plant : ₹ 60 / kW-year + 12 p / kWh

Determine, for minimum overall cost of the following :

(i) The load shared by peak load plant.

(ii) The annual load factors for both stations.

Solution. (i) Load shared by peak load plant :

Let, C_{base} = Operating cost of base load plant,

C_{peak} = Operation cost of peak load plant,

P_{base} = Load (peak) on the base load plant,

and P_{peak} = Load (peak) on the peak load plant.

The operating costs of base load and peak load plants may be expressed as follows :

$$C_{base} = A_1 \text{ kW} + B_1 \text{ kWh}$$
$$C_{peak} = A_2 \text{ kW} + B_2 \text{ kWh}$$

From the given data :

$A_1 = 240$, $B_1 = 0.06$

$A_2 = 60$, $B_2 = 0.12$

The time, h hours, for which base load to be operated *for minimum overall cost* is given by :

$$h = \frac{A_1 - A_2}{B_2 - B_1} = \frac{240 - 60}{0.12 - 0.06} = 3000 \text{ hrs.}$$

Now, $P_{base} + P_{peak} = 120$

$\therefore$ $P_{peak} = 120 - P_{base}$

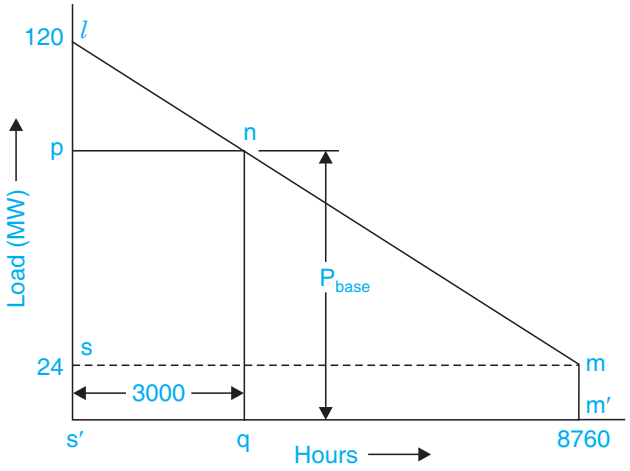


Fig. 8.6

Now, from Δs *lms* and *lnp*, we have

$$\frac{120 - P_{base}}{120 - 24} = \frac{3000}{8760}$$

$$P_{base} = 120 - (120 - 24) \times \frac{3000}{8760} = \mathbf{87\ MW.} \quad \textbf{(Ans.)}$$

$\therefore$ $P_{peak} = 120 - 87 = \mathbf{33\ MW.}$ **(Ans.)**

(ii) Annual load factors (L.F.) for both the stations :

L.F. (base load plant)

$$= \frac{\text{Average load}}{\text{Peak load}} \times \frac{8760}{8760} = \frac{\text{Area } 'pnmm's'p'}{P_{base} \times 8760}$$

$$= \frac{\text{Area } 'pnmsp' + \text{area } 'smm's's'}{P_{base} \times 8760}$$

$$= \frac{\frac{1}{2}(3000 + 8760) \times (87 - 24) + 24 \times 8760}{87 \times 8760}$$

$$= \frac{370440 + 210240}{762120} = 0.762 \text{ or } 76.2\%$$

i.e., Load factor for base load plant = **76.2%.** **(Ans.)**

$$\text{L.F. (peak load plant)} = \frac{\text{Area } 'lnpl'}{P_{peak} \times 8760}$$

$$= \frac{\frac{1}{2} \times 3000 \times 33}{33 \times 8760} = 0.171 \text{ or } 17.1\%$$

i.e., Load factor for peak load plant = **17.1%.** **(Ans.)**

Example 8.3. *The two power stations X and Y supply to a system whose maximum load is 120 MW and minimum load is 12 MW during the year. The estimated costs of these stations are as follows :*

$$C_X = ₹ (120 \times kW + 0.028 \times kWh)$$
$$C_Y = ₹ (115 \times kW + 0.032 \times kWh)$$

If the load varies as a straight line, find for minimum cost of generation :

(i) Installed capacity of each station.

(ii) The annual load factor, capacity factor and use factor of each machine.

(iii) The average cost of production per kWh for the entire system.

Assume reserve capacity of Y as 22%.

Solution. Given :

$$C_X = ₹ (120 \times \text{kW} + 0.028 \times \text{kWh})$$
$$C_Y = ₹ (115 \times \text{kW} + 0.032 \times \text{kWh})$$

i.e., $A_1 = 120$, $B_1 = 0.028$

and $A_2 = 115$, $B_2 = 0.032$

$$h = \frac{A_1 - A_2}{B_2 - B_1} = \frac{120 - 115}{0.032 - 0.028} = 1250 \text{ hours}$$

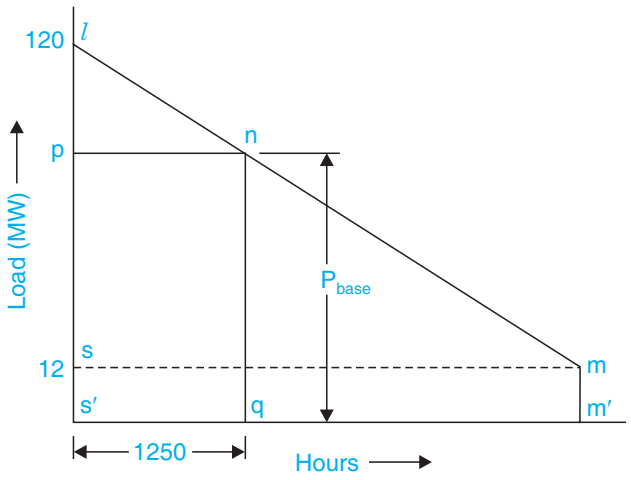


Fig. 8.7

From Δs *lms* and *lnp*, we have

$$\frac{120 - P_{base}}{120 - 12} = \frac{1250}{8760}$$

$$\therefore \quad P_{base} = 120 - (120 - 12) \times \frac{1250}{8760} \simeq 105 \text{ MW}$$

$$\therefore \quad P_{peak} = 120 - 105 = 15 \text{ MW}$$

(*i*) Installed capacity of each station :

Installed capacity of base load plant,

$$P_{base} = \mathbf{105 \text{ MW.}} \quad \textbf{(Ans.)}$$

Installed capacity of peak load plant = 15 × 1.22 = **18.3 MW.** **(Ans.)**

(*ii*) The annual load, capacity and use factors for each station :

For base load plant :

Load factor (L.F.)

$$= \frac{\text{Actual units generated}}{P_{base} \times 8760}$$

$$= \frac{\frac{1}{2}(1250 + 8760) \times (105 - 12) + 112 \times 8760}{105 \times 8760}$$

$$= \frac{465465 + 105120}{919800} = \mathbf{0.62 \text{ or } 62\%.} \quad \textbf{(Ans.)}$$

As there is no reserve capacity of plant *X*,

$\therefore$ *Capacity factor (C.F.)* = L.F. = **62%.** **(Ans.)**

$$\textit{Use factor (U.F.)} = \frac{\text{C.F.}}{\text{L.F.}} = \frac{0.62}{0.62} = \mathbf{1.} \quad \textbf{(Ans.)}$$

For peak load plant :

$$\text{L.F.} = \frac{\text{Actual units generated}}{P_{peak} \times 8760}$$

$$= \frac{\frac{1}{2} \times 1250 \times 15}{15 \times 8760} = \mathbf{0.071 \text{ or } 7.1\%.} \quad \textbf{(Ans.)}$$

$$\text{C.F.} = \frac{\text{Average load}}{\text{Actual plant capacity}} = \frac{\text{Actual units generated}}{18.3 \times 8760}$$

$$= \frac{\frac{1}{2} \times 1250 \times 15}{18.3 \times 8760} = \mathbf{0.058 \text{ or } 5.8\%.} \quad \textbf{(Ans.)}$$

$$\text{U.F.} = \frac{\text{C.F.}}{\text{L.F.}} = \frac{0.058}{0.071} = \mathbf{0.816 \text{ or } 81.6\%.} \quad \textbf{(Ans.)}$$

(*iii*) Average cost of production per kWh for the entire system :

For plant X (base) :

Total units generated

$$= \frac{1}{2}(1250 + 8760) \times (105 - 12) + 12 \times 8760$$

$$= 570585 \text{ MWh} = 570.585 \times 10^6 \text{ kWh}$$

$$\therefore C_X = ₹ (120 \times 105 \times 10^3 + 0.028 \times 570.585 \times 10^6)$$

$$= ₹ (12.6 \times 10^6 + 15.97 \times 10^6) = ₹ 28.57 \times 10^6$$

For plant Y (peak) :

Total units generated = $(\frac{1}{2} \times 1250 \times 15) = 9375$ MWh

$$= 9.375 \times 10^6 \text{ kWh}$$

$$\therefore \quad C_Y = ₹ (115 \times 15 \times 10^3 + 0.032 \times 9.375 \times 10^6)$$

$$= ₹ (1.725 \times 10^6 + 0.3 \times 10^6) = ₹ 2.025 \times 10^6$$

Total units generated from both the plants

$$= 570.585 \times 10^6 + 9.375 \times 10^6 \simeq 580 \times 10^6 \text{ kWh}$$

Total generation cost,

$$C = C_X + C_Y = 28.57 \times 10^6 + 2.025 \times 10^6$$

$$= ₹ 30.595 \times 10^6$$

$\therefore$ *Average cost*

$$= \frac{\text{Total generation cost}}{\text{Total units generated}} = \frac{30.595 \times 10^6}{580 \times 10^6}$$

$$= ₹ \mathbf{0.0527 \text{ or } 5.3 \text{ paise/kWh.}} \quad \textbf{(Ans.)}$$

Example 8.4. *In an industry the maximum and minimum demands are 60 MW and 12 MW respectively and the variation is linear. The hydro-power plant can take the load of 72 MWh per day of the factory at the time of minimum regulated flow and the remaining is supplied by the thermal plant. It is proposed to pump the water from tailrace of the existing plant to reservoir during off-peak period of thermal plant and allow the thermal plant to run always of full load condition to economise the supply of power.*

If the overall efficiency of conversion of steam off-peak power to hydel potential power and then hydel power to electric power is 62%, calculate the capacity of steam and hydel plants considering the pumping of water during off-peak period of steam plants.

Solution. Fig. 8.8 shows the load duration curve.

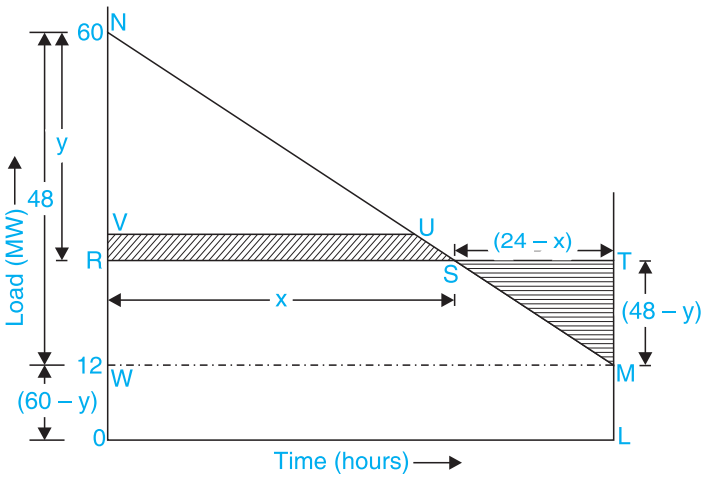


Fig. 8.8

Maximum supply = 60 MW

Let, y = The load taken by existing hydel plant and pump storage plant (in MW).

Then $(60 - y)$ = The power supplied by thermal plant (in MW).

The off-peak power of thermal plant represented by the area '*STMS*' can be used for pumping the water. The power supplied by the existing hydel plant will be given by the area '*NVUN*'.

Hydel potential in electrical form supplied by pump-storage plant must be equal to the area '*RSUVR*'.

$\therefore$ Area '*RSUVR*' = 0.62 × area '*STMS*' (data given)

$\therefore$ Area '*NSRN*' – area '*NUVN*'

= 0.62 × area '*STMS*'.

But area '*NUVN*' represents the energy supplied by the existing hydel plant which is given as 72 MWh.

Let x = Number of hours (out of 24 hours) for which the steam plant operates at full load condition.

Then $(24 - x)$ = Number of hours for which the steam plant works under off-peak conditions.

$$\therefore \quad \frac{1}{2} xy - 72 = \frac{1}{2} (24 - x)(48 - y) \times 0.62$$

or $$xy - 144 = (24 - x)(48 - y) \times 0.62 \quad ...(i)$$

Now, from Δs NRS and NWM, we can write

$$\frac{y}{48} = \frac{x}{24}$$

$$\therefore \quad y = 2x \quad ...(ii)$$

Substituting the value of 'y' in eqn. (i), we get:

$$2x^2 - 144 = (24 - x)(48 - 2x) \times 0.62$$

or $$2x^2 - 144 = (1152 - 48x - 48x + 2x^2) \times 0.62$$

or $$2x^2 - 144 = (1152 - 96x + 2x^2) \times 0.62$$

$$2x^2 - 144 = 714.24 - 59.52x + 1.24x^2$$

or $$0.76x^2 + 59.52x - 858.24 = 0$$

$$\therefore \quad x = \frac{-59.52 \pm \sqrt{(59.52)^2 + 4 \times 0.76 \times 858.24}}{2 \times 0.76}$$

$$= \frac{-59.52 \pm \sqrt{3542.63 + 2609}}{1.52} = \frac{-59.52 \pm 78.43}{2}$$

= 9.455 hours

i.e., x = 9.455 hours

$\therefore$ y (*total capacity of hydel-plant*)

= $2x$ = 2 × 9.455 = **18.91 MW.** **(Ans.)**

$\therefore$ *Steam plant capacity*

= $60 - y$ = 60 – 18.91 = **41.1 MW.** **(Ans.)**

THEORETICAL QUESTIONS

1. State the advantages of operating the power plants combinedly in electric power system.
2. Describe the working of hydro-electric plants having ample storage with steam power plants.
3. How would you make an economic analysis of the combined operation of the hydro and steam power plants ?
4. What are the advantages of pump storage plant as peak load plant in an interconnected system ?
5. State the advantages of gas turbine plant as peak load plant in an interconnected system.
6. Discuss the suitability of steam power plants to supply the load in case of an interconnected system.
7. List the factors which decide the distribution of plants for operation on different portions of the annual load duration curve of a power system.

UNSOLVED EXAMPLES

1. The two power stations I and II supply to a system whose maximum load is 120 MW and minimum load is 12 MW during the year. The estimated costs of these stations are as follows :

C_I = ₹ (125 × kW + 0.0275 × kWh)

C_{II} = ₹ (120 × kW + 0.03 × kWh)

If the load varies as a straight line, find for minimum cost of generation :

(i) Installed capacity of each station.

(ii) The annual load, capacity and capacity use factor of each station.

(*iii*) The average cost of production per kWh for entire system.

Assume reserve capacity of II as 20 per cent.

[**Ans.** (*i*) 80 MW, 24 MW; (*ii*) 65%, 65%, U.F. = 1 ; 11.5%, 9.5%, U.F. = 82.5%; (*iii*) 5.4 paise/kWh]

2. The annual load duration curve of a station varies uniformly from 64000 kW to zero. The load is supplied by two stations whose cost equations are given as :

C_1 = ₹ (84000 + 84 kW + 0.0116 kWh)

C_2 = ₹ (50000 + 44 kW + 0.02985 kWh)

Find the minimum cost of generation in paise/kWh for the system. [**Ans.** 3 paise/kWh (approx.)]

3. An annual load duration curve of a system of loads is a straight line with maximum of 12 MW at the beginning and 2 MW at the end of the year. Annual costs of base and peak load stations are given as :

C_1 = 8000 + ₹ 75/kW + 3 paise/kWh (base load)

C_2 = 6000 + ₹ 55/kW + 4 paise/kWh (peak load)

Determine the following :

(*i*) The duration of time when peak load station will work in order to obtain the minimum annual cost.

(*ii*) The lowest overall cost per kW (in paise).

[**Ans.** (*i*) 2000 hours; (*ii*) 4.66 paise/kWh]

4. In a system the load duration curve is a straight line with a maximum demand of 45 MW tapering to zero. The load is to be taken from two sources whose annual cost equations are : C_1 = ₹ (100×10^3 + 65.7 × kW + 0.012 × kWh) and C_2 = ₹ (60×10^3 + 36.5 × kW + 2.122 × kWh). Find the installed capacity and service hours for each station per year to give minimum cost per unit and cost per unit.

[**Ans.** 30 MW and 15 MW, 2920 hours and 58 hours, 2.72 paise/kWh]

Economics of Power Generation

9

9.1. Introduction. 9.2. Terms and definitions. 9.3. Principles of power plant design. 9.4. Location of power plant. 9.5. Layout of power plant building. 9.6. Cost analysis. 9.7. Selection of type of generation. 9.8. Selection of power plant equipment—Selection of boilers—Selection of prime movers—Selection of size and number of generating units. **9.9. Economics in plant selection. 9.10. Factors affecting economics of generation and distribution of power. 9.11. How to reduce power generation cost ? 9.12. Power plant—useful life. 9.13. Economics of hydro-electric power plants. 9.14. Economics of combined hydro and steam power plants. 9.15. Performance and operating characteristics of power plants. 9.16. Economic load sharing. 9.17. Tariff for electrical energy**—Introduction—Objectives and requirements of tariff—General tariff form—*Worked Examples—Highlights—Theoretical Questions— Unsolved Examples—Competitive Examinations Questions.*

9.1. INTRODUCTION

In all fields of industry economics plays an important role. In power plant engineering economics of power system use certain well established techniques for choosing the most suitable system. The power plant design must be made on the basis of most economical condition and not on the most efficient condition as the profit is the main basis in the design of the plant and its effectiveness is measured financially. *The main purpose of design and operation of the plant is to bring the cost of energy produced to minimum.* Among many factors, the efficiency of the plant is one of the factors that determines the energy cost. In majority of cases, unfortunately, the most thermally efficient plant is not economic one.

9.2. TERMS AND DEFINITIONS

1. Connected load. The connected load on any system, or part of a system, *is the combined continuous rating of all the receiving apparatus on consumers' premises, which is connected to the system, or part of the system, under consideration.*

2. Demand. The demand of an installation or system *is the load that is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time.* Demand is expressed in kilowatts (kW), kilovolt-amperes (kVA), amperes (A), or other suitable units.

3. Maximum demand or Peak load. The maximum demand of an installation or system *is the greatest of all the demands that have occurred during a given period.* It is determined by measurement, according to specifications, over a prescribed interval of time.

4. Demand factor. The demand factor of any system, or part of a system, is *the ratio of maximum demand of the system, a part of the system, to the total connected load of the system, or of the part of the system, under consideration.* Expressing the definition mathematically,

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}} . \qquad ...(9.1)$$

5. Load factor. The load factor is *the ratio of the average power to the maximum demand.* In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load factor. The proper interval and period are usually *dependent upon local conditions and upon the purpose for which the load factor is to be used.* Expressing the definition mathematically,

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} . \qquad ...(9.2)$$

6. Diversity factor. The diversity factor of any system, or part of a system, *is the ratio of the maximum power demands of the subdivisions of the system, or part of a system, to the maximum demand of the whole system, or part of the system, under consideration, measured at the point of supply*. Expressing the definition mathematically,

$$\text{Diversity factor} = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand of entire group}} . \qquad ...(9.3)$$

7. Utilization factor. The utilization factor is defined as *the ratio of the maximum generator demand to the generator capacity.*

8. Plant capacity factor. It is defined as the *ratio of actual energy produced in kilowatt hours (kWh) to the maximum possible energy that could have been produced during the same period.* Expressing the definition mathematically,

$$\text{Plant capacity factor} = \frac{E}{C \times t} \qquad ...(9.4)$$

where, E = Energy produced (kWh) in a given period,
C = Capacity of the plant in kW, and
t = Total number of hours in the given period.

9. Plant use factor. It is defined as *the ratio of energy produced in a given time to the maximum possible energy that could have been produced during the actual number of hours the plant was in operation.* Expressing the definition mathematically,

$$\text{Plant use factor} = \frac{E}{C \times t'} \qquad ...(9.5)$$

where t' = Actual number of hours the plant has been in operation.

10. Types of loads.

(*i*) ***Residential load.*** This type of load includes domestic lights, power needed for domestic appliances such as radios, television, water heaters, refrigerators, electric cookers and small motors for pumping water.

(*ii*) ***Commercial load.*** It includes lighting for shops, advertisements and electrical appliances used in shops and restaurants etc.

(*iii*) ***Industrial load.*** It consists of load demand of various industries.

(*iv*) ***Municipal load.*** It consists of street lighting, power required for water supply and drainage purposes.

(*v*) ***Irrigation load.*** This type of load includes electrical power needed for pumps driven by electric motors to supply water to fields.

(*vi*) ***Traction load.*** It includes trams, cars, trolley, buses and railways.

11. Load curve. A load curve (or load graph) *is a graphic record showing the power demands for every instant during a certain time interval.* Such a record may cover 1 hour, in which case it would be an *hourly load graph* ; 24 hours, in which case it would be a *daily load graph* ; a month in which case it would be a *monthly load graph* ; or a year (8760 hours), in which case it would be a *yearly load graph*. The following points are worth noting :

Refer to Fig. 9.1.

(*i*) *The area under the load curve represents the energy generated in the period considered.*

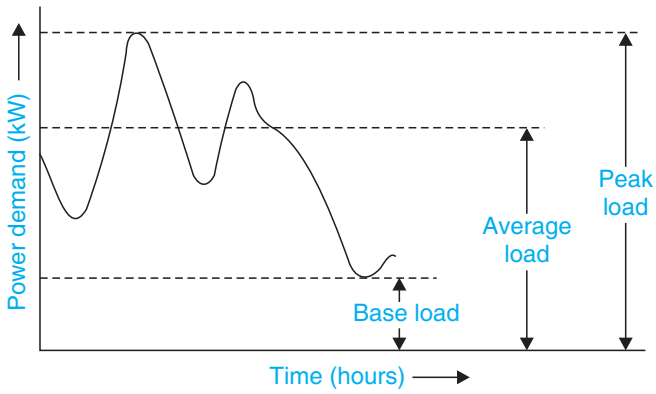


Fig. 9.1. Load curve.

(*ii*) *The area under the curve divided by the total number of hours gives the average load on the power station.*

(*iii*) *The peak load indicated by the load curve / graph represents the maximum demand of the power station.*

Significance of load curves :

- Load curves give full information about the incoming load and help to decide the installed capacity of the power station and to decide the economical sizes of various generating units.
- These curves also help to estimate the generating cost and to decide the operating schedule of the power station *i.e.,* the sequence in which different units should be run.

12. Load duration curve. A load duration curve represents re-arrangements of all the load elements of chronological load curve in order of descending magnitude. This curve is derived from the chronological load curve.

Fig. 9.2 shows a typical daily load curve for a power station. It may be observed that the maximum load on power station is 35 kW from 8 A.M to 2 P.M. This is plotted in Fig. 9.3. Similarly other loads of the load curve are plotted in *descending order* in the same figure. This is called *load duration curve* (Fig. 9.3).

The following points are worth noting :

(*i*) *The area under the load duration curve and the corresponding chronological load curve is equal and represents total energy delivered by the generating station.*

(*ii*) *Load duration curve gives a clear analysis of generating power economically. Proper selection of base load power plants and peak load power plants becomes easier.*

13. Dump power. This term is used in hydroplants and it shows the *power in excess of the load requirements* and it is made available by *surplus water*.

14. Firm power. It is the power which *should always be available even under emergency conditions.*

15. Prime power. It is the power which may be mechanical, hydraulic or thermal that is *always available for conversion into electric power.*

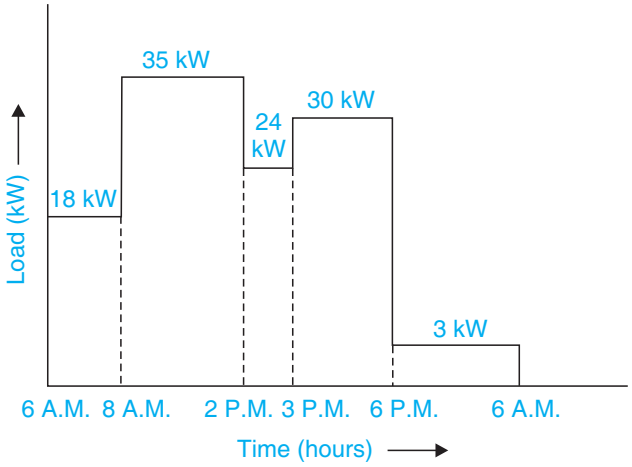


Fig. 9.2. Typical daily load curve.

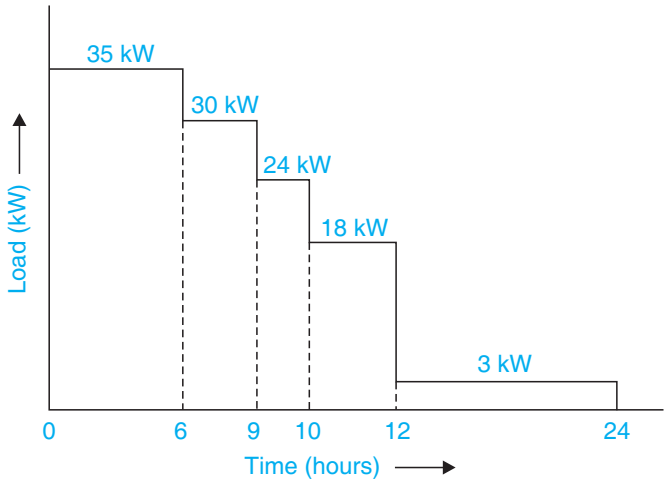


Fig. 9.3. Load duration curve.

16. Cold reserve. It is that *reserve generating capacity which is not in operation but can be made available for service.*

17. Hot reserve. It is that *reserve generating capacity which is in operation but not in service.*

18. Spinning reserve. It is that *reserve generating capacity which is connected to the bus and is ready to take the load.*

9.3. PRINCIPLES OF POWER PLANT DESIGN

The following *factors* should be considered while designing a power plant :

1. Simplicity of design.
2. Low capital cost.
3. Low cost of energy generated.
4. High efficiency.
5. Low maintenance cost.
6. Low operating cost.
7. Reliability of supplying power.
8. Reserve capacity to meet future power demand.

9.4. LOCATION OF POWER PLANT

Some of the considerations on which the location of a power plant depends are :

1. Centre of electrical load. The plant should be located where there are industries and other important consumption places of electricity. There will be considerable advantage in placing the power station *nearer to the centre of the load.*

— There will be *saving in the cost of copper* used for transmitting electricity as the distance of transmission line is reduced.

— The cross-section of the transmission line directly depends upon the maximum current to be carried. In case of alternating current the voltage to be transmitted can be increased thus reducing the current and hence the *cross-section of the transmission line can be reduced.* This will *save the amount of copper.*

— It is desirable now to have a national grid connecting all power stations. This provides for selecting a site which has other advantages such as nearer to fuel supply, condensing water available.

2. Nearness to the fuel source. The cost of transportation of fuel may be quite high if the distance of location of the power plant is considerable. It may be advisable to locate big thermal power plants at the mouth of the coal mines. Lignite coal mines should have centralised thermal power station located in the mines itself as this type of coal cannot be transported. Such type of power stations could be located near oil fields if oil is to be used as a fuel and near gas wells where natural gas is available in abundance. In any case it has been seen that *it is cheaper to transmit electricity than to transport fuel.* Hence the power plant should be located nearer the fuel supply source.

3. Availability of water. The availability of water is of greater importance than all other factors governing station location. Water is required for a thermal power station using turbines for the following two purposes :

(*i*) To supply the make-up water which should be reasonably pure water.

(*ii*) To cool the exhaust steam. This cooling process is done in case of diesel engines too. For *bigger power stations* the quantity of this cooling water is tremendous and requires *some natural source of water* such as *lake, river or even sea.* Cooling towers could be used economically as the same cooling water could be used again and again. Only a part of make up water for cooling will then be required. For *small plants spray pounds* could sometimes be used. *It is economical to limit the rise in cooling-water temperature to a small value (between 6°C and 12°C), and to gain in cycle efficiency at the expense of increased cooling water pumping requirement.*

4. Type of soil available and land cost. While selecting a site for a power plant it is important to know about the character of the soil. If the soil is loose having low bearing power the pile foundations have to be used. Boring should be made at most of the projected site to have an idea of the character of the various strata as well as of the bearing power of the soil. *The best location is that for which costly and special foundation is not required.*

In case of power plants being situated near metropolitan load centres, the land there will be very costly as compared to the land at a distance from the city.

9.5. LAYOUT OF POWER PLANT BUILDING

The following points should be taken care of while deciding about power plant building and its layout :

1. The power plant structure should be simple and rugged with pleasing appearance.

2. Costly materials and ornamental work should be avoided.

3. The power plant interior should be clean, airy and attractive.

4. The exterior of the building should be impressive and attractive.

5. Generally the building should be *single storeyed*.

6. The layout of the power plant should first be made on paper, the necessary equipment well arranged and then design the covering structure. In all layout, allowances must be made for sufficient clearances and for walkways. Good clearance should be allowed around generators, boilers, heaters, condensers etc. Walkway clearances around hot objects and rapidly moving machinery should be wider than those just necessary to allow passage. Also the galleries in the neighbourhood of high tension bus bars should be sufficient as the space will permit.

7. Provision for future extension of the building should be made.

8. The height of the building should be sufficient so that overhead cranes could operate well and the overhauling of the turbines etc. is no problem. Sufficient room should be provided to lift the massive parts of the machines.

9. Each wall should receive a symmetrical treatment in window openings etc.

10. The principal materials used for building the power plant building are brick, stone, hollow tiles, concrete and steel.

11. In case of a *steam power plant*, there are distinct parts of the building *viz*., *boiler room, turbine room* and *electrical bays*. Head room required in the boiler room should be greater than in the others. Ventilation in boiler room presents greater difficulty because of heat liberated from the boiler surfaces. The turbine room is actually the show room of the plant. Mezzanine flooring should be used in the power plant. The chimney height should be sufficient so as to release the flue gases sufficiently high so that the atmosphere is not polluted and the nearby buildings are not affected.

12. The foundation of a power plant is one of the most important considerations. For this the bearing capacity of the sub-soil, selection of a working factor of safety and proportioning the wall footings to economical construction should be well thought of and tested. The pile foundations may have to be used where the soils have low bearing values.

13. In any power plant *machine foundation* plays an important part. The machine foundation should be able to distribute the weight of the machine, bed plate and its own weight over a safe subsoil area. It must also provide sufficient mass *to absorb machine vibrations*.

14. Sufficient room for storage of fuel should be provided indoor as well as outdoor so as to ensure against any prolonged breakdown.

9.6. COST ANALYSIS

The cost of a power system depends upon whether :

(*i*) an entirely new power system has to be set up, or

(*ii*) an existing system has to be replaced, or

(*iii*) an extension has to be provided to the existing system. The cost interalia includes :

1. Capital Cost or Fixed Cost. It includes the following :

(*i*) Initial cost (*ii*) Interest
(*iii*) Depreciation cost (*iv*) Taxes
(*v*) Insurance.

2. Operational Cost. It includes the following :

(*i*) Fuel cost (*ii*) Operating labour cost
(*iii*) Maintenance cost (*iv*) Supplies
(*v*) Supervision (*vi*) Operating taxes.

The above mentioned costs are discussed as follows :

(*a*) Initial cost

Some of the several factors on which cost of a generating station or a power plant depends are :

(*i*) Location of the plant.

(*ii*) Time of construction.

(*iii*) Size of units.

(*iv*) Number of main generating units.

(*v*) The type of structure to be used.

The *initial cost* of a power station includes the following :

1. Land cost
2. Building cost
3. Equipment cost
4. Installation cost
5. Overhead charges which will include the transportation cost, stores and storekeeping charges, interest during construction etc.

— To *reduce the cost of building*, it is desirable to eliminate the superstructure over the boiler house and as far as possible on turbine house also.

— The *cost on equipment can be reduced* by adopting unit system where one boiler is used for one turbogenerator. Also by simplifying the piping system and elimination of duplicate system such as steam headers and boiler feed headers. The cost can be further reduced by eliminating duplicate or stand-by auxiliaries.

— When the power plant is not situated in the proximity to the load served, the cost of a primary distribution system will be a part of the initial investment.

(*b*) Interest

All enterprises need investment of money and this money may be obtained as loan, through bonds and shares or from owners of personal funds. *Interest is the difference between money borrowed and money returned*. It may be charged at a simple rate expressed as percentage per annum or may be compounded, in which case the interest is reinvested and adds to the principal, thereby earning more interest in subsequent years. Even if the owner invests his own capital the charge of interest is necessary to cover the income that he would have derived from it through an alternative investment or fixed deposit with a bank. *Amortization* in the periodic repayment of the principal as a uniform annual expense.

(*c*) Depreciation

Depreciation accounts for the deterioration of the equipment and decrease in its value due to corrosion, weathering and wear and tear with use. It also covers the decrease in value of equipment due to obsolescence. With rapid improvements in design and construction of plants, obsolescence factor is of enormous importance. Availability of better models with lesser overall cost of generation makes it imperative to replace the old equipment earlier than its useful life is spent. The actual life span of the plant has, therefore, to be taken as shorter than what would be normally expected out of it.

The following methods are used to calculate the depreciation cost :

(*i*) Straight line method

(*ii*) Percentage method

(*iii*) Sinking fund method

(*iv*) Unit method.

(*i*) Straight line method. It is the *simplest* and *commonly used method*. The life of the equipment or the enterprise is first assessed as also the residual or salvage value of the same after the estimated life span. This salvage value is *deducted* from the initial capital cost and the balance is *divided by the life as assessed in years*. Thus, the annual value of decrease in cost of equipment is found and is set aside as depreciation annually from the income. *Thus, the rate of depreciation is uniform throughout the life of the equipment*. By the time the equipment has lived out its useful life, an amount equivalent to its net cost is accumulated which can be utilised for replacement of the plant.

(*ii*) Percentage method. In this method the deterioration in value of equipment from year to year is taken into account and the amount of depreciation calculated upon actual residual value for each year. It thus, reduces for successive years.

(*iii*) Sinking fund method. This method is based on the *conception that the annual uniform deduction from income for depreciation will accumulate to the capital value of the plant at the end of life of the plant or equipment*. In this method, the amount set aside per year consists of annual instalments and the interest earned on all the instalments.

Let, A = Amount set aside at the end of each year for n years,

n = Life of plant in years,

S = Salvage value at the end of plant life,

i = Annual rate of compound interest on the invested capital, and

P = Initial investment to install the plant.

Then, amount set aside at the end of first year = A

Amount at the end of second year

$= A$ + interest on $A = A + Ai = A(1 + i)$

Amount at the end of third year

$= A(1 + i)$ + interest on $A(1 + i)$

$= A(1 + i) + A(1 + i)i$

$= A(1 + i)^2$

$\therefore$ Amount at the end of nth year $= A(1 + i)^{n-1}$

Total amount accumulated in n years (say x)

= Sum of the amounts accumulated in n years

$$i.e., \quad x = A + A(1+i) + A(1+i)^2 + \ldots\ldots + A(1+i)^{n-1}$$
$$= A\,[1 + (1+i) + (1+i)^2 + \ldots\ldots + (1+i)^{n-1}] \quad \ldots(i)$$

Multiplying the above equation by $(1+i)$, we get

$$x(1+i) = A\,[(1+i) + (1+i)^2 + (1+i)^3 + \ldots\ldots + (1+i)^n] \quad \ldots(ii)$$

Subtracting equation (i) from (ii), we get

$$x.i = [(1+i)^n - 1]\,A$$

$$\therefore \quad x = \left[\frac{(1+i)^n - 1}{i}\right] A$$

where $x = (P - S)$

$$\therefore \quad P - S = \left[\frac{(1+i)^n - 1}{i}\right] A \quad \ldots(9.6)$$

or
$$A = \left[\frac{i}{(1+i)^n - 1}\right] (P - S) \quad \ldots(9.7)$$

(iv) **Unit method.** In this method *some factor is taken as a standard one and depreciation is measured by that standard*. In place of years an equipment will last, the number of hours that an equipment will last is calculated. This total number of hours is then divided by the capital value of the equipment. This constant is then multiplied by the number of actual working hours each year to get the value of depreciation for that year. In place of number of hours, the number of units of production is taken as the measuring standard.

(d) Operational cost

The elements that make up the operating expenditure of a power plant include the following costs :

(i) Cost of fuels.

(ii) Labour cost.

(iii) Cost of maintenance and repairs.

(iv) Cost of stores (other than fuel).

(v) Supervision.

(vi) Taxes.

Cost of fuels. In a thermal station fuel is the heaviest item of operating cost. The selection of the fuel and the maximum economy in its use are, therefore, very important considerations in thermal plant design. It is desirable to achieve the highest thermal efficiency for the plant so that fuel charges are reduced. *The cost of fuel includes not only its price at the site of purchase but its transportation and handling costs also*. In the hydroplants the absence of fuel factor in cost is responsible for lowering the operating cost. *Plant heat rate can be improved by the use of better quality of fuel or by employing better thermodynamic conditions in the plant design*.

The cost of fuel varies with the following :

(i) Unit price of the fuel.

(ii) Amount of energy produced.

(iii) Efficiency of the plant.

Labour cost. For plant operation labour cost is another item of operating cost. Maximum labour is needed in a thermal power plant using coal as a fuel. A hydraulic power plant or a diesel power plant of equal capacity require a lesser number of persons. In case of automatic power station the cost of labour is reduced to a great extent. However labour cost cannot be completely eliminated even with fully automatic station as they will still require some manpower for periodic inspection etc.

Cost of maintenance and repairs. In order to avoid plant breakdowns *maintenance* is necessary. *Maintenance* includes *periodic cleaning, greasing, adjustments and overhauling of equipment*. The material used for maintenance is also charged under this head. Sometimes an arbitrary percentage is assumed as maintenance cost. A good plan of maintenance would keep the sets in dependable condition and avoid the necessity of too many stand-by plants.

Repairs are necessitated when the plant breaks down or stops due to faults developing in the mechanism. The repairs may be minor, major or periodic overhauls and are charged to the depreciation fund of the equipment. This item of cost is higher for thermal plants than for hydro-plants due to complex nature of principal equipment and auxiliaries in the former.

Cost of stores (other than fuel). The items of consumable stores other than fuel include such articles as lubricating oil and greases, cotton waste, small tools, chemicals, paints and such other things. The incidence of this cost is also higher in thermal stations than in hydro-electric power stations.

Supervision. In this head the salary of supervising staff is included. A good supervision is reflected in lesser breakdowns and extended plant life. The supervising staff includes the station superintendent, chief engineer, chemist, engineers, supervisors, stores incharges, purchase officer and other establishment. Again, thermal stations, particularly coal fed, have a greater incidence of this cost than the hydro-electric power stations.

Taxes. The taxes under operating head includes the following :

(i) Income tax

(ii) Sales tax

(iii) Social security and employee's security etc.

9.7. SELECTION OF TYPE OF GENERATION

While choosing the type of generation the following points should be taken into consideration :

1. The type of fuel available or availability of suitable sites for water power generation.

2. Fuel transportation cost.
3. Land required.
4. Foundation cost.
5. The availability of cooling water.
6. The type of load to be taken by the power plant.
7. Reliability in operation.
8. Plant life.
9. Cost of transmitting the energy.

9.8. SELECTION OF POWER PLANT EQUIPMENT

Selection of some important power plant equipment is discussed below :

9.8.1. Selection of Boilers

It is now well known fact that only water tube boilers (fire tube boilers not suitable) should be used for all central power stations. While selecting a boiler the following points should be taken care of :

1. Type of fuel to be burnt.
2. Type of load.
3. Cost of fuel.
4. Desirability of heat-reclaiming equipment.
5. Availability of space for boiler installation.

— The design and efficiency of the boiler is considerably influenced by the *type of fuel* used in a boiler. *A high efficiency can be obtained with coal firing as compared to oil or gas firing*. This is due to increased hydrogen loss in gaseous fuels.

— *The location of the plant* will also decide the type of fuel to be used. If the plant is nearer the coal fields, coal will be cheaper. Power plants near to the oil fields and gas wells will naturally use these fuels.

— *Coal firing* will also *influence furnace design and hence the cost of boiler*. In case of low ranking fuel such as lignites etc., pulverised firing is used. Very low fusing temperatures of coal require water cooled walls and in some cases the slag tap furnaces. The yearly minimum operating cost has to be considered which may include production cost and fixed charges. In case of anthracite coal or metallurgical coke etc. the wear on pulverising machinery is relatively much higher than that of bituminous coal.

The cost of boilers vary with the following :

(*i*) Type of boiler used.
(*ii*) Operating pressure.
(*iii*) Operating temperature.
(*iv*) Type of firing.
(*v*) Efficiency desired.

— '*Heat-reclaiming equipment*' such as *economisers* and *air preheaters* should be provided with boilers. With the addition of economisers and air preheaters the efficiency of the boiler increases from 75% to 90% and above.

— The '*increased pressure*' *affects the cost of boiler drum, boiler tubes, headers, economisers and other accessories*. Similarly high temperatures increase the cost of superheaters as higher pressure and higher temperatures require special alloy steels. *High pressures require forced circulation also. This also increases the cost but this forced circulation also increases the efficiency of the boiler*.

— The *method of firing* has also an influence on the percentage of total time for which the boiler will be available and should be considered when planning boiler capacity. Stoker firing is in general *slightly less costly than pulverised fuel firing. The pulverised fuel firing increases the efficiency*.

— *Economisers* improve the boiler efficiency by 4 to 10%. The *air preheater* further improves the boiler efficiency from 6 to 8%.

— The exhaust gases should not be cooled *below 150°C*. Below this temperature the condensation of moisture may take place and when mixed with SO_2 this moisture produces a dilute solution of H_2SO_4 which is finitely detrimental to the equipment.

— While selecting the proper economiser size as well as the size of the air preheaters *fixed* as well as *operating* charges should be considered. The fixed charges include the cost of heat recovery equipment, flue work, ducts and also increased fan cost and building cost.

9.8.2. Selection of Prime Movers

For proper selection of prime mover it is of paramount importance to construct the following curves :

(*i*) A typical daily load curve.
(*ii*) A peak-load curve.
(*iii*) A probable future-load curve.

The prime movers to be used for generating electricity could be *diesel engines, steam engines, steam turbines, gas turbines, water turbines* etc.

— While selecting a prime mover the *initial cost of a unit erected* has to be taken into consideration. The *efficiency of this unit at various loads* is also to be taken into consideration. *As the capacity of the unit increases there is a corresponding reduction in floor space per kW*.

— The selection of the prime mover depends also on the type of use whether it is used for *industrial purpose* or *for central power stations*.

Prime movers used for industrial purpose should be *non-condensing so that steam after exhausting could be used for processing*.

In case of *central power stations condensing steam turbines should be used. Diesel engines* have an advantage of higher efficiency and low cost. It also requires less labour and the initial investment is also less. But the cost of coal is less as compared to diesel oil. Also the capacity of diesel engines is limited and hence for *bigger power stations they are unsuitable*. The diesel engines are used as *standby plant* in all the central power stations whether thermal or hydro.

— In places where water is in abundance and a certain head is available hydro power plants/ stations are installed. In rivers where there is a natural fall, the same could be used for driving a *water turbine* in a hydro power plant. The maintenance of hydro power plant is the cheapest.

9.8.3. Selection of Size and Number of Generating Units

There can be no hard and fast rules, but however *looking at the load curve of the station one can guess for the total generating capacity, size and number of the units. Minimum generating capacity of a plant must be more than the predicted maximum demand*. Obviously, the minimum number of generators can be one but this will not be a wise suggestion. As the load on a power station is never constant, owing to variable demands at the different times of the day, the generator will have to run continuously at variable loads, which will be much less than the rated capacity of the generator for most of the times, *without any provision for the maintenance*. So a power station which is expected to be reliable in service, must have at *least two generators, irrespective of the total capacity of the plant.*

The following points are worth noting :

(*i*) The most appropriate way of deciding the size, and number of generating sets in a station is *to select the number of sets in such a way so as to fit in the load curve as closely as possible, so that the plant capacity may be used efficiently*.

(*ii*) Extra spare capacity is not desired as it increases the capital expenditure.

(*iii*) The main aim should be to have units of different capacities which will suitably fit in the load curve so that most of the generators when in use can be operated at nearly full load.

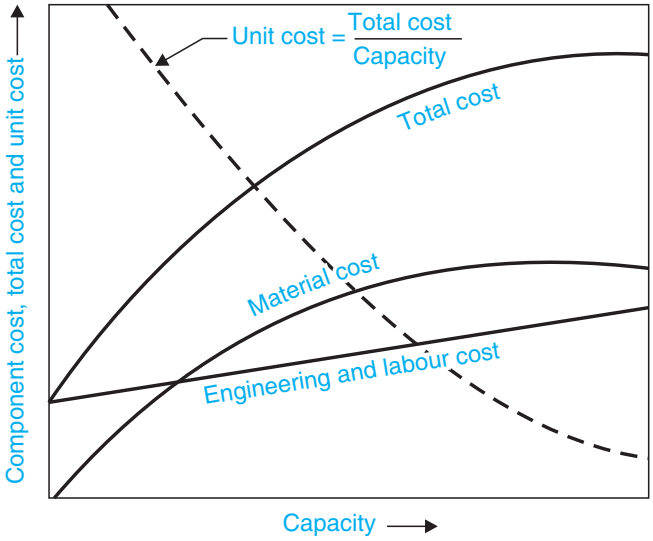


Fig. 9.4. Variation of costs of power plant *versus* its capacity.

The equipment prices are usually compared on the basis of price per unit of capacity, usually termed 'unit price'. *The unit price decreases as the capacity of the machine increases*. This is the main reason for adopting a large size generating unit in power plants. Fig. 9.4 shows the general trend and trend of the major cost components in building a given type of machine. The following points are worth noting :

— The labour and engineering cost curve *increases slightly* with the capacity of the unit.

— The material cost curve *decreases in slope* with an increase in capacity of plant.

— The total cost curve follows the pattern of material cost curve. The total cost curve shows the *positive intercept at zero capacity which represents the cost of just maintaining an organisation of men and plant ready to produce*.

— The dotted curve shows the *reduction in unit price with an increase in capacity* and this is the major argument for installing large units. *The large units are always preferred for the loads with higher load factor (0.8 to 1)*.

9.9. ECONOMICS IN PLANT SELECTION

After selection of type of drive (such as steam, gas diesel or water power) which depends on availability of cheap fuels or water resources, further selection of the design and size of the equipment is primarily based upon economic consideration and a *plant that gives the lowest unit cost of*

production is usually chosen. In case of all types of equipment the working *efficiency is generally higher with larger sizes of plants and with high load factor operation. Also, the capital cost per unit installation reduces as the plant is increased in size*. However, *a bigger size of plant would require greater investment, and possibilities of lower than optimum load factor usually increase with larger size of the plant*.

Steam power plants. In case of steam power plants the choice of *steam conditions* such as throttle pressure and temperature, is an important factor affecting operating costs and is, therefore, very carefully made. *As throttle pressure and temperature are raised the capital cost increases but the cycle efficiency is increased*. The advantage of higher pressures and temperatures is generally not apparent below capacity of 10,000 kW unless fuel cost is very high.

Heat rates may be improved further through *reheating* and *regeneration*, but again the capital cost of additional equipment has to be *balanced against gain in operating cost*.

The use of heat reclaiming devices, such as air preheaters and economisers, has to be considered from the point of economy in the consumption of fuel.

Internal combustion engine plants. In this case also the selection of I.C. engines also depends on thermodynamic considerations. *The efficiency of the engine improves with compression ratio but high pressures necessitate heavier construction of equipment which increases cost*.

The choice may also have to be made between *four-stroke* and *two-stroke* engines, the *former having higher thermal efficiency* and the *latter lower weight* and *cost*.

The cost of the *supercharger* may be justified if there *is a substantial gain in engine power which may balance the additional supercharge cost*.

Gas turbine power plant. The cost of the gas turbine power plant increases as the simple plant is modified by inclusion of other equipment such as *intercooler*, *regenerator, reheater*, etc. but the gain in thermal efficiency and thereby a reduction in operating cost may justify this additional expense in first cost.

Hydro-electric power plant. As compared with thermal stations an hydro-electric power plant has little operating cost and if sufficient water is available to cater to peak loads and special conditions for application of these plants justify, *power can be produced at a small cost*.

The *capital cost* per unit installed is *higher if the quantity of water is small*. Also, the unit cost of conveying water to the power house is greater if the quantity of water is small. The cost of storage per unit is also lower if the quantity of water stored is large.

An existing plant capacity may be *increased by storing additional water* through increasing the height of dam or by diverting water from other streams into the head reservoir. However, again it would be an economic study whether this additional cost of civil works would guarantee sufficient returns.

Some hydro-power plants may be made *automatic* or *remote controlled* to reduce the operating cost further, but the cost of automation has to be *balanced against the saving effected in the unit cost of generation*.

Interconnected hydro-steam system. In such a system where *peak loads are taken up by steam units*, the capacity of water turbine may be kept somewhat higher than the water flow capacity at peak loads, and lesser than or equal to maximum flow of river. This would make it possible for the water turbine to generate adequate energy at low cost during sufficient water flow.

Some of the principal characteristics of hydro-electric, steam and diesel power plants are listed below :

S.No.	Characteristics	Hydro-plant	Steam plant	Diesel plant
1.	*Planning and construction*	Difficult and takes long time	Easier than hydro-plant	Easiest
2.	*Civil works cost*	Highest	Lower than hydro-plant	Lowest
3.	*Running and maintenance cost* (as a fraction of total generation cost)	$\frac{1}{10}$	$\frac{1}{7}$	$\frac{1}{6}$
4.	*Overall generation cost*	Lowest	Lower than for diesel plants	Highest
5.	*Reliability*	Good	Good	Excellent

Advantages of interconnection :

Major advantages of interconnecting various power stations are :

1. Increased reliability of supply.
2. Reduction in total installed capacity.
3. Economic operation.
4. Operating savings.
5. Low capital and maintenance costs.
6. Peak loads of combined system can be carried at a *much lower cost* than what is possible with small individual system.

9.10. FACTORS AFFECTING ECONOMICS OF GENERATION AND DISTRIBUTION OF POWER

The economics of power plant operation is greatly influenced by :

(*i*) Load factor (*ii*) Demand factor

(*iii*) Utilisation factor.

Load factor. In a *hydro-electric power station* with water available and a fixed staff for maximum output, the cost per unit generated at 100% *load factor* would be *half* the cost per unit at 50% load factor. In a *steam power station* the difference would not be so pronounced since fuel cost constitutes the major item in operating costs and does not vary in the same proportion as load factor. The cost at 100% load factor in case of this station may, therefore, be about 2/3rd of the cost 50% load factor. For a *diesel station* the cost per unit generated at 100% load factor may be about 3/4th of the same cost at 50% load factor. From the above discussion it follows that :

(*i*) *Hydro-electric power station should be run at its maximum load continuously on all units.*

(*ii*) *Steam power station* should be run in such a way that *all its running units are economically loaded.*

(*iii*) *Diesel power station* should be worked for *fluctuating loads* or *as a stand by.*

Demand factor and utilisation factor. *A highly efficient station, if worked at low utilisation factor, may produce power at high unit cost.*

The time of maximum demand occurring in a system is also important. In an interconnected system, *a study of the curves of all stations is necessary to plan most economical operations.*

The endeavour should be to load the most efficient and cheapest power producing stations to the greatest extent possible. Such stations, called "*base load stations*" carry full load over 24 hours *i.e.,* for three shifts of 8 hours.

— The stations in the *medium range of efficiency* are operated only during the two shifts of 8 hours during 16 hours of average load.

— The older or *less efficient stations* are used *as peak or standby stations* only, and are operated *rarely* or for *short periods of time.*

Presently there is a tendency to use units of large capacities to reduce space costs and to handle larger loads. However, the *maximum economical benefit of large sets occurs only when these are run continuously at near full load. Running of large sets for long periods at lower than maximum continuous rating increases cost of unit generated.*

9.11. HOW TO REDUCE POWER GENERATION COST ?

The cost of power generation can be *reduced by* :

1. Using a plant of simple design that *does not need highly skilled personnel.*
2. Selecting equipment of *longer life and proper capacities.*
3. Carrying out *proper maintenance* of power plant equipment to avoid plant breakdowns.
4. Running the power stations at *high load factors.*
5. Increasing the efficiency of the power plant.
6. Keeping proper supervision, which ensures *less breakdowns* and extended plant life.

9.12. POWER PLANT—USEFUL LIFE

The useful life of a power plant is that *after which repairs become so frequent and extensive that it is found economical to replace the power plant by a new one.* Useful life of some of the power plants is given below :

Plant	*Useful life*
1. Conventional thermal power plant	20–25 years
2. Nuclear power plant	15–20 years
3. Diesel power plant	About 15 years.

The useful life of some of the equipment of a *steam power plant* is given below :

Equipment	*Useful life (years)*
1. Boilers	
(*i*) Fire tube	10–20
(*ii*) Water tube	20
2. Steam turbine	5–20
3. Steam turbo-generators	10–20
4. Condensers	20
5. Pumps	15–20
6. Coal and ash machinery	10–20
7. Feed water heaters	20–30
8. Stacks	10–30
9. Stokers	10–20
10. Transformers	15–20

11.	Motors	20
12.	Electric meters and instruments	10–15
13.	Transmission lines	10–20

9.13. ECONOMICS OF HYDRO-ELECTRIC POWER PLANTS

The cost analysis of an hydro-electric power plant is different from those of the other plants in the respect that the fixed *coal is the major item of the total cost and the operating cost is relatively much smaller* whereas in the steam and other plants, the *operating cost is a large part of the total cost*.

In a hydro-plant the total annual cost can be divided into two following categories :

1. Fixed costs :

(*i*) Interest on capital

(*ii*) Amortization of the capital

2. Running costs :

(*i*) Maintenance and repairs.

(*ii*) Operating costs including salaries and wages.

(*iii*) Rates and taxes.

(*iv*) Stores, oil and other supplies.

(*v*) Management expenses including insurance.

— The *fixed charges* of a hydro-plant are about 60 to 70% of the total cost of power and *these do not depend upon the station output*.

— The *running charges depend upon the station output, but not so much as in the thermal power plants*.

The following items go to form the *total capital outlay* or the *investment on a hydro-plant* :

(*i*) Preliminary surveys and investigations of the topography and geology of the proposed site of the plant.

(*ii*) Purchase of land (needed for adequate storage or pondage) and water rights.

(*iii*) Compensation to oustees.

(*iv*) Cost of preparation of detailed designs and specifications.

(*v*) Cost of testing the materials of construction.

(*vi*) Cost of carrying out experimental work and model tests or designs for hydraulic structures.

(*vii*) The actual cost of construction.

(*viii*) Cost relating the purchase and installation of the equipment.

(*ix*) Interest on capital during construction.

(*x*) Working capital during the period of load development.

(*xi*) Cost in respect of new roads, railway lines, residential houses and even new towns which may have to be constructed.

A typical cost analysis of a hydro-plant is as follows :

S.No.	Components	Cost
1.	Reservoir, dam and water ways	55%
2.	Land	15%
3.	Structures	10%
4.	Power plant and equipment	20%

Besides this there is an another important item called *transmission liability* which refers to the *transmission charges for conveying the electricity from the plant site to the load centre*.

— The total cost of construction of hydro-plant is *invariably higher than that of a thermal plant of equal capacity*. Therefore, the annual charges for interest and depreciation are comparatively higher.

— In case of a *hydro-plant*, the *smaller the quantity of water stored higher is the cost per kW*.

9.14. ECONOMICS OF COMBINED HYDRO AND STEAM POWER PLANTS

It has been established that if a region/country is neither rich in fuel reserves nor in hydro resources then a combined operation of hydro and steam power plants give the best results in regard to generation of electricity at *the economical cost*. The following advantages accrue from combined plants :

1. Flexibility of operation.
2. Security of supply.
3. Improved utilisation of hydro-power.
4. Spare plant.

Practically all large power systems in the world have hydro-steam interconnected. *Hydro-plant may function as a capacity plant i.e., to supply system peak with minimum flow conditions*, or it may work as an *energy plant* to replace the costly steam generated electricity by *low cost hydro power*.

In such a system (interconnected) *there should be a daily or seasonal load allocation plan set prehand so that the use of the two power systems is made to the best advantage. A certain amount of forecasting of load and capacity of the system as well as flexibility are necessary for optimum results and experience is a big factor in good co-ordinated action*.

A knowledge of system plant loading schedules for minimum production cost is as important as that of reservoir levels, pond storage and stages of low flow and heavy loads.

9.15. PERFORMANCE AND OPERATING CHARACTERISTICS OF POWER PLANTS

The *performance* of generating power plants is compared by their *average efficiency* over a period of time. The average efficiency of a power plant is the *ratio of useful energy output to the total energy input during the period considered*. This *measure of performance varies with uncontrolled conditions viz. (i)* cooling water temperature, (*ii*) quality of fuel, and (*iii*) shape of load curve. Thus, unless all plant performances are corrected to the same controlled conditions it is not a satisfactory standard of comparison.

The performance of a plant can be precisely represented by the *input-output curve* from the tests conducted on individual power plant. The input-output curve is *graphical representation* between the net energy output (L) and input (I). The input is generally expressed in millions of kcal/h or kJ/h and load output is expressed as megawatts (MW). The input to hydro-plant is measured in cusecs or m^3/s of water.

In general input-output may be represented as follows :

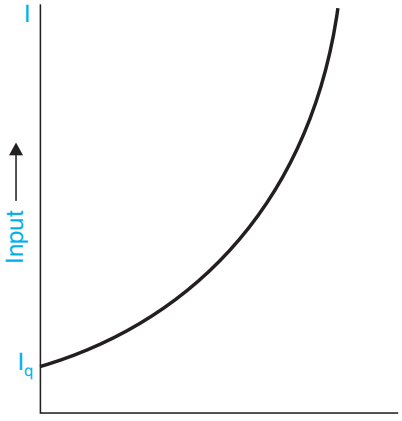
$$I = a + bL + cL^2 + dL^3$$

where I = Input,

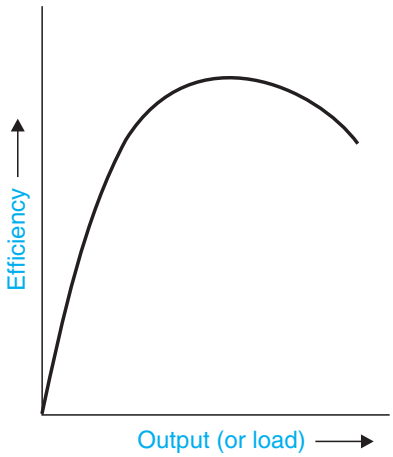
L = Output, and

a, b, c and d = Constants

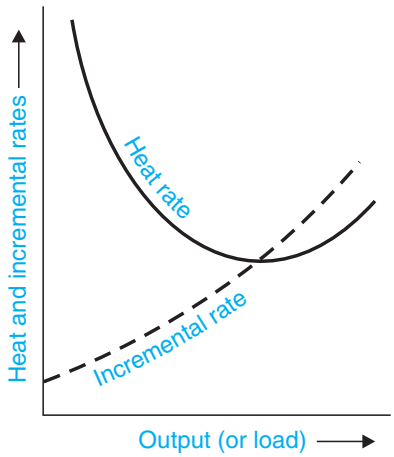
Input-output curve. Fig. 9.5 (a) shows an *input-output curve*. In order to keep the apparatus functioning at zero load, a certain input (I_0) is required *to meet frictional and heat losses*.



(a) Input - output curve.



(b) Efficiency curve.



(c) Heat rate and incremental rate curves.

Fig. 9.5

Efficiency curve. The efficiency of the power plant is defined *as the ratio of output to input*.

$$\therefore \quad \text{Efficiency,} \quad \eta = \frac{L}{I} = \frac{L}{a + bL + cL^2 + dL^3}$$

By using the above formula the efficiency *for any given load* can be calculated.

An *efficiency curve* is shown in Fig. 9.5 (b).

Heat rate and incremental rate curves. These curves can be derived from basic input-output curve.

Heat rate (HR) is defined as the *ratio of input to output*.

$$i.e., \quad \textit{Heat rate (HR)} = \frac{I}{L} = \frac{a + bL + cL^2 + dL^3}{L}$$

$$= \frac{a}{L} + b + cL + dL^2$$

Heat rate curve is obtained by plotting values of heat rate against corresponding values of output. Fig. 9.5 (*c*) shows a heat rate curve.

Incremental rate (IR) is defined as the *ratio of additional input (dI) required to increase additional output (dL).*

i.e., $$\text{Incremental rate } (IR) = \frac{dI}{dL}.$$

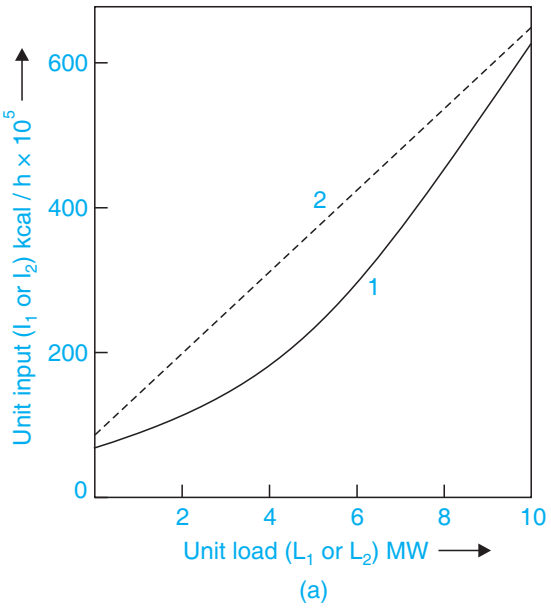
Incremental rate curve is obtained by plotting values of *IR* against corresponding values of output. Such a curve is shown in Fig. 9.5 (*c*). *This curve expresses additional energy required to produce an added unit of output at the given load.*

9.16. ECONOMIC LOAD SHARING

The primary objective of the design of all generating stations is the *economy*. For a power system to return a profit on the capital invested, proper operation of the plant is essential. As far as the efficiency of boilers, turbines, alternators etc. is concerned, engineers have been successful in increasing the efficiency continuously so that each unit added results in comparatively more efficient operation. Methods have also been devised for economic operation of plants at part loads and under variable load conditions. Attempts have been made to minimise the transmission losses too. Now the *only aspect that remains is the economic distribution of the output of a plant between the generators, or units within the plant.*

Let us consider two generators 1 and 2 which supply in parallel a common load. Generator 1 is more efficient than generator 2 as for the same input, output of generator 1 is more than that of generator 2.

Fig. 9.6 shows the input-output curves of the two generators/units.



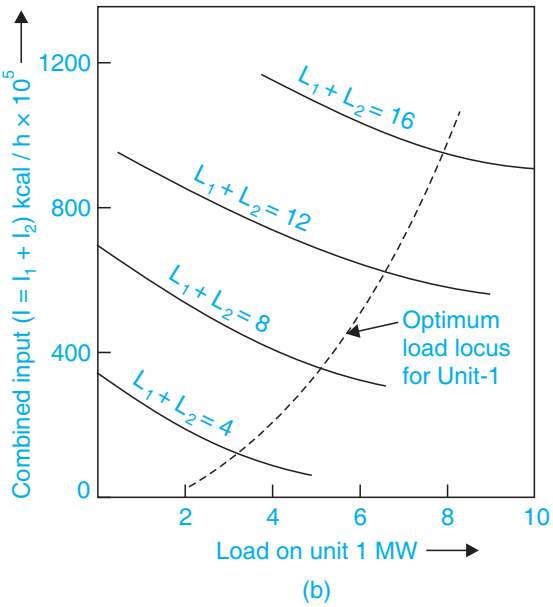


Fig. 9.6

In the Fig. 9.6 (*b*) is shown the plot of combined input of generators 1 and 2 *versus* load on generator 1, for a *constant total load*.

Although generator 1 requires less input for a given output it is not essential that unit 1 should be loaded first and then generator 2. For economical loading the combined input of units 1 and 2 should be plotted against load on unit 1 for a constant total load. Let a total load of 4 MW be supplied by generators 1 and 2.

$$L = L_1 + L_2$$

where, L = combined output

L_1 = output of generator 1

L_2 = output of generator 2

Let the generator 2 supply total load of 4 MW and generator 1 supply zero load. Now corresponding to zero load on generator 1 and 4 MW on generator 2 the values of input to generator 1 (I_1) and input to generator 2 (I_2) can be determined respectively from Fig. 9.6 (*a*) and thus value of ($I_1 + I_2$) can be plotted against zero load on generator 1. Again let 2 MW be supplied by generator 1 and 2 MW be supplied by generator 2 (so that total load remains 4 MW) then values of I_1 and I_2 can be determined corresponding to 2 MW load on each generator and value of ($I_1 + I_2$) can be plotted against 2 MW load on generator 1 as shown in Fig. 9.6 (*b*). In this way curve for a total load of 4 MW can be plotted corresponding to different output of generator 1.

Similarly curve for total load of 8 MW etc. can be plotted. In these curves *there is at least one point where combined input is minimum for a given total load. Corresponding to this point of minimum, the load generator 1 can be found.* Then the load on generator 2 will be

difference of total load and load on generator 1. *This load saving will be the most economical.*

This method is difficult to apply in practice as such because generally stations have got more than two generators/units and in that case the application of above principles becomes a cumbersome process.

Considering any combined constant input in Fig. 9.6 (*b*), at the point of minimum input

$$\frac{dI}{dI_1} = 0 \qquad ...(i)$$

where, $I = I_1 + I_2$ = input of generator 1 + input of generator 2

= combined input to generators 1 and 2

$L = L_1 + L_2$ = output of generator 1 + output of generator 2

= combined output of generators 1 and 2

Then $$\frac{dI}{dI_1} = \frac{dI_1}{dL_1} + \frac{dI_2}{dL_1} = 0 \qquad \left(\because \frac{dI}{dI_1} = 0\right)$$

As I is constant.

$$\therefore \quad \frac{dI_1}{dL_1} = -\frac{dI_2}{dL_1} \qquad ...(ii)$$

But $$\frac{dI_2}{dL_1} = \frac{dI_2}{dL_2} \times \frac{dL_2}{dL_1} \qquad ...(iii)$$

Also, $L_2 = L - L_1$

$$\therefore \quad \frac{dL_2}{dL_1} = \frac{dL}{dL_1} - \frac{dL_1}{dL_1}$$

Since L is constant.

$$\therefore \quad \frac{dL}{dL_1} = 0$$

Hence, $$\frac{dL_2}{dL_1} = -\frac{dL_1}{dL_1} = -1 \qquad ..(iv)$$

Substituting in (*iii*), we get

$$\frac{dI_2}{dL_1} = -\frac{dI_2}{dL_2} \qquad ...(v)$$

$\therefore$ From (*ii*) and (*v*),

$$\frac{dI_1}{dL_1} = \frac{dI_2}{dL_2} \qquad ...(vi)$$

Thus, *for minimum combined input to carry a given combined output, the slopes of the input-output curve for each unit must be equal.*

If there are n units, supplying a constant load, then the required condition for the minimum input or maximum system efficiency is

$$\frac{dI_1}{dL_1} = \frac{dI_2}{dL_2} = \frac{dI_3}{dL_3} = ... = \frac{dI_n}{dL_n} \qquad ...(vii)$$

Condition for maximum efficiency :

Refer to Fig. 9.7. *The load at which efficiency will be maximum, the heat rate will be minimum at that load as efficiency is inverse of heat.*

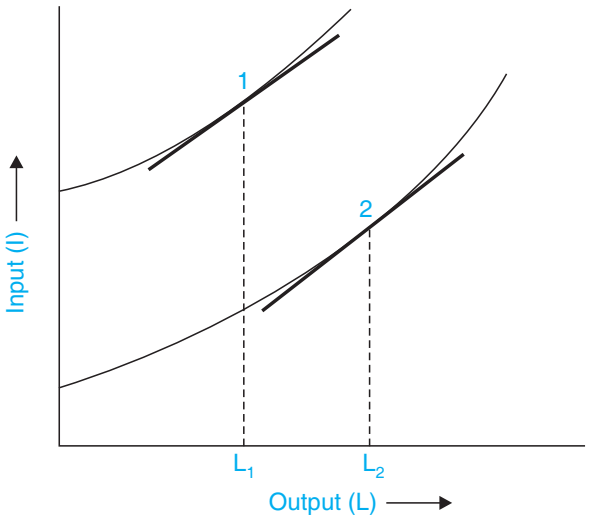


Fig. 9.7

$$\text{Efficiency} = \frac{L}{I}$$

$$\text{Heat rate } (HR) = \frac{I}{L}$$

$\therefore$ For minimum value of heat rate

$$\frac{d}{dL}(HR) = 0 \quad \text{or} \quad \frac{d}{dL}\left(\frac{I}{L}\right)$$

$$\therefore \quad \frac{LdI - IdL}{L^2} = 0 \quad \text{or} \quad LdI = IdL$$

or $$\frac{I}{L} = \frac{dI}{dL}$$

This shows that efficiency will be maximum at a load where heat rate is equal to incremental heat rate.

9.17. TARIFF FOR ELECTRICAL ENERGY

9.17.1. Introduction

The cost of generation of electrical energy consists of *fixed cost and running cost*. Since the electricity generated is to be supplied to the consumers, the total cost of generation has to be recovered from the consumers. *Tariffs or energy rates are the different methods of charging the consumers for the consumption of electricity*. It is desirable to charge the consumer according to the maximum demand (kW) and the energy consumed (kWh). *The tariff chosen should recover the fixed cost, operating cost and profit etc. incurred in generating the electrical energy.*

9.17.2. Objectives and Requirements of Tariff

Objectives of tariff :

1. Recovery of cost of capital investment in generating equipment, transmission and distribution system.

2. Recovery of the cost of operation, supplies and maintenance of the equipment.
3. Recovery of the cost of material, equipment, billing and collection cost as well as for miscellaneous services.
4. A net return on the total capital investment must be ensured.

Requirements of tariff :

1. It should be easier to understand.
2. It should provide low rates for high consumption.
3. It should be uniform over large population.
4. It should encourage the consumers having high load factors.
5. It should take into account maximum demand charges and energy charges.
6. It should provide incentive for using power during off-peak hours.
7. It should provide less charges for power connection than lighting.
8. It should have a provision of penalty for low power factors.
9. It should have a provision for higher demand charges for high loads demanded at system peaks.
10. It should apportion equitably the cost of service to the different categories of consumers.

9.17.3. General Tariff Form

A large number of tariffs have been proposed from time to time and are in use. They are all derived from the following general equation :

$$z = a.x + b.y + c$$

where, z = Total amount of bill for the period considered,

x = Maximum demand in kW,

y = Energy consumed in kWh during the period considered,

a = Rate per kW of maximum demand, and

b = Energy rate per kWh,

c = Constant amount charged to the consumer during each billing period. This charge is independent of demand or total energy because a consumer that remains connected to the line incurs expenses even if he does not use energy.

Various types of tariffs :

The various types of tariffs are :

1. Flat demand rate.
2. Straight meter rate.
3. Block meter rate.
4. Hopkinson demand rate (Two-part tariff).
5. Doherty rate (Three-part tariff).
6. Wright demand rate.

1. Flat demand rate :

The flat demand rate is expressed as follows :

$$z = ax \qquad ...(9.8)$$

i.e., the bill *depends only on the maximum demand irrespective of the amount of energy consumed*. It is based on the customer's installation of energy consuming devices which is generally denoted by so many kW per month or per year. It is probably one of the early systems of charging energy rates. It was based upon the total number of lamps installed and a fixed number of hours of use per year. Hence the rate could be expressed as a price per lamp or unit of installed capacity.

Now-a-days the use of *this tariff is restricted to signal system, street lighting* etc., where the number of hours are fixed and energy consumption can be easily predicted. *Its use is very common to supplies to irrigation tubewells*, since the number of hours for which the tubewell feeders are switched on are fixed. The charge is made according to horse power of the motor installed.

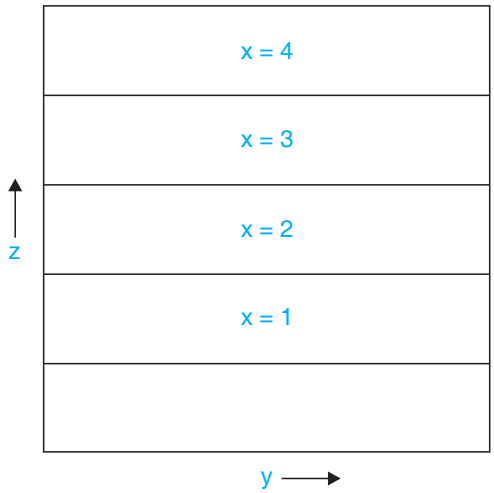


Fig. 9.8. Flat demand rate.

In this form of tariff the unit energy cost decreases progressively with an increased energy usage since the total cost remains constant. The variation in total cost and unit cost are given in Fig. 9.8.

By the use of this form of tariff the cost of metering equipment and meter reading is eliminated.

2. Straight meter rate :

The straight meter rate can be expressed in the form :

$$z = b \, . \, y \qquad ...(9.9)$$

This is the simplest form of tariff. Here the charge per unit is constant. The charges depend on the energy

used. This tariff is *sometimes used for residential and commercial consumer*. The variation of bill according to the variation of energy consumed is shown in Fig. 9.9.

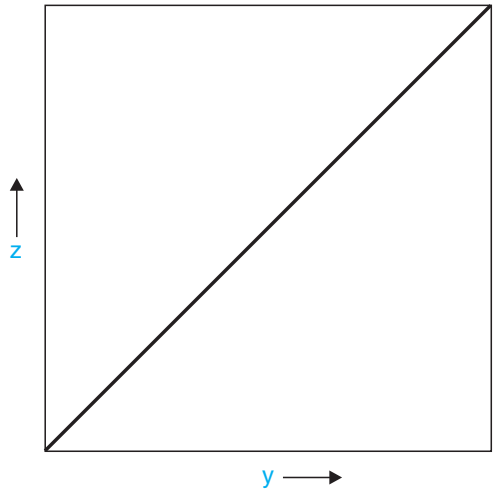


Fig. 9.9. Straight meter rate.

Advantage. *Simplicity.*

Disadvantages 1. The consumer using no energy will not pay any amount although he has incurred some expenses to the power station.

2. This method does not encourage the use of electricity unless the tariff is very low.

3. Block meter rate :

In order to remove the inconsistency of straight meter rate, the block meter rate charges the consumers on a sliding scale. The term '*block*' indicates that a certain specified price per unit is charged for all or any part of such units. The reduced prices per unit are charged for all or any part of succeeding block of units, each such reduced price per unit applying only to a particular block or portion thereof.

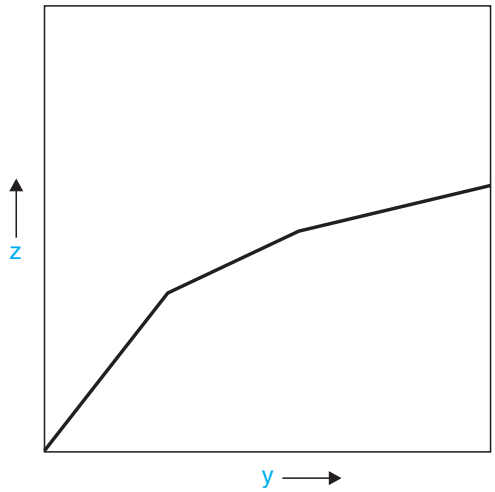


Fig. 9.10. Block meter rate.

The variation of bill according to this method is shown in Fig. 9.10.

The block meter rate accomplishes the same purpose of decreasing unit energy charges with increasing consumption as the step meter rate without its defect. Its *main defect is that it lacks a measure of the customer's demand*.

This tariff is very commonly used for residential and commercial customers. In many states of India, a *reverse form* of this tariff is being used *to restrict the energy consumption*. In this reverse form the unit energy charge increases with increase in energy consumption.

4. Hopkinson demand rate (Two-part tariff) :

This method *charges the consumer according to his maximum demand and energy consumption*. This can be expressed as

$$z = a + by \qquad ...(9.10)$$

This method requires *two meters to record the maximum demand and energy consumption of the consumer*. The variation of z with respect to y taking x as parameter is shown in Fig. 9.11.

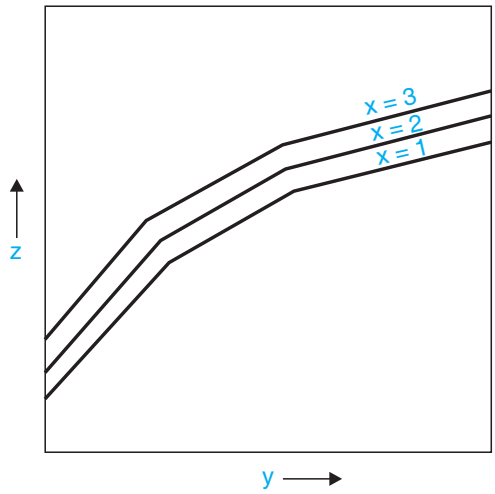


Fig. 9.11. Hopkinson demand rate (Two-part tariff).

This form of tariff is generally used for *industrial customers*.

5. Doherty rate (Three-part tariff) :

Refer to Fig. 9.12. When the Hopkinson demand rate is modified by the addition of a customer charge, it becomes a three charge rate or Doherty rate. It was first introduced by Henry L. Doherty at the beginning of twentieth century. It consists of a *customer* or *meter charge,* plus *a demand charge* plus *any energy charge*. This is expressed as follows :

$$y = ax + by + c$$

Many people consider that theoretically this is an ideal type of rate. As it requires *two meters, it is better suited for industrial than for residential customers*.

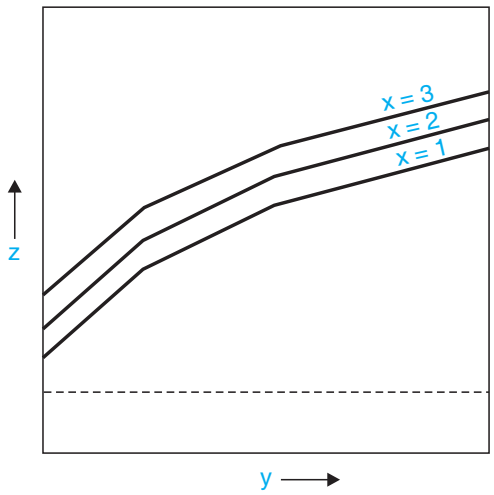


Fig. 9.12. Doherty rate (Three-part tariff).

The Doherty rate is sometimes modified by specifying the minimum demand and the minimum energy consumption that must be paid for, if they are less than the minimum values specified. In this manner the customer charge is incorporated with the demand and energy component.

6. Wright demand rate :

This tariff was introduced by Arthur Wright (of England) in 1896. This rate intensifies the inducement by lowering both the demand and energy charge for a reduction in maximum demand or in other words an improvement in load factor. *This rate is usually specified for industrial consumers who have some measure of control over their maximum demands.*

The rate is modified by stating a minimum charge which must be paid if the energy for the billing period falls below the amount by such charge. For allowing fair returns some adjustment in the rate forms are provided. Some of them are :

(*i*) Higher demand charges in summer.
(*ii*) Fuel price adjustment to provide a rate change when fuel prices deviate from the standard.
(*iii*) Wage adjustment.
(*iv*) Tax adjustment.
(*v*) Power factor adjustment.
(*vi*) Discount to be given to the customers for prompt payment of bills.

WORKED EXAMPLES

Example 9.1. *The maximum demand of a power station is 96000 kW and daily load curve is described as follows :*

Time hours	*0–6*	*6–8*	*8–12*	*12–14*	*14–18*	*18–22*	*22–24*
Load (MW)	*48*	*60*	*72*	*60*	*84*	*96*	*48*

(*i*) *Determine the load factor of power station.*

(*ii*) *What is the load factor of standby equipment rated at 30 MW that takes up all load in excess of 72 MW ? Also calculate its use factor.*

Solution. Load curve is shown in Fig. 9.13.

Energy generated = area under the load curve
$= 48 \times 6 + 60 \times 2 + 72 \times 4 + 60 \times 2 + 84 \times 4 + 96 \times 4 + 48 \times 2$
$= 1632$ MWh $= 1632 \times 10^3$ kWh.

(*i*) Load factor :

$$\text{Average load} = \frac{1632 \times 10^3}{24} = 68000 \text{ kW}$$

Maximum demand = 96000 kW (given)

$$\therefore \text{ Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} = \frac{68000}{96000}$$

$$= \mathbf{0.71.} \quad \textbf{(Ans.)}$$

(*ii*) Load factor of standby equipment :

The standby equipment supplies

84 – 72 = 12 MW for 4 hours (14 – 18)

96 – 72 = 24 MW for 4 hours (18 – 22)

$\therefore$ Energy generated by standby equipment
$= (12 \times 4 + 24 \times 4) \times 10^3$
$= 144 \times 10^3$ kWh

Time for which standby equipment *remains in operation* (from the load curve)
$= 4 + 4 = 8$ hours

$$\text{Average} = \frac{144 \times 10^3}{8} = 18 \times 10^3 \text{ kW}$$

$$\textbf{Load factor} = \frac{18 \times 10^3}{24 \times 10^3} = \mathbf{0.75.} \quad \textbf{(Ans.)}$$

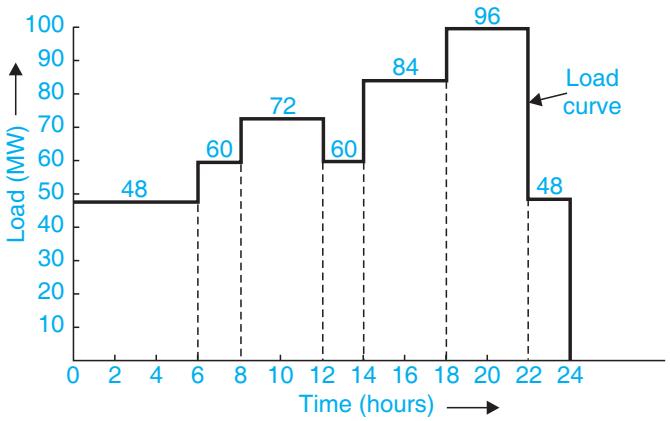


Fig. 9.13

$$\text{Use factor} = \frac{E}{C \times t'}$$

where, E = Energy generated,

C = Capacity of the standby equipment, and

t' = Actual number of hours the plant has been in operation.

$$\therefore \quad \textbf{Use factor} = \frac{144 \times 10^3}{30 \times 10^3 \times 8}$$

$$= \textbf{0.6.} \quad \textbf{(Ans.)}$$

☞**Example 9.2.** *An electrical system experiences linear changes in load such that its daily load curve is defined as follows :*

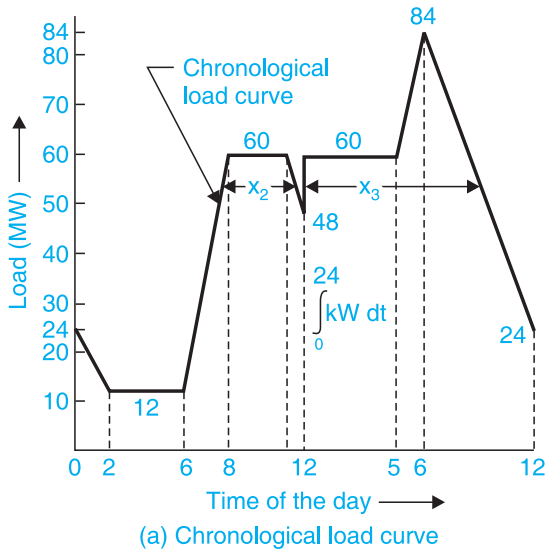
Time	*Load (MW)*
12 PM	*24*
2 AM	*12*
6 AM	*12*
8 AM	*60*
12 AM	*60*
12.30 PM	*48*
1 PM	*60*
5 PM	*60*
6 PM	*84*
12 PM	*24*

(*i*) *Plot the chronological and load duration curve for the system.*

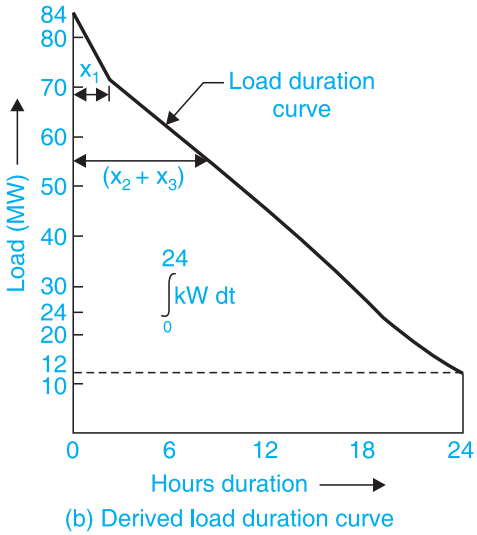
(*ii*) *Find the load factor.*

(*iii*) *What is the utilisation factor of the plant serving this load if its capacity is 120 MW.*

Solution. (*i*) **Chronological load and load duration curves :**



(a) Chronological load curve



(b) Derived load duration curve

Fig. 9.14

Chronological load and load duration curves are drawn as shown in Fig. 9.14 (*a*), (*b*). The procedure for constructing the load duration curve from chronological load curve is as follows :

— The abscissa of the load duration curve is laid off *equal to the number of hours in the chronological curve*, in this case 24 hours.

— The criterion of plotting the load duration curve *makes the abscissa at any load ordinate equal to the length of the abscissa intercepted by that load ordinate on the chronological curve*. Thus :

(*i*) At the maximum demand or peak load, the intercept is one point which will be plotted at 0 hour.

(*ii*) At 70 MW load the intercept is x_1 hours and is plotted as x_1 hour on the load duration curve.

(*iii*) At 55 MW load the intercept is a total of $(x_2 + x_3)$ and is plotted accordingly.

(*iv*) At minimum load of 12 MW the intercept covers the entire period of 24 hours.

Following points may be noted :

1. *Any point on the load duration curve is a measure of number of hours in a given period during which the given load and higher loads have prevailed.*
2. *If the chronological curve indicated a constant demand during the entire day, it would be of rectangular shape and load duration curve would be an exact duplicate.*

(*ii*) Load factor :

From the load duration curve, the average load can be estimated.

Average load for the period

$$= \frac{\text{Total energy in load curve for period}}{\text{Total number of hours in period}}$$

$$= \frac{\left(\frac{24+12}{2}\right)\times 2 + 12\times 4 + \left(\frac{12+60}{2}\right)\times 2 + 60\times 4 + \left(\frac{60+48}{2}\right)\times\frac{1}{2} + \left(\frac{48+60}{2}\right)\times\frac{1}{2} + 60\times 4 + \left(\frac{60+84}{2}\right)\times 1 + \left(\frac{84+24}{2}\right)\times 6}{24}$$

$$= \frac{36+48+72+240+27+27+240+72+324}{24}$$

$$= \frac{1086}{24} = 45.2 \text{ MW}$$

$\therefore$ **Load factor**

$$= \frac{45.2}{84} = \mathbf{0.45 \text{ or } 54\%.} \quad \textbf{(Ans.)}$$

(*iii*) Utilisation factor :

Utilisation factor

$$= \frac{\text{Maximum load}}{\text{Rated capacity of the plant}}$$

$$= \frac{84}{120} = \mathbf{0.70 \text{ or } 70\%.} \quad \textbf{(Ans.)}$$

☞**Example 9.3.** *A power station has to supply load as follows :*

Time (hours) :	*0–6*	*6–12*	*12–14*	*14–18*	*18–24*
Load (MW) :	*45*	*135*	*90*	*150*	*75*

(*i*) *Draw the load curve.*

(*ii*) *Draw load duration curve.*

(*iii*) *Choose suitable generating units to supply the load.*

(*iv*) *Calculate the load factor.*

(*v*) *Calculate the plant capacity factor.*

Solution. (*i*) Load curve :

The load curve is shown in Fig. 9.15 (*a*).

(*ii*) Load duration curve :

The load duration curve is shown in Fig. 9.15 (*b*).

(*iii*) Selection of generating units :

Load duration curve will indicate the operation schedule of different generating units.

1. One generating unit (unit 1) of 45 MW will run for **24 hours**
2. Second generating unit (unit 2) of 45 MW will run for **18 hours**
3. Third generating unit (unit 3) of 45 MW will run for **10 hours**
4. Fourth generating unit (unit 4) of 15 MW will run for **4 hours**

One additional unit (unit 5) should be kept as standby. Its capacity should be equal to the capacity of biggest set, *i.e.,* 45 MW.

Energy generated

$= 45 \times 6 + 135 \times 6 + 90 \times 2 + 150 \times 4 + 75 \times 6$

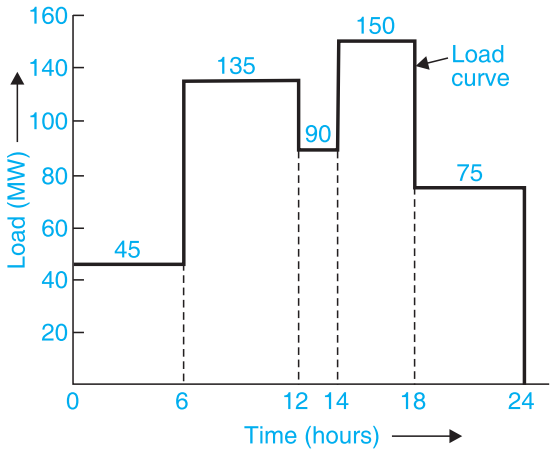
$= 270 + 810 + 180 + 600 + 450 = 2310$ MWh

Average load

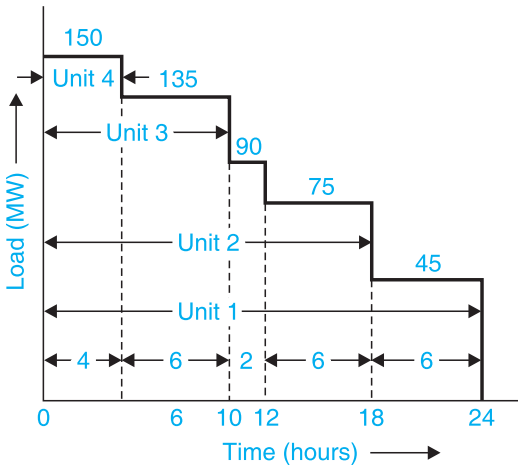
$$= \frac{2310 \times 10^3}{24} \text{ kW} = 96250 \text{ kW}$$

Maximum demand

$= 150 \times 10^3 = 150000$ kW



(a) Load curve



(b) Load duration curve

Fig. 9.15

(iv) Load factor :

$$\therefore \quad \textit{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$= \frac{96250}{150000} = \mathbf{0.64.} \quad \textbf{(Ans.)}$$

(v) Plant capacity factor :

Plant capacity factor

$$= \frac{E}{C \times t}$$

where, E = Energy generated (kWh),

C = Capacity of the plant (kW),

$= 45 \times 4 + 1 \times 15 = 195$ MW $= 195 \times 10^3$ kW, and

t = Number of hours in the given period

$= 24$ hours.

$\therefore$ *Plant capacity factor*

$$= \frac{2310 \times 10^3}{195 \times 10^3 \times 24} = \mathbf{0.49.} \quad \textbf{(Ans.)}$$

Example 9.4. *A generating station has a maximum demand of 5000 kW, and the daily load on the station is as follows :*

Load (MW)	*1000*	*1750*	*4000*	*1500*
Time	*11 PM to 8 AM*	*6 AM to 8 AM*	*8 AM to 12.00 Noon*	*12 PM to 1 PM*
Load (MW)	*3750*	*4250*	*5000*	*2250*
Time (hours)	*1 PM to 5 PM*	*5 PM to 7 PM*	*7 PM to 9 PM*	*9 PM to 11 PM*

(*i*) *Draw the load curve.*

(*ii*) *Draw the load duration curve.*

(*iii*) *Select the size and number of generator units.*

(*iv*) *What reserve plant would be necessary ?*

(*v*) *Load factor.*

(*vi*) *Plant capacity factor.*

Solution. (*i*) **Load curve** is shown in Fig. 9.16 (*a*).

(*ii*) **Load duration curve** is shown in Fig. 9.16 (*b*).

(iii) Size and number of generator units :

From the load duration curve it is evident that generating sets of capacity 1000 kW, 1500 kW and 2500 kW will fulfil the requirement.

(iv) Reserve capacity :

Also, reserve capacity = largest size of the unit in the station = **2500 kW.** **(Ans.)**

(v) Load factor :

Area under the load curve gives the energy generated during 24 hours

$$= 1000 \times 7 + 1750 \times 2 + 4000 \times 4 + 1500 \times 1 + 3750 \times 4 + 4250 \times 2 + 5000 \times 2 + 2250 \times 2$$

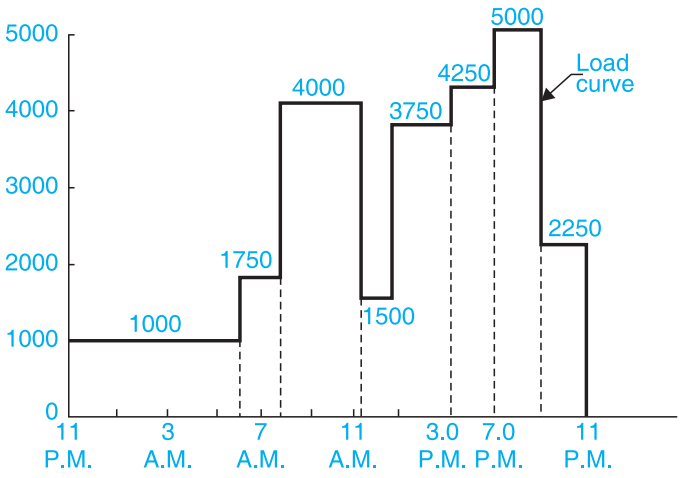
$$= 7000 + 3500 + 16000 + 1500 + 15000 + 8500 + 10000 + 4500$$

$$= 66000 \text{ kWh}$$

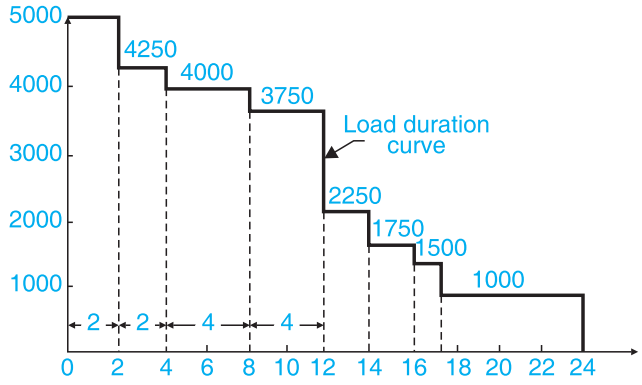
or $$\text{Average load} = \frac{66000}{24} = 2750 \text{ kW}$$

$$\therefore \quad \textit{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} = \frac{2750}{5000}$$

$$= \mathbf{0.5.} \quad \textbf{(Ans.)}$$



(a) Load curve



(b) Load duration curve

Fig. 9.16

(*vi*) **Plant capacity factor :**

Plant capacity factor

$$= \frac{E}{C \times t} = \frac{66000}{(2500 + 1500 + 1000 + 2500) \times 24}$$

$$= \mathbf{0.367.} \quad \textbf{(Ans.)}$$

Example 9.5. *A 60 MW power station has an annual peak load of 50 MW. The power station supplies loads having maximum demands of 20 MW, 17 MW, 10 MW and 9 MW. The annual load factor is 0.45. Find :*

(i) Average load.

(ii) Energy supplied per year.

(iii) Diversity factor.

(iv) Demand factor.

Solution. Capacity of power station = 60 MW

Maximum demand on power station = 50 MW

(*i*) **Average load :**

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

i.e., $$0.45 = \frac{\text{Average load}}{50}$$

$\therefore$ *Average load* = $50 \times 0.45 = \mathbf{22.5\ MW.}$ **(Ans.)**

(*ii*) **Energy supplied per year :**

Energy supplied per year

= Average load × number of hours in one year

= $(22.5 \times 10^3) \times 365 \times 24$

= $\mathbf{197.1 \times 10^6\ kWh.}$ **(Ans.)**

(*iii*) **Diversity factor :**

Diversity factor

$$= \frac{\text{Sum of individuals maximum demands}}{\text{Simultaneous maximum demand}}$$

$$= \frac{20 + 17 + 10 + 9}{50} = \frac{56}{50} = 1.12$$

Hence diversity factor = **1.12.** **(Ans.)**

(*iv*) **Demand factor :**

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}}$$

$$= \frac{50}{20 + 17 + 10 + 9} = \frac{50}{56} = 0.89$$

Hence, demand factor = **0.89.** **(Ans.)**

Example 9.6. *The yearly duration curve of a certain plant can be considered as a straight line from 300 MW to 80 MW. Power is supplied with one generating unit of 200 MW capacity and two units of 100 MW capacity each. Determine :*

(i) Installed capacity *(ii) Load factor*

(iii) Plant factor *(iv) Maximum demand*

(v) Utilization factor.

Solution. The load duration curve is shown in Fig. 9.17.

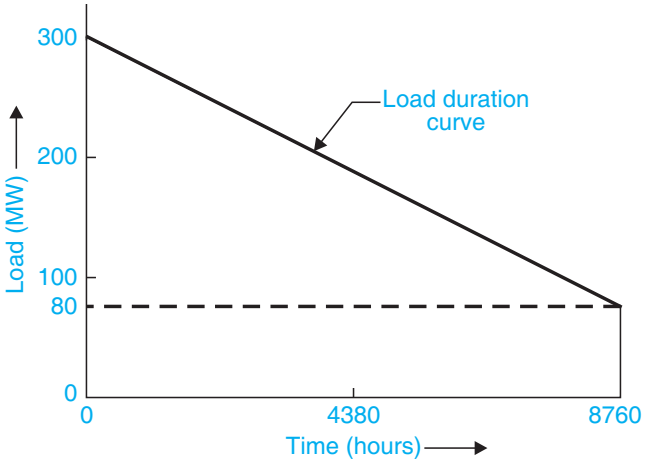


Fig. 9.17. Load duration curve.

(*i*) **Installed capacity :**

Installed capacity

= $200 + 2 \times 100 = \mathbf{400\ MW.}$ **(Ans.)**

(*ii*) **Load factor :**

Load factor

$$= \frac{\text{Average load}}{\text{Maximum demand}}$$

Average load

$$= \frac{\text{Total energy in load curve for the period}}{\text{Total number of hours in the period}}$$

$$= \frac{80 \times 8760 + \frac{1}{2} \times (300 - 80) \times 8760}{8760}$$

$$= \frac{8760}{8760}\left[80 + \frac{1}{2}(300 - 80)\right] = 190\ \text{MW}$$

$\therefore$ *Load factor* $= \frac{190}{300} = \mathbf{0.633.}$ **(Ans.)**

(iii) Plant factor :

$$\text{Plant factor} = \frac{\text{Average load}}{\text{Capacity of the plant}} = \frac{190}{400}$$

$$= \mathbf{0.475.} \quad \textbf{(Ans.)}$$

(iv) Maximum demand = 300 MW. (Ans.)

(v) Utilization factor :

$$\text{Utilization factor} = \frac{\text{Maximum load}}{\text{Rated capacity of the plant}}$$

$$= \frac{300}{400} = \mathbf{0.75.} \quad \textbf{(Ans.)}$$

☞**Example 9.7.** *A generating station has a maximum demand of 30 MW, a load factor of 0.6, a plant capacity of 0.48, and a plant use factor of 0.82. Find :*

(i) The daily energy produced.

(ii) The reserve capacity of the plant.

(iii) The maximum energy that could be produced if the plant were running all the time.

(iv) The maximum energy that could be produced daily, if the plant when running according to operating schedule were fully loaded.

Solution. Maximum demand of the power station = 30 MW

Load factor = 0.6

Plant capacity = 0.48

Plant use factor = 0.82

(i) The daily energy produced :

$$\text{Load factor} = \frac{\text{Average demand}}{\text{Maximum demand}}$$

$$0.6 = \frac{\text{Average demand}}{30}$$

$\therefore$ Average demand = $30 \times 0.6 = 18$ MW or 18000 kW

Daily energy product = Average demand × number of hours

$$= 18000 \times 24 = \mathbf{4.32 \times 10^5\ kWh.} \quad \textbf{(Ans.)}$$

(ii) Reserve capacity of the plant :

$$\text{Plant capacity factor} = \frac{\text{Average demand}}{\text{Installed capacity}}$$

$$0.48 = \frac{18000}{\text{Installed capacity}}$$

$$\therefore \text{Installed capacity} = \frac{18000}{0.48} = 37500 \text{ kW}$$

$\therefore$ *Reserve capacity of the plant*

= Installed capacity – maximum demand

$= 37500 - 30000 = \mathbf{7500\ kW.}$ **(Ans.)**

(iii) Maximum daily energy produced when running all the time

$= \mathbf{4.32 \times 10^5\ kWh.}$ **(Ans.)**

(iv) Maximum energy that could be produced daily :

Maximum energy that could be produced, operating as per operating schedule

$$= \frac{\text{Actual energy produced}}{\text{Plant use factor}}$$

$$= \frac{4.32 \times 10^5}{0.82} = \mathbf{5.268 \times 10^5\ kWh.} \quad \textbf{(Ans.)}$$

Example 9.8. *A power station has the following loads :*

1. Residential lighting load :

Maximum demand	*= 1200 kW*
Load factor	*= 0.21*
Diversity between consumers	*= 1.32*

2. Commercial load :

Maximum demand	*= 2400 kW*
Load factor	*= 0.32*
Diversity between consumers	*= 1.2*

3. Industrial load :

Maximum demand	*= 6000 kW*
Load factor	*= 0.82*
Diversity between consumers	*= 1.22*

Overall diversity factor may be taken as 1.42.

Determine the following :

(i) Maximum demand on system.

(ii) Daily energy consumption (total).

(iii) Overall load factor.

(iv) Connected load (total) assuming that demand factor for each load is unity.

Solution. (i) Maximum demand on system :

Group diversity factor

$$= \frac{\text{Sum of individual maximum demands}}{\text{Actual maximum demand of the group}}$$

$$\therefore \quad 1.42 = \frac{1200 + 2400 + 6000}{\text{Maximum demand on system}}$$

i.e., Maximum demand on system

$$= \frac{1200 + 2400 + 6000}{1.42}$$

$= \mathbf{6760.5\ kW.}$ **(Ans.)**

(ii) Daily energy consumption :

$$\text{Load factor} = \frac{\text{Average demand}}{\text{Maximum demand}}$$

or Average demand = Maximum demand × load factor

$= 1200 \times 0.21 + 2400 \times 0.32 + 6000 \times 0.82$

$= 5940$ kW

$\therefore$ *Daily energy consumption*

$= 5940 \times 24 = \mathbf{142560\ kWh.}$ **(Ans.)**

(iii) Overall load factor :

$$\text{Overall load factor} = \frac{\text{Average demand}}{\text{Maximum demand}}$$

$$= \frac{5940}{6760.5} = \mathbf{0.878.} \quad \textbf{(Ans.)}$$

(iv) Connected load :

Maximum demand

$= 1200 \times 1.32 + 2400 \times 1.2 + 6000 \times 1.22$

$= 11784$ kW

Connected load

$$= \frac{\text{Maximum demand}}{\text{Demand factor}} = \frac{11784}{1}$$

$= \mathbf{11784\ kW.}$ **(Ans.)**

Example 9.9. *The following data relates to a steam power plant :*

Maximum demand	*= 30000 kW*
Load factor	*= 0.42*
Coal consumption	*= 1.1 kg/kWh*
Boiler efficiency	*= 84%*
Turbine efficiency	*= 88%*
Price of coal	*= ₹ 70 per tonne.*

Determine the following :

(i) Thermal efficiency of the plant.

(ii) Coal bill of the plant for one year.

Solution. (i) Thermal efficiency of the plant :

Thermal efficiency of the plant

= Boiler efficiency × turbine efficiency

$= 0.84 \times 0.88 =$ **0.7392 or 73.92%.** **(Ans.)**

(ii) Coal bill :

Average demand on station = Maximum demand × load factor

$= 30000 \times 0.42 = 12600$ kW

$\therefore$ Energy generated per year

$= 12600 \times (365 \times 24)$ kWh

$\therefore$ Coal consumption

$= 12600 \times (365 \times 24) \times 1.1$ kg per year

$\therefore$ *Coal bill*

$$= \frac{12600 \times (365 \times 24) \times 1.1 \times 70}{1000}$$

$= \mathbf{₹\ 8498952.}$ **(Ans.)**

☞**Example 9.10.** *A power station is to supply for regions of load whose peak loads are 10 MW, 5 MW, 8 MW and 7 MW. The diversity factor of the load at the station is 1.5 and the average annual load factor is 0.6. Calculate :*

(i) Maximum demand on the station.

(ii) Annual energy supplied from the station.

Suggest the installed capacity and the number of units taking all aspects into account.

Solution. (i) Maximum demand :

Maximum demand on power station

$$= \frac{\text{Sum of individual maximum demands}}{\text{Diversity factor}}$$

$$= \frac{10 + 5 + 8 + 7}{1.5}$$

$= \mathbf{20\ MW \quad or \quad 20000\ kW.}$ **(Ans.)**

(ii) Annual energy supplied :

Average load = Maximum demand × load factor

$= 20000 \times 0.6 = 12000$ kW

Annual energy supplied from the station

$= \text{Average load} \times (365 \times 24)$

$= 12000 \times (365 \times 24)$

$= \mathbf{105.12 \times 10^6\ kWh.}$ **(Ans.)**

Installed capacity and number of units :

Considering 50% increase in maximum demand on the power station in next five years, the *installed capacity* should be **30000 kW or 30 MW.** **(Ans.)**

Select, four similar units each of 7.5 MW capacity because minimum number of spare parts will be required to be stored, at the same time *three units can supply present maximum demand and fourth unit can be taken out for routine maintenance or during breakdown without any disruption in supply.*

Example 9.11. *The peak load on a 50 MW power station is 39 MW. It supplies power through four transformers whose connected loads are 17, 12, 9 and 10 MW. The maximum demands on these transformers are 15, 10, 8 and 9 MW respectively. If the annual load factor is 50% and the plant is operating for 65% of the period in a year, find out the following :*

(i) Average load on the station

(ii) Energy supplied per year

(iii) Demand factor

(iv) Diversity factor

(v) Power station use factor.

Solution. Power station rated capacity

$= 50$ MW or 50000 kW

Maximum demand on the power station

$= 39$ MW or 39000 kW

Sum of connected load

$= 17 + 12 + 9 + 10 = 48$ MW or 48000 kW

Sum of maximum demands on the transformers

$= 15 + 10 + 8 + 9 = 42$ MW or 42000 kW

Annual load factor = 50% or 0.5

Plant operating period

$= 0.65 \times (365 \times 24) = 5964$ hours.

(i) Average load on the station :

Average load on the station = Maximum demand × load factor

$= 39000 \times 0.5 =$ **19500 kW.** **(Ans.)**

(ii) Energy supplied per year :

Energy supplied per year

$= \text{Average load} \times (365 \times 24)$

$= 19500 \times 8760$

$=$ **170.82×10^6 kWh.** **(Ans.)**

(iii) Demand factor :

$$\textit{Demand factor} = \frac{\text{Maximum demand}}{\text{Sum of connected load}}$$

$$= \frac{39000}{48000} = \textbf{0.8125.} \quad \textbf{(Ans.)}$$

(iv) Diversity factor :

$$\textit{Diversity factor} = \frac{\text{Sum of maximum demands}}{\text{Maximum demand}}$$

$$= \frac{42000}{39000} = \textbf{1.077.} \quad \textbf{(Ans.)}$$

(v) Power station use factor :

Use factor

$$= \frac{\text{Energy generated per year}}{\text{Rated capacity} \times \text{number of operating hours}}$$

$$= \frac{170.82 \times 10^6}{50000 \times 5694} = \textbf{0.6 or 60\%.} \quad \textbf{(Ans.)}$$

Example 9.12. *A base load power station and standby power station share a common load as follows :*

Base load station annual output $= 180 \times 10^6$ *kWh*

Base load station capacity $= 42$ *MW*

Maximum demand on base load station $= 36$ *MW*

Standby station capacity $= 22$ *MW*

Standby station annual output $= 17 \times 10^6$ *kWh*

Maximum demand (peak load) on stand by station $= 18$ *MW*

Determine the following for both power stations :

(i) Load factor.

(ii) Capacity (or plant) factor.

Solution. Base load station :

$$\text{Average load} = \frac{180 \times 10^6}{365 \times 24} = 20548 \text{ kW}$$

(i) Load factor $= \dfrac{\text{Average load}}{\text{Maximum demand}} = \dfrac{20548}{36 \times 10^3}$

$=$ **0.57.** **(Ans.)**

(ii) Capacity factor

$$= \frac{\text{Energy generated}}{\text{Capacity of plant} \times (24 \times 365)}$$

$$= \frac{180 \times 10^6}{42 \times 1000 \times 24 \times 365}$$

$=$ **0.489.** **(Ans.)**

Standby power station :

$$\text{Annual average load} = \frac{17 \times 10^6}{365 \times 24} = 1940.6 \text{ kW}$$

(i) Load factor

$$= \frac{\text{Average load}}{\text{Maximum demand}} = \frac{1940.6}{18 \times 1000}$$

$=$ **0.1078.** **(Ans.)**

(ii) Capacity factor $= \dfrac{\text{Energy generated}}{\text{Capacity} \times (24 \times 365)}$

$$= \frac{17 \times 10^6}{22 \times 1000 \times 24 \times 365}$$

$=$ **0.088.** **(Ans.)**

☞**Example 9.13.** *A base load station having a capacity of 18 MW a standby station having a capacity of 20 MW share a common load. Find (i) annual load factor, (ii) use factor, and (iii) capacity factor of the two power stations from the following data :*

Annual standby station output $= 7.35 \times 10^6$ *kWh*

Annual base load station output $= 101.35 \times 10^6$ *kWh*

Peak load on the standby station $= 12$ *MW*

Hours of use of standby station during the year $= 2190$ *hours.*

Solution. Standby station :

Capacity of standby station $= 20$ MW or 20000 kW

Maximum demand on standby station $= 12$ MW or 12000 kW

Annual standby station output $= 7.35 \times 10^6$ kWh

Hours of use of standby station during the year $= 2190$ hours

Annual average load of standby station

$$= \frac{\text{Output in kWh}}{365 \times 24} = \frac{7.35 \times 10^6}{365 \times 24}$$

$= 839$ kW

(i) Annual load factor :

Annual load factor

$$= \frac{\text{Annual average load}}{\text{Maximum demand}} = \frac{839}{12000}$$

$=$ **0.07 or 7%.** **(Ans.)**

(ii) Use factor :

Use factor

$$= \frac{\text{Total kWh generated}}{\text{Rated capacity of station} \times \text{Number of operating hours}}$$

$$= \frac{7.35 \times 10^6}{20000 \times 2190}$$

$$= \mathbf{0.1678 \quad or \quad 16.78\%.} \quad \textbf{(Ans.)}$$

(iii) Capacity factor :

$$\textit{Capacity factor} = \frac{\text{Average load}}{\text{Rated capacity}} = \frac{839}{20000}$$

$$= \mathbf{0.0419 \quad or \quad 4.19\%.} \quad \textbf{(Ans.)}$$

Base load station :

Capacity of base load station

$$= 18 \text{ MW or } 18000 \text{ kW}$$

Assume maximum demand on base load station equal to its rated capacity *i.e.,* 18 MW.

Annual base load station output

$$= 101.35 \times 10^6 \text{ kWh}$$

Annual average load of base load station

$$= \frac{\text{Output in kWh}}{365 \times 24}$$

$$= \frac{101.35 \times 10^6}{365 \times 24} = 11570 \text{ kW}$$

(i) Annual load factor :

Annual load factor

$$= \frac{\text{Annual average load}}{\text{Maximum demand}}$$

$$= \frac{11570}{18000} = \mathbf{0.643 \quad or \quad 64.3\%.} \quad \textbf{(Ans.)}$$

(ii) Use factor :

Use factor

$$= \frac{\text{Total kWh generated}}{\text{Rated capacity} \times \text{Number of operating hours}}$$

$$= \frac{101.35 \times 10^6}{18000 \times (365 \times 24)}$$

$$= \mathbf{0.643 \quad or \quad 64.3\%.} \quad \textbf{(Ans.)}$$

(iii) Capacity factor :

$$\textit{Capacity factor} = \frac{\text{Average load}}{\text{Rated capacity}} = \frac{11570}{18000}$$

$$= \mathbf{0.643 \quad or \quad 64.3\%.} \quad \textbf{(Ans.)}$$

COST ANALYSIS

Example 9.14. *Determine the annual cost of a feed water softner from the following data :*

Cost	= ₹ *96000*
Salvage value	= *5%*
Life	= *10 years*
Annual repair and maintenance cost	= ₹ *3000*
Annual cost of chemicals	= ₹ *6000*
Labour cost per month	= ₹ *360*
Interest on sinking fund	= *5%.*

Solution. Capital cost, P = ₹ 96000.

Salvage value, $S = \frac{5}{100} \times 96000$ = ₹ 4800

Rate of interest on sinking fund, i = 5% or 0.05

Life, n = 10 years

∴ Annual sinking fund payment

$$= (P - S)\left[\frac{i}{(1+i)^n - 1}\right]$$

$$= (9600 - 4800)\left[\frac{0.05}{(1+0.05)^{10} - 1}\right]$$

= ₹ 7250.8

Total cost per year :

Annual sinking fund

= ₹ 7250.8

Annual repair and maintenance cost

= ₹ 3000

Annual cost of chemicals

= ₹ 6000

Annual labour cost

= (360 × 12) = ₹ 4320

∴ *Total cost per year*

= 7250.8 + 3000 + 6000 + 4320

= ₹ **20570.8.** **(Ans.)**

Example 9.15. *The output of a generating station is 500 × 10^6 kWh per year and average load factor is 0.7. If the annual fixed charges are ₹50 per kW of installed plant and annual running charges are 5 per kWh, what is the cost per kWh of energy at the bus bar.*

Solution. Output energy per annum = 500 × 10^6 kWh

Average load

$$= \frac{\text{Annual average load}}{365 \times 24} = \frac{500 \times 10^6}{365 \times 24}$$

= 57077 kW

Maximum demand

$$= \frac{\text{Average load}}{\text{Load factor}} = \frac{57077}{0.7}$$

= 81538 kW

Assuming installed capacity equal to maximum demand,

Fixed charges = 50 × 81538 = ₹ 4076900

Running charges

$$= ₹ \frac{5}{100} \times 500 \times 10^6 = ₹ 25000000$$

Total annual charges

= ₹ 25000000 + ₹ 4076900

= ₹ 29076900

Cost of energy at bus-bar

$$= \frac{\text{Total annual charges}}{\text{Output energy per annum}}$$

$$= \frac{29076900}{500 \times 10^6}$$

= ₹ 0.058 or 5.8 p/kWh. (Ans.)

Example 9.16. *From the following data calculate the cost of generation per unit delivered from the power plant :*

Installed capacity of the power plant = 200 MW
Annual load factor = 0.4
Capital cost of power plant = ₹280 lacs
Annual cost of fuel, oil, salaries, taxation = ₹60 lacs.
Interest and depreciation = 13%.

Solution. Installed capacity of the power plant

= 200 MW or 200×10^3 kW

Assuming maximum demand equal to installed capacity,

Maximum demand $= 200 \times 10^3$ kW

Annual load factor = 0.4

Total units generated per annum

= Maximum demand × load factor × (365 × 24)

$= 200 \times 10^3 \times 0.4 \times (365 \times 24) = 700.8 \times 10^6$ kWh

Capital cost of the power plant = ₹ 280×10^5

Annual interest and depreciation

$$= ₹\ 280 \times 10^6 \times \frac{13}{100} = ₹\ 3.64 \times 10^6$$

Annual cost of fuel, oil, salaries, taxation etc.

$= ₹\ 60 \times 10^5$ or 6×10^6

Total annual cost

$= ₹\ 3.64 \times 10^6 + ₹\ 6 \times 10^6 = ₹\ 9.64 \times 10^6$

Generating cost

$$= \frac{\text{Total annual cost}}{\text{Total units generated per annum}}$$

$$= \frac{9.64 \times 10^6}{700.8 \times 10^6}$$

= ₹ 0.0137 or 1.37 p/kWh. (Ans.)

☞**Example 9.17.** *The following data relate to a 10 MW power station :*

Cost of plant = ₹1200 per kW
Interest, insurances and taxes = 5% per annum
Depreciation = 5%
Cost of primary distribution = ₹500000
Interest, insurances, taxes and depreciation = 5%
Cost of coal including transportation = ₹4.4 per kN
Operating cost = ₹500000
Plant maintenance cost :
(i) Fixed = ₹20000 per annum
(ii) Variable = ₹30000 per annum
Installed plant capacity = 10000 kW
Maximum demand = 9000 kW
Annual load factor = 0.6
Consumption of coal = 255000 kN
Determine the following :
(i) Cost of power generation per kW per year.
(ii) Cost per kWh generated.
(iii) Total cost of generation per kWh.
Transmission or primary distribution chargeable to generation.

Solution. Installed capacity of plant

= 10 MW or 10000 kW

Total cost of plant

$= ₹\ 10000 \times 1200 = ₹\ 12 \times 10^6$

Annual interest, insurances and taxes

$= ₹\ 0.05 \times 12 \times 10^6 = ₹\ 0.06 \times 10^6$

= ₹ 600000

Annual depreciation

$= ₹\ 0.05 \times 12 \times 10^6 = ₹\ 0.6 \times 10^6$

= ₹ 600000

Annual interest, insurance, taxes and depreciation on primary distribution

= ₹ 0.05 × 500000 = ₹ 25000

Annual plant maintenance cost (fixed)

= ₹ 20000

Total fixed cost

= ₹ (600000 + 600000 + 25000 + 20000)

= ₹ 1245000

Annual operating cost

= ₹ 500000

Annual plant maintenance cost (variable)

= ₹ 30000

Annual cost of coal

= ₹ 4.4 × 255000 = ₹ 1122000

Total annual running cost

= ₹ (500000 + 300000 + 1122000)

= ₹ 1652000

Maximum demand

= 9000 kW

Annual load factor
$= 0.6$
Average load
$= 9000 \times 0.6 = 5400$ kW
Annual energy generated
$= 5400 \times 365 \times 24 = 47.3 \times 10^6$ kWh

(i) Cost of power generation per kW per year :

Annual cost per kW of maximum demand

$$= \frac{\text{Fixed cost per annum}}{\text{Maximum demand}}$$

$$= \frac{1245000}{9000} = ₹\ 138.33. \quad \textbf{(Ans.)}$$

(ii) Cost per kWh generated :

Annual cost/kWh

$$= \frac{\text{Annual running cost}}{\text{Annual energy generated}}$$

$$= \frac{1652000}{47.3 \times 10^6} = ₹\ 0.035 \text{ or } 3.5 \text{ p.} \quad \textbf{(Ans.)}$$

(iii) Total cost per kWh :

Total cost per kWh

$$= \frac{\text{Total annual cost}}{\text{Annual energy generated}}$$

$$= \frac{1245000 + 1652000}{47.3 \times 10^6}$$

$= ₹\ 0.06$ or 6 p. **(Ans.)**

Example 9.18. *Annual 200 MW steam power station is estimated to cost ₹350 millions. Other costs are as follows :*

Insurance and taxes
$= ₹5$ *lacs per annum*
Fuel and lubricants
$= ₹70$ *lacs per annum*
Transport and storage
$= ₹10$ *lacs per annum*
Salaries and wages
$= ₹12$ *lacs per annum*
Miscellaneous
$= ₹2$ *lacs per annum*

Reckoning interest and depreciation at 15% per annum of capital cost, determine :

The cost of energy generated per unit if the power station works at an average load factor of 0.6. What would it be, if the load factor be increased to 75% with a consequent increase in fuel costs by 10%, other costs remaining the same ?

Solution. Capacity of steam power station
$= 200$ MW or 200000 kW
Cost of power station
$= ₹\ 350$ millions $= ₹\ 350 \times 10^6$
Annual cost of insurance and taxes
$= ₹\ 5$ lacs $= ₹\ 0.5 \times 10^6$
Annual cost of fuel and lubricants
$= ₹\ 70$ lacs $= ₹\ 7 \times 10^6$
Annual cost of transport and storage
$= ₹\ 10$ lacs $= ₹\ 1 \times 10^6$
Annual cost of salaries and wages
$= ₹\ 12$ lacs $= ₹\ 1.2 \times 10^6$
Annual miscellaneous cost
$= ₹\ 2$ lacs $= ₹\ 0.2 \times 10^6$
Annual interest and depreciation

$$= ₹\ 350 \times 10^6 \times \frac{15}{100} = ₹\ 52.5 \times 10^6$$

Total annual cost
$= ₹\ (0.5 + 7 + 1 + 1.2 + 0.2 + 52.5) \times 10^6$
$= ₹\ 62.4 \times 10^6$
Total energy generated per annum
$=$ Maximum demand $\times$ average load factor $\times (365 \times 24)$
$= 200000 \times 0.6 \times (365 \times 24)$
$= 1051.2 \times 10^6$ kWh
Cost of generation

$$= \frac{\text{Total annual cost}}{\text{Total units generated}}$$

$$= \frac{62.4 \times 10^6}{1051.2 \times 10^6} = ₹\ 0.0594 \text{ per kWh}$$

or 5.94 paise per kWh. **(Ans.)**

If the load factor is improved to 75% :

Total energy generated per annum
$= 200000 \times 0.75 \times (365 \times 24)$
$= 1314 \times 10^6$ kWh
Annual operating cost
$= ₹\ (0.5 + 7 \times 1.1 \times 10^6 + 1 + 1.2 + 0.2 + 52.5) \times 10^6$
$= ₹\ 63.1 \times 10^6$

Cost of generation

$$= \frac{\text{Total annual cost}}{\text{Total units generated}}$$

$$= \frac{63.1 \times 10^6}{1314 \times 10^6} = ₹\ 0.048 \text{ per kWh}$$

or 4.8 paise per kWh. **(Ans.)**

Example 9.19. *A steam station has two 110 MW units. Following cost data are given :*

Particulars	***Units A***	***Units B***
Capital cost	*₹2400 per kW*	*₹3000 per kW*
Fixed charge rate	*10%*	*10%*
Capital factor	*0.55*	*0.60*
Fuel consumption	*1 kg/kWh*	*0.9 kg/kWh*
Fuel cost	*₹96 per 1000 kg*	*₹96 per 1000 kg*

Annual cost of operation, labour maintenance and supplies	*20% of annual fuel cost*	*15% of annual fuel cost*
Utilisation factor	*1*	*1*

Calculate the following :

(i) Annual plant cost and generation cost of unit A.

(ii) Annual plant cost and generation cost of unit B.

(iii) Overall generation cost of the station.

Solution. (*i*) Annual plant cost and generation cost of unit A :

Annual fixed cost of unit A

$$= \frac{10}{100} \times 2400 \times (100 \times 1000)$$

$$= ₹\ 26.4 \times 10^6$$

Annual energy output

= Maximum demand × capacity factor × no. of hours

$$= (100 \times 1000) \times 0.55 \times (356 \times 24)$$

$$= 52.998 \times 10^7 \text{ kWh}$$

Annual fuel consumption

$$= 1 \times 52.998 \times 10^7$$

$$= 52.998 \times 10^7 \text{ kg}$$

$$\text{Fuel cost} = \frac{96}{1000} \times 52.998 \times 10^7 = ₹\ 50.87 \times 10^7$$

Annual cost of operating labour, maintenance and supplies

= 20% of annual cost

$$= \frac{20}{100} \times 50.87 \times 10^6 = ₹\ 10.174 \times 10^6$$

The annual operating cost of unit A

= Annual fuel cost + annual cost of operation, labour and maintenance

$$= ₹\ (50.87 \times 10^6 + 10.174 \times 10^6)$$

$$= ₹\ 61.044 \times 10^6$$

Annual plant cost of unit A

= Annual fixed cost + annual operating cost

$$= ₹\ (26.4 \times 10^6 + 61.044 \times 10^6)$$

$$= ₹\ \mathbf{87.444 \times 10^6}. \quad \textbf{(Ans.)}$$

Generation cost of unit A

$$= \frac{\text{Annual plant cost}}{\text{Annual energy output}}$$

$$= \frac{87.444 \times 10^6}{52.998 \times 10^7} = ₹\ \mathbf{0.165}$$

or 165.5 p/kWh. (Ans.)

(*ii*) Annual plant cost and generation cost of unit B :

Annual fixed cost of unit B

$$= ₹\ \frac{10}{100} \times 3000 \times 110 \times 1000 = ₹\ 33 \times 10^6$$

Expected annual energy output

$$= (110 \times 1000) \times (365 \times 24) \times 0.6$$

$$= 57.816 \times 10^7 \text{ kWh}$$

Annual fuel consumption

$$= 0.9 \times 57.816 \times 10^7 = 52.0344 \times 10^7 \text{ kg}$$

$$\text{Fuel cost} = \frac{96}{100} \times 52.0344 \times 10^7 = ₹\ 49.95 \times 10^6$$

Annual cost of maintenance, repair etc.

$$= ₹\ \frac{15}{100} \times 49.95 \times 10^6 = ₹\ 7.4925 \times 10^6$$

Annual operating cost

= Fuel cost + maintenance cost

$$= ₹\ (49.95 \times 10^6 + 7.4925 \times 10^6)$$

$$= ₹\ 57.4425 \times 10^6$$

Annual plant cost of unit B

= Fixed cost + operating cost

$$= ₹\ 33 \times 10^6 + 57.4425 \times 10^6$$

$$= ₹\ \mathbf{90.4425 \times 10^6} \quad \textbf{(Ans.)}$$

Generation cost of unit B

$$= \frac{\text{Annual plant cost}}{\text{Annual energy output}}$$

$$= \frac{90.4425 \times 10^6}{57.816 \times 10^7}$$

$$= ₹\ \mathbf{0.1564} \quad \textbf{or} \quad \mathbf{15.64\ p/kWh.} \quad \textbf{(Ans.)}$$

(*iii*) Overall generation cost of the station

$$= \frac{\text{Sum of annual plant cost of both units}}{\text{Sum of energy supplied}}$$

$$= \frac{87.444 \times 10^6 + 90.4425 \times 10^6}{52.998 \times 10^7 + 57.816 \times 10^7}$$

$$= ₹\ \mathbf{0.16 \text{ or } 16\ p/kWh.} \quad \textbf{(Ans.)}$$

☞**Example 9.20.** *The annual costs of operating a 15000 kW thermal power station are as follows :*

Cost of plant = ₹ 1080 per kW

Interest, insurance, taxes on plant = 5 per cent

Depreciation = 5 per cent

Cost of primary distribution system = ₹ 600000

Interest, insurance, taxes and depreciation on primary distribution system = 5 per cent

Cost of secondary distribution system = ₹ 1080000

Interest, taxes, insurance and depreciation on secondary distribution system = 5 per cent

Maintenance of secondary distribution system = ₹ 216000

Plant maintenance cost
(i) Fixed cost = ₹ *36000*
(ii) Variable cost = ₹ *48000*
Operating costs = ₹ *720000*
Cost of coal = ₹ *7.2 per kN*
Consumption of coal = *300000 kN*
Dividend to stock holders = ₹ *1200000*
Energy loss in transmission = *10 per cent*
Maximum demand = *14000 kW*
Diversity factor = *1.5*
Load factor = *0.7*
Determine : (i) Charge per kW per year
(ii) Rate per kWh.

Solution. Maximum demand = 14000 kW

$$\text{Load factor} = 0.7 = \frac{\text{Average load}}{\text{Maximum demand}}$$

$\therefore$ Average load = $0.7 \times 14000 = 9800$ kW

$\therefore$ Energy generated per year
$= 9800 \times (365 \times 24)$
$= 85.8 \times 10^6$ kWh

Cost of plant = Capacity of plant × cost per kW
$= 15000 \times 1080 = ₹\ 16.2 \times 10^6$

Interest, insurances, taxes on plant

$$= \frac{5}{100} \times 16.2 \times 10^6 = ₹\ 810000$$

$$\text{Plant depreciation} = \frac{5}{100} \times 16.2 \times 10^6 = ₹\ 810000$$

Cost of primary distribution system = ₹ 600000

Interest, insurance, taxes, depreciation on primary distribution system

$$= \frac{5}{100} \times 600000 = ₹\ 30000$$

Cost of secondary distribution system = ₹ 1080000

$$= \frac{5}{100} \times 1080000 = ₹\ 54000$$

Cost of coal = $7.2 \times 300000 = ₹\ 2160000$.

(i) Charge per kW per year :

Fixed costs

Interest, taxes and insurance on plant
= ₹ 810000

Plant depreciation
= ₹ 810000

Interest, taxes, insurance and depreciation on :

Primary distribution system
= ₹ 30000

Secondary distribution system
= ₹ 54000

Fixed part of plant maintenance
= ₹ 36000

Dividend of stock-holder
= ₹ 1200000

$\therefore$ Total fixed cost
= ₹ 2940000

Sum of maximum demand of consumers
= Maximum demand × diversity factor
$= 14000 \times 1.5 = 21000$ kW

$$\textbf{Charge per kW per year} = \frac{2940000}{21000}$$

= ₹ 140 per kW. **(Ans.)**

(ii) Rate per kWh :

Variable costs

Cost of coal = ₹ 2160000
Plant maintenance = ₹ 48000
Operating costs = ₹ 720000
Maintenance of secondary distribution system
= ₹ 216000
Total variable cost = ₹ 3144000
Energy loss in transmission
= 10 per cent

$\therefore$ Net energy transmitted
$= 0.9 \times 85.8 \times 10^6$
$= 77.22 \times 10^6$ kWh

$$\therefore \textbf{ Rate per kWh} = \frac{3144000}{77.22 \times 10^6}$$

= ₹ 0.0407
or 4.07 p/kWh. **(Ans.)**

Example 9.21. *It is proposed to supply a load with a maximum demand of 100 MW and a load factor of 0.4. Choice is to be made from nuclear, hydro and steam power plants. Calculate the overall cost per kWh in each scheme.*

Cost	*Nuclear power plant*	*Hydro-power plant*	*Steam power plant*
Capital per kW installed	₹ *6000*	₹ *4320*	₹ *2160*
Interest	*10%*	*10%*	*12%*
Depreciation	*10%*	*8%*	*12%*
Operating cost per kWh	*12 paise*	*6 paise*	*18 paise*
Transmission and distribution cost/kWh	*0.24 paise*	*0.96 paise*	*0.24 paise*

Solution. *(i)* **Nuclear power plant :**

Capital cost $= 6000 \times (100 \times 10^3) = ₹\ 60 \times 10^7$

Interest $= \frac{10}{100} \times 60 \times 10^7 = ₹\ 6 \times 10^7$

Depreciation $= ₹\ 6 \times 10^7$

Annual fixed cost (interest + depreciation)

$= ₹\ 12 \times 10^7$

Energy generated per year

= Average load × (365 × 24)

= Load factor × maximum demand × (365 × 24)

$= 0.4 \times (100 \times 10^3) \times (365 \times 24)$

$= 350.4 \times 10^6$ kWh

Running cost per kWh

= Operating cost per kWh + transmission and distribution cost per kWh

= 12 + 0.24 = 12.24 p

∴ **Overall cost per kWh**

= Running cost/kWh + fixed cost/kWh

$= 12.24 + \frac{12 \times 10^7}{350.4 \times 10^6} \times 100$

= **46.48 p.** **(Ans.)**

(ii) **Hydro-electric power plant :**

Capital cost $= 4320 \times 100 \times 10^3 = ₹\ 43.2 \times 10^7$

Interest $= \frac{10}{100} \times 43.2 \times 10^7 = ₹\ 43.2 \times 10^6$

Depreciation $= \frac{8}{100} \times 43.2 \times 10^7 = 34.56 \times 10^6$

Annual fixed cost

= Interest + depreciation

$= ₹\ (43.2 + 34.56) \times 10^6$

$= ₹\ 77.76 \times 10^6$

Running cost per kWh

= (Operation cost + transmission cost)

= (6 + 0.96) p = 6.96 p

Overall cost per kWh

= Running cost/kWh + annual fixed cost/kWh

$= 6.96 + \frac{77.76 \times 10^6}{350.4 \times 10^6} \times 100$

= 6.96 + 22.2 = **29.16 p.** **(Ans.)**

(iii) **Steam power plant :**

Capital cost $= ₹\ 2160 \times 100 \times 10^3$

$= ₹\ 21.6 \times 10^7$

Interest $= ₹\ \frac{12}{100} \times 21.6 \times 10^7$

$= ₹\ 25.92 \times 10^6$

Depreciation $= ₹\ \frac{12}{100} \times 21.6 \times 10^7$

$= ₹\ 25.92 \times 10^6$

Annual fixed cost = Interest + depreciation

$= ₹\ 2 \times 25.92 \times 10^6 = ₹\ 51.84 \times 10^6$

Running cost/kWh = 18 + 0.24 = 18.24 p

Overall cost/kWh = Running cost/kWh + fixed cost/kWh

$= 18.24 + \frac{51.84 \times 10^6}{350.4 \times 10^6} \times 100$

= 18.24 + 14.79 = **33.03 p.** **(Ans.)**

From the above calculations it is concluded that overall cost/kWh is *minimum in case of hydropower plant*.

☞**Example 9.22.** *A power plant of 180 MW installed capacity has the following data :*

Capital cost = *₹2160/kW installed*

Interest and depreciation = *12 per cent*

Annual load factor = *0.6*

Annual capacity factor = *0.5*

Annual running charges = *₹36 × 10⁶*

Energy consumed by power auxiliaries = *6 per cent*

Calculate : (i) Reserve capacity

(ii) Generation capacity.

Solution. Load factor $= \frac{\text{Average load}}{\text{Maximum demand}}$

and Capacity factor $= \frac{\text{Average load}}{\text{Rated capacity}}$

$\therefore \quad \frac{\text{Load factor}}{\text{Capacity factor}} = \frac{\text{Rated capacity}}{\text{Maximum demand}}$

$\frac{0.6}{0.5} = \frac{180}{\text{Maximum demand}}$

∴ Maximum demand

$= \frac{0.5 \times 180}{0.6} = 150$ MW.

(i) **Reserved capacity :**

Reserved capacity

= Installed/rated capacity – maximum demand

= 180 – 150 = **30 MW.** **(Ans.)**

(ii) **Generation cost :**

Average load = Load factor × maximum demand

= 0.6 × 150 = 90 MW

Energy generated per annum

$= 90 \times 10^3 \times (365 \times 24)$

$= 788.4 \times 10^6$ kWh

Energy consumed by auxiliaries

$= \frac{6}{100} \times 788.4 \times 10^6 = 47.3 \times 10^6$ kWh

Net energy available

$= 788.4 \times 10^6 - 47.3 \times 10^6$

$= 741.1 \times 10^6$ kWh

Fixed cost of generation

= Interest + depreciation

$= ₹ \frac{12}{100} \times 2160 \times 180 \times 10^3 = ₹ 46.65 \times 10^6$

Total annual cost

= Running cost + fixed cost

$= 36 \times 10^6 + 46.65 \times 10^6 = ₹ 82.65 \times 10^6$

$\therefore$ *Generation cost*

$= \frac{82.65 \times 10^6}{741.1 \times 10^6} \times 100 =$ **11.1 p.** **(Ans.)**

Example 9.23. *A power station has the installed capacity of 180 MW. Calculate the cost of generation, other data pertaining to power station are given below :*

Capital cost $= ₹ 300 \times 10^6$

Rate of interest and depreciation

$= 18$ *per cent*

Annual cost of fuel oil, salaries and taxation

$= ₹ 36 \times 10^6$

Load factor $= 0.4$

Also calculate the saving in cost per kWh if the annual load factor is raised to 0.5.

Solution. Assuming maximum demand equal to the capacity of the power plant,

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$0.4 = \frac{\text{Average load}}{180}$$

$\therefore$ Average load $= 0.4 \times 180 = 72$ MW

Energy generated per annum

$= 72 \times 10^3 \times (365 \times 24)$

$= 630.72 \times 10^6$ kWh

Fixed cost = Interest and depreciation on capital cost

$= \frac{18}{100} \times 300 \times 10^6 = ₹ 54 \times 10^6$

Running (operating cost)

= Cost of fuel oil, salaries and taxation

$= ₹ 36 \times 10^6$

Total annual cost

= Fixed cost + operating cost

$= ₹ (54 + 36) \times 10^6$

$= ₹ 90 \times 10^6$

$\therefore$ *Cost per kWh*

$= \frac{90 \times 10^6}{630.72 \times 10^6} \times 100$

$=$ **14.27 p. per kWh.** **(Ans.)**

When the load factor is raised to 0.5 :

Average load = Load factor × maximum demand

$= 0.5 \times 180 = 90$ MW

Energy produced per annum

$= 90 \times 10^3 \times 365 \times 24$

$= 788.4 \times 10^6$ kWh

Total annual cost will not change.

$\therefore$ Cost per kWh $= \frac{90 \times 10^6}{788.4 \times 10^6} \times 100$

$= 11.41$ p. per kWh

$\therefore$ *Saving in cost per kWh*

$= 14.27 - 11.41$

$=$ **2.86 p.** **(Ans.)**

Example 9.24. *A 60 MW generating station has the following data :*

Capital cost $= ₹ 18 \times 10^6$

Annual taxation $= ₹ 0.48 \times 10^6$

Annual salaries and wages $= ₹ 1.44 \times 10^6$

Cost of coal $= ₹ 72$ *per tonne*

Calorific value (C.V.) of coal $= 23000$ *kJ/kg*

Rate of interest and depreciation

$= 12$ *per cent*

Plant heat rate $= 138000$ *kJ/kWh at 100% capacity*

Calculate the generating cost/kWh at 100% capacity factor.

Solution. Maximum demand

= 60 MW (= peak load)

Fixed cost = Interest and depreciation on capital cost

$= ₹ \frac{12}{100} \times 18 \times 10^6 = ₹ 2.16 \times 10^6$

Running cost = Annual salaries, wages and taxation

$= ₹ (1.44 + 0.48)\ 10^6$

$= ₹ 1.92 \times 10^6$

At 100% capacity factor :

Rated/installed capacity

= 60 MW

$$\text{Capacity factor} = \frac{\text{Average load}}{\text{Rated capacity}} = 1$$

or Average load = Rated capacity = 60 MW

Average energy produced per annum

$= 60 \times 10^3 \times (365 \times 24)$ kWh

$= 525.6 \times 10^6$ kWh

Total plant heat rate

$= 138000 \times 525.6 \times 10^6$ kJ

Weight of coal required per annum

$$= \frac{138000 \times 525.6 \times 10^6}{23000 \times 1000} \text{ tonnes}$$

$$= 3.15 \times 10^6 \text{ tonnes}$$

Cost of fuel $= ₹\ 72 \times 3.15 \times 10^6$

$= ₹\ 226.8 \times 10^6$

Total annual cost $= ₹\ (2.16 + 1.92 + 226.8) \times 10^6$

$= ₹\ 230.88 \times 10^6$

Generation cost $= \frac{230.88 \times 10^6}{525.6 \times 10^6} \times 100$

$=$ **43.93 p.** **(Ans.)**

ECONOMIC LOAD SHARING

Example 9.25. *An input-output curve of a 10 MW station is expressed as follows :*

$$I = 4 \times 10^6 (10 + 8L + 0.4L^2)$$

where I is in kJ/hour and L is in megawatts.

(i) Without plotting any curve find the load at which the maximum efficiency occurs.

(ii) Find the increase in input required to increase station output from 3 to 5 MW by means of the input-output curve and also by incremental rate curve.

Solution. *(i)* **Load at which maximum efficiency occurs :**

$$I = 4 \times 10^6 (10 + 8L + 0.4L^2)$$

or $$\frac{I}{L} = 4 \times 10^6 \left(\frac{10}{L} + 8 + 0.4L\right)$$

Efficiency $$= \frac{\text{Output}}{\text{Input}} = \frac{L}{I}$$

$\therefore$ Efficiency, $$\eta = \frac{1}{4 \times 10^6 \left(\frac{10}{L} + 8 + 0.4L\right)} \quad ...(i)$$

Now the *efficiency will be maximum* when $\left(\frac{10}{L} + 8 + 0.4L\right)$ is *minimum*

i.e., $$\frac{d}{dL}\left(\frac{10}{L} + 8 + 0.4L\right) = 0$$

$\therefore$ $$-\frac{10}{L^2} + 0.4 = 0$$

or $$L^2 = \frac{10}{0.4} = 25 \quad \text{or} \quad L = 5 \text{ MW}$$

Hence the load at which the maximum efficiency occurs $=$ **5 MW.** **(Ans.)**

(ii) **Increase in input :**

(a) ***By input output curve :***

When load, L = 3 MW

Input, $I_3 = 4 \times 10^6 (10 + 8 \times 3 + 0.4 \times 3^2)$

$= 150.4 \times 10^6$ kJ/h

When load, $L = 5$ *MW*

Input, $I_5 = 4 \times 10^6 (10 + 8 \times 5 + 0.4 \times 5^2)$

$= 240 \times 10^6$ kJ/h

Increase in input required

$= I_5 - I_3$

$= (240 - 150.4) \times 10^6$

$=$ **89.6 × 10⁶ kJ/h.** **(Ans.)**

(b) ***By incremental rate curve :***

When load varies from 3 to 5 MW, the incremental rate may be considered to be straight line and the average height of area under the curve between 3 MW and 5 MW would be

$$= \frac{3+5}{2} = 4 \text{ MW}$$

$$I = 4 \times 10^6 (10 + 8L + 0.4L^2)$$

Increment rate,

$$IR = \frac{dI}{dL} = 4 \times 10^6 (8 + 0.8L)$$

$\therefore$ $IR = 4 \times 10^6 (8 + 0.8 \times 4)$ when load

$= 4$ MW

$= 4 \times 10^6 (8 + 3.2) = 4 \times 10^6 \times 11.2$

Hence total increase in input

$= 4 \times 10^6 \times 11.2 (5 - 3)$

$=$ **89.6 × 10⁶ kJ/h.** **(Ans.)**

This shows that increase in input required to increase the required output in both cases *(a)* and *(b)* is same. This *indicates that the incremental rate curve can be taken as straight line for small increase in output.*

Example 9.26. *The input-output curve of a 50 MW power station is given by :*

$$I = 4 \times 10^6 (8 + 8L + 0.4L^2) \text{ kJ/hour}$$

where I is the input in kJ/hour and L is load in MW.

(i) Determine the heat input per day to the power station if it works for 20 hours at full load and remaining period at no load.

(ii) Also find the saving per kWh of energy produced if the plant works at full load for all 24 hours generating the same amount of energy.

Solution. *(i)* **Heat input per day :**

Total energy generated by the plant during 24 hours

$= 20 \times 50 + 4 \times 0 = 1000$ MWh

Input to the plant when the plant is running at full load

$$I_{50} = 4 \times 10^6 (8 + 8 \times 50 + 0.4 \times 50^2) \times 20$$

$= 4 \times 1408 \times 20$ kJ during 20 hours

when the plant was running at *full load.*

Input at no load,

$I_0 = 4 \times 10^6 \times 8 \times 4$

$= 128 \times 10^6$ kJ during 4 hours when the plant was running at *no load.*

Total input to the plant during 24 hours

$$= I_{50} + I_0 = 4 \times 10^6 \times 1408 \times 20 + 128 \times 10^6$$
$$= 10^6 (5632 \times 20 + 128)$$
$$= \mathbf{112768 \times 10^6\ kJ/day.} \quad \textbf{(Ans.)}$$

(ii) Saving per kWh :

Average heat supplied per kWh generated

$$= \frac{112768 \times 10^6}{1000 \times 10^3} = 112768 \text{ kJ/kWh}$$

If the same energy is generated within 24 hours, the average load is given by :

$$\text{Average load} = \frac{1000}{24} = 41.67 \text{ MW}$$

Heat supplied during 24 hours in this case

$$I_{50} = 4 \times 10^6 (8 + 8 \times 50 + 0.4 \times 41.67^2) \times 24$$
$$= 4 \times 10^6 (8 + 400 + 694.5) \times 24$$
$$= 4 \times 10^6 \times 1102.5 \times 24 \text{ kJ/day}$$
$$= 105840 \times 10^6 \text{ kJ/day}$$

Net saving per day

$$= 112768 \times 10^6 - 105840 \times 10^6$$
$$= 6928 \times 10^6 \text{ kJ/day}$$

$\therefore$ *Saving per kWh*

$$= \frac{6928 \times 10^6}{1000 \times 10^3} = \mathbf{6928\ kJ/kWh.} \quad \textbf{(Ans.)}$$

Example 9.27. *The incremental fuel costs for two generating units 1 and 2 of a power plant are given by the following equations :*

$$\frac{dF_1}{dP_1} = 0.07\ P_1 + 24$$

$$\frac{dF_2}{dP_2} = 0.075\ P_2 + 22$$

where F is fuel cost in rupees per hour and P is power output in MW. Determine :

(i) The economic loading of the two units when the total load supplied by the power plants is 180 MW.

(ii) The loss in fuel cost per hour if the load is equally shared by both units.

Solution. (i) Economic loading of two units :

$$P_1 + P_2 = 180 \quad \text{...(Given)} \quad ...(i)$$

The condition required for economic loading is given by :

$$\frac{dF_1}{dP_1} = \frac{dF_2}{dP_2}$$

$$\therefore \quad 0.07\ P_1 + 24 = 0.075\ P_2 + 22 \quad ...(ii)$$

Substituting the value of P_2 (= $180 - P_1$) from (*i*) in (*ii*), we get

$$0.07\ P_1 + 24 = 0.075\ (180 - P_1) + 22$$

or $$0.07\ P_1 + 24 = 13.5 - 0.075\ P_1 + 22$$

or $$0.145\ P_1 = 11.5$$

or, $$P_1 = \frac{11.5}{0.145} = \mathbf{79.3\ MW.} \quad \textbf{(Ans.)}$$

and, $$P_2 = 180 - 79.3 = \mathbf{100.7\ MW.} \quad \textbf{(Ans.)}$$

(ii) Loss in fuel cost :

If the load is equally shared by both the units $\left(\text{supplying } \frac{180}{2} = 90 \text{ MW each}\right)$, then the increase in cost of fuel for *unit 1*

$$= \int_{79.3}^{90} (0.07\ P_1 + 24)\ dP_1$$
$$= \left[\frac{0.07\ P_1^2}{2} + 24 P_1\right]_{79.3}^{90}$$
$$= 0.035\ (90^2 - 79.3^2) + 24\ (90 - 79.3)$$
$$= 63.4 + 256.8 = ₹\ 320.2/\text{hour}$$

Increase in cost of fuel for *unit 2*

$$= \int_{100.7}^{90} (0.075\ P_2 + 22)\ dP_2$$
$$= \left[\frac{0.075 P_2^2}{2} + 22 P_2\right]_{100.7}^{90}$$
$$= \frac{0.075}{2}\ (90^2 - 100.7^2) + 22\ (90 - 100.7)$$
$$= -76.5 - 235.4 = ₹\ -311.9/\text{hour}$$

This indicates that the cost of fuel for unit 2 **decreases**.

Net increase in cost (or *loss in fuel cost*) due to departure from economic distribution of load

$$= 320.2 - 311.9 = \mathbf{₹\ 8.3/hour.} \quad \textbf{(Ans.)}$$

Example 9.28. *Two steam turbines each of 30 MW capacity take a load 45 MW. The steam consumption rates in kg per hour for both turbines are given by the following equations :*

$$S_1 = 2400 + 12 L_1 - 0.00012\ L_1^2$$
$$S_2 = 1200 + 8.4 L_2 - 0.00006\ L_2^2$$

L represents the load in kW and S represents the steam consumption per hour. Find the most economical loading when the load taken by both units is 45 MW.

Solution. $$L_1 + L_2 = 45 \text{ MW} = 45000 \text{ kW} \quad ...(i)$$

For the most economical loading, the required condition is

$$\frac{dS_1}{dL_1} = \frac{dS_2}{dL_2}$$

$$\therefore \quad 12 - 2 \times 0.00012\ L_1 = 8.4 - 2 \times 0.00006\ L_2$$
$$12 - 0.00024\ L_1 = 8.4 - 0.00012\ L_2 \quad ...(ii)$$

Substituting the value of L_2 (= $45000 - L_1$) from (*i*) in (*ii*), we get

$$12 - 0.00024\ L_1 = 8.4 - 0.00012\ (45000 - L_1)$$
$$12 - 0.00024\ L_1 = 8.4 - 5.4 + 0.00012\ L_1$$
$$0.00036\ L_1 = 9$$

$$\therefore \quad L_1 = \frac{9}{0.00036} = \mathbf{25000\ kW}$$

or 25 MW. **(Ans.)**

and $L_2 = 45000 - 25000 = \mathbf{20000\ kW}$

or 20 MW. **(Ans.)**

TARIFF

Example 9.29. *Two electrical units used for same purpose are compared for their economical working :*

(i) Cost of Unit-1 is ₹ 6000 and it takes 120 kW.

(ii) Cost of Unit-2 is ₹ 16800 and it takes 72 kW.

Each of them has a useful life of 40000 hours.

Which unit will prove economical if the energy is charged at ₹ 96 per kW of maximum demand per year and 6 p. per kWh ?

Assume both units run at full load.

Solution. *(i)* **Unit-1 :**

Capital cost per hour $= \frac{6000}{40000} = ₹\ 0.15$

Maximum demand $= 120$ kW

Charge for maximum demand per hour

$$= \frac{120 \times 96}{(365 \times 24)} = ₹\ 1.315$$

Energy charge per hour = Maximum demand × one hour × charge per kWh

$$= 120 \times 1 \times \frac{6}{100} = ₹\ 7.2$$

$\therefore$ Total charges per hour for operation of Unit-1

$$= 0.15 + 1.135 + 7.2 = ₹\ 8.485$$

(ii) **Unit-2 :**

Capital cost per hour

$$= \frac{16800}{40000} = ₹\ 0.42.$$

Charge for maximum demand per hour

$$= \frac{72 \times 96}{365 \times 24} = ₹\ 0.789$$

Energy charge per hour

$$= 72 \times 1 \times \frac{6}{100} = ₹\ 4.32$$

Total charges per hour for the operation of Unit-2

$$= 0.42 + 0.789 + 4.32 = ₹\ 5.529$$

The charges of operation for the Unit-2 per hour are less than the charges of operation for the Unit-1, therefore *Unit-2 is more economical* in this case. **(Ans.)**

Example 9.30. *The monthly electricity consumption of a residence can be approximated as under :*

Light load : 6 tube lights 40 watts each working for 4 hours daily

Fan load : 6 fans 100 watts each working for 6 hours daily

Refrigerator load : 2 kWh daily

Miscellaneous load : 2 kW for 2 hours daily

Find the monthly bill at the following tariff :

First 20 units ₹ 0.50/kWh

Next 30 units ₹ 0.40/kWh

Remaining units ₹ 0.30/kWh

Constant charge ₹ 2.50 per month

Discount for prompt payment = 5 per cent.

Solution. Total energy consumption in 30 days

$$= (6 \times 40 \times 4 \times 30 + 6 \times 100 \times 6 \times 30) \times \frac{1}{1000} + 2 \times 30 + 2 \times 2 \times 30$$

$$= (28800 + 108000) \times \frac{1}{1000} + 60 + 120$$

$= 316.8$ kWh per month

The monthly bill

$= ₹\ [(20 \times 0.5 + 30 \times 0.4 + 266.8 \times 0.3) + 2.5]$

$= ₹\ [(10 + 12 + 80.04) + 2.5] = ₹\ 104.54$

[$\because$ Remaining units per month $= 316.8 - 20 - 30 = 266.8$]

Net monthly bill if the payment is made promptly

$= 104.54 \times 0.9 = \mathbf{₹\ 94.08.}$ **(Ans.)**

Example 9.31. *An industrial undertaking has a connected load of 220 kW. The maximum demand is 180 kW. On an average each machine works for 60% time. Find the yearly expenditure on electricity if the tariff is :*

₹ 1200 + ₹ 120 per kW of maximum demand per year + ₹ 0.15 per kWh.

Solution. Energy consumption in one year

$= 180 \times 0.6 \times (365 \times 24) = 946080$ kWh

Total electricity bill

$= ₹\ (1200 + 120 \times 180 + 0.15 \times 946080)$

$= \mathbf{₹\ 164712.}$ **(Ans.)**

☞**Example 9.32.** *A Hopkinson demand rate is quoted as follows :*

Demand rates :

First 1 kW of maximum demand = ₹ 6/kW/month

Next 4 kW of maximum demand = ₹ 5/kW/month

Excess 5 kW of maximum demand = ₹ 4/kW/month

Energy rates :

First 50 kWh = 7 paise/kWh

Next 50 kWh = 5 paise/kWh

Next 200 kWh = 4 paise/kWh

Next 400 kWh = 3 paise/kWh

Excess over 700 kWh = 2 paise/kWh.

Determine : (i) The monthly bill for a total consumption of 2000 kWh and a maximum demand of 15 kW. Also find out the unit energy cost.

(ii) Lowest possible bill for a month and a corresponding unit energy cost.

Solution. *(i)* **Monthly bill and energy cost :**

Demand charges per month

$= ₹ (1 \times 6 + 4 \times 5 + 10 \times 4) = ₹ 66$

Energy charge $= ₹ [50 \times 7 + 50 \times 5 + 200 \times 4 + 400 \times 3 + 1300 \times 2] \times \frac{1}{100}$

$= ₹ (350 + 250 + 800 + 1200 + 2600) \times \frac{1}{100} = ₹ 52$

$\therefore$ *Monthly bill* $= 66 + 52 =$ **₹ 118.** **(Ans.)**

Average unit energy cost

$= \frac{118}{2000} \times 100$

$=$ **5.9 paise/kWh.** **(Ans.)**

(ii) **Lowest possible bill :**

The lowest possible bill will occur when average load

= Maximum load or at 100% load factor

$\therefore$ Maximum load

$= \text{Average load} = \frac{2000}{30 \times 24} = 2.77$ kW

$\therefore$ Demand charges

$= ₹ (6 + 1.77 \times 5) = ₹ 14.85$

Energy charges will be same

$= ₹ 52$

$\therefore$ *Minimum monthly bill*

$= 14.85 + 52 =$ **₹ 66.85.** **(Ans.)**

Unity energy cost for this condition

$= \frac{66.85}{2000} \times 100 =$ **3.34 paise/kWh.** **(Ans.)**

TARIFF AND COST ANALYSIS

☞**Example 9.33.** *A new factory requires a maximum demand of 700 kW and load factor of 25%. The following two suppliers are available :*

(i) Public supply tariff is ₹ 48 per kW of maximum demand plus 2.4 p. per kWh.

Capital cost	*= ₹ 84000*
Interest and depreciation	*= 10 per cent*

(ii) Private oil engine generating station :

Capital cost	*= ₹ 300000*
Fuel consumption	*= 3 N/kWh*
Cost of fuel	*= ₹ 8.4 per kN*
Wages	*= 0.48 p/kWh*
Maintenance cost	*= 0.36 p/kWh*
Interest and depreciation	*= 15 per cent.*

Find which supply will be more economical ?

Solution. Load factor $= \frac{\text{Average load}}{\text{Maximum demand}}$

$\therefore$ Average load

= Load factor × maximum demand

$= 0.25 \times 700 = 175$ kW

Energy consumed per year

$= 175 \times (365 \times 24) = 1.533 \times 10^6$ kWh.

(i) **Public supply :**

Maximum demand charges per year

$= 48 \times 700 = ₹ 33600$

Energy charge per year

$= \frac{2.4}{100} \times 1.533 \times 10^6 = ₹ 36792$

Interest and depreciation

$= \frac{10}{100} \times 84000 = ₹ 8400$

Total cost $= ₹ (33600 + 36792 + 8400) = ₹ 78792$

$\therefore$ *Energy cost per kWh*

$= \frac{78792}{1.533 \times 10^6} \times 100 =$ **5.14 p.**

(ii) **Private oil engine generating station :**

Fuel consumption

$= \frac{3 \times 1.533 \times 10^6}{1000} = 4599$ kN

Cost of fuel $= 4599 \times 8.4 = ₹ 38631$

Cost of wages and maintenance

$= \left(\frac{0.48 + 0.36}{100}\right) \times 1.533 \times 10^6 = ₹ 12877$

Interest and depreciation

$= \frac{15}{100} \times 300000 = ₹ 45000$

Total cost

$= ₹ (38631 + 12877 + 45000) = ₹ 96508$

Energy cost per kWh

$= \frac{96508}{1.533 \times 10^6} \times 100 =$ **6.29 p.**

As the energy cost per kWh for oil engine is less than the public supply, the oil engine generation is more preferable. **(Ans.)**

☞**Example 9.34.** *A load having a maximum demand of 100 MW and a load factor of 0.4 may be supplied by one of the following schemes :*

(i) A steam station capable of supplying the whole load.

(ii) A steam station in conjunction with pump storage plant which is capable of supplying 130 × 10^6 kWh energy per year with a maximum output of 40 MW.

Find out the cost of energy per unit in each of the two cases mentioned above.

Use the following data :

Capital cost of steam station

$= ₹\,2000/kW$ *of installed capacity*

Capital cost of pump storage plant

$= ₹\,1300/kW$ *of installed capacity*

Operating cost of steam plant

$= 6$ *p./kWh*

Operating cost of pump storage plant

$= 0.5$ *p./kWh*

Interest and depreciation together on the capital invested should be taken as 12 per cent. Assume that no space capacity is required.

Solution. (*i*) **Steam station :**

Capital cost $= 100 \times 10^3 \times 2000 = ₹\ 200 \times 10^6$

Interest and depreciation

$$= \frac{12}{100} \times 200 \times 10^6 = ₹\ 24 \times 10^6$$

Average load

= Load factor × maximum demand

$= 0.4 \times 100 \times 10^3 = 40000$ kW

Energy supplied per year

= Average load × (365 × 24)

$= 40000 \times 365 \times 24 = 350.4 \times 10^6$ kWh

∴ Interest and depreciation charges *per unit of energy*

$$= \frac{24 \times 10^6}{350.4 \times 10^6} \times 100 = 6.85 \text{ p/kWh}$$

∴ *Total cost per unit*

$= 6 + 6.85 =$ **12.85 p/kWh.** **(Ans.)**

(*ii*) **Steam station in conjunction with pump-storage plant :**

The load supplied by the steam plant

$= 100 - 40 = 60$ MW

∴ Capital cost of steam plant

$= 60 \times 1000 \times 2000 = ₹\ 120 \times 10^6$

Capital cost of pump storage plant

$= 40 \times 1000 \times 1300 = ₹\ 52 \times 10^6$

∴ Total capital cost of combined station

$= 120 \times 10^6 + 52 \times 10^6 = ₹\ 172 \times 10^6$

Interest and depreciation charges on capital investment

$$= \frac{12}{100} \times 172 \times 10^6 = ₹\ 20.64 \times 10^6$$

∴ Operating cost of pump storage plant

$$= \frac{0.5}{100} \times 130 \times 10^6 = ₹\ 0.65 \times 10^6$$

The energy units supplied by steam station

= Total units required – energy units supplied by pump storage plant

$= 350.4 \times 10^6 - 130 \times 10^6$

$= 220.4 \times 10^6$ kWh

Operating cost of the steam station

$$= \frac{6}{100} \times 220.4 \times 10^6 = ₹\ 13.22 \times 10^6$$

Total cost per year

$= ₹\ (20.64 \times 10^6 + 0.65 \times 10^6 + 13.22 \times 10^6)$

$= ₹\ 34.51 \times 10^6$

Total cost per unit

$$= \frac{34.51 \times 10^6}{350.4 \times 10^6} \times 100$$

$=$ **9.85 p/kWh.** **(Ans.)**

Note. If the above example is repeated with a load factor of 0.7 it will be observed from the results that the *cost of generation becomes less with higher load factor irrespective of the type of the plant.*

Example 9.35. *The following data relate to a 2000 kW diesel power station :*

The peak load on the plant $= 1500$ *kW*

Load factor $= 0.4$

Capital cost per kW installed $= ₹\,1200$

Annual costs $= 15$ *per cent of capital*

Annual operating costs $= ₹\,50000$

Annual maintenance costs :

(*i*) *Fixed* $= ₹\,9000$

(*ii*) *Variable* $= ₹\,18000$

Cost of fuel $= ₹\,0.45$ *per kg*

Cost of lubricating oil $= ₹\,1.3$ *per kg*

C.V. of fuel $= 41800$ *kJ/kg*

Consumption of fuel $= 0.45$ *kg/kWh*

Consumption of lubricating oil $= 0.002$ *kg/kWh*

Determine the following :

(*i*) *The annual energy generated.*

(*ii*) *The cost of generation per kWh.*

Solution. Capital cost of the plant

$= 2000 \times 1200 = ₹\ 2.4 \times 10^6$ per year

Interest on capital

$$= \frac{15}{100} \times 2.4 \times 10^6$$

$= ₹\ 0.36 \times 10^6$ per year.

(*i*) **Annual energy generated**

= Load factor × maximum demand × (365 × 24)

$= 0.4 \times 1500 \times 365 \times 24 =$ **5.256 × 10⁶ kWh.** **(Ans.)**

(ii) Cost of generation :

Fuel consumption $= 0.45 \times 5.256 \times 10^6$
$= 2.365 \times 10^6$ kg per year

Cost of fuel $= ₹\ 0.45 \times 2.365 \times 10^6$
$= ₹\ 1.064 \times 10^6$ per year

Lubricant consumption $= 0.002 \times 5.256 \times 10^6$
$= 10512$ kg per year

Cost of lubricating oil $= 1.3 \times 10512$
$= ₹\ 13665$ per year

Total fixed cost = Interest + maintenance (fixed)
$= 0.36 \times 10^6 + 9000$
$= ₹\ 369000$ per year

Total running or variable costs
= Fuel cost + lubricant cost
+ maintenance (running)
+ annual operating costs
$= 1.064 \times 10^6 + 13665 + 18000 + 50000$
$= ₹\ 1145665$ per year

Total cost = Fixed cost + running cost
$= 369000 + 1145665 = ₹\ 1514665$

Cost of generation

$$= \frac{1514665}{5.256 \times 10^6} \times 100$$

$=$ **28.8 paise/kWh.** **(Ans.)**

☞Example 9.36. *The annual costs of operating a 15 MW thermal plant are given below :*

Capital cost of plant
$= ₹\ 1500/kW$

Interest, insurance and depreciation
$= 10$ *per cent of plant cost*

Capital cost of primary and secondary distribution
$= ₹\ 20 \times 10^6$

Interest, insurance and depreciation on the capital cost of primary and secondary distribution
$= 5\%$ *the capital cost*

Plant maintenance cost
$= ₹\ 100 \times 10^3$ *per year*

Maintenance cost of primary and secondary equipment
$= ₹\ 2.2 \times 10^5$ *per year*

Salaries and wages
$= ₹\ 6.5 \times 10^5$ *per year*

Consumption of coal
$= 40 \times 10^4$ *kN per year*

Cost of coal $= ₹\ 9$ *per kN*

Dividend to stockholders
$= ₹\ 1.5 \times 10^6$ *per year*

Energy loss in transmission
$= 10$ *per cent*

Diversity factor $= 1.5$

Load factor $= 0.75$

Maximum demand
$= 12$ *MW*

(*i*) *Devise a two-part tariff.*

(*ii*) *Find the average cost per kWh.*

Solution. (i) Two-part tariff :

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$\therefore$ Average load
= Load factor × maximum demand
$= 0.75 \times 12 \times 10^3 = 9000$ kW

Energy generated per year
$= 9000 \times (365 \times 24) = 78.84 \times 10^6$ kWh

Cost of the plant
$= 15 \times 10^3 \times 1500 = ₹\ 22.5 \times 10^6$

Interest, insurance and depreciation charges of the plant

$$= \frac{10}{100} \times 22.5 \times 10^6 = ₹\ 2.25 \times 10^6$$

Interest, insurance and depreciation charges of primary and secondary equipments

$$= \frac{5}{100} \times 20 \times 10^6 = ₹\ 1.0 \times 10^6$$

Total fixed cost = Insurance, interest and depreciation costs + dividend to stock-holders
$= ₹\ (2.25 \times 10^6 + 1.5 \times 10^6) = ₹\ 3.75 \times 10^6$

Sum of individual maximum demand
= Maximum demand × diversity factor
$= 12 \times 10^3 \times 1.5 = 18000$ kW

$\therefore$ *Fixed charges per kW*

$$= \frac{3.75 \times 10^6}{18000} = ₹\ \mathbf{208.3.}$$

Total variable charges
= All maintenance costs
+ salaries and wages + fuel cost
$= (100 \times 10^3 + 2.2 \times 10^5) + 6.5 \times 10^5 + 40 \times 10^4 \times 9$
$= (1 \times 10^5 + 2.2 \times 10^5) + 6.5 \times 10^5 + 36 \times 10^5$
$= ₹\ 45.7 \times 10^5$ or $₹\ 4.57 \times 10^6$

Energy transmitted
= Energy generated × transmission efficiency
$= 78.84 \times 10^6$

$$\times \left(\frac{100 - \text{energy loss in transmission}}{100} \right)$$

$$= 78.84 \times 10^6 \times \frac{90}{100} = 70.956 \times 10^6 \text{ kWh}$$

$\therefore$ *Charges for energy consumption*

$$= \frac{4.57 \times 10^6}{70.956 \times 10^6} \times 100 = \textbf{6.44 paise/kWh.}$$

$\therefore$ *Two-part tariff*

$$= \textbf{₹ 208.3/kW + 6.44 paise/kWh.} \quad \textbf{(Ans.)}$$

(ii) Average cost per kWh :

Total charges = Fixed charges + variable charges

$$= 3.75 \times 10^6 + 4.57 \times 10^6$$

$$= ₹\ 8.32 \times 10^6$$

Average cost of supply

$$= \frac{8.32 \times 10^6}{70.956 \times 10^6} \times 100$$

$$= \textbf{11.72 paise/kWh.} \quad \textbf{(Ans.)}$$

Example 9.37. *A 10 MW thermal power plant has the following data :*

Peak load = *8 MW*

Plant annual load factor = *0.72*

Cost of the plant = *₹800/kW installed capacity*

Interest, insurance and depreciation = *10 per cent of the capital cost*

Cost of transmission and distribution system = *₹350 × 10³*

Interest, depreciation on distribution system = *5 per cent*

Operating cost = *₹350 × 10³ per year*

Cost of coal = *₹6 per kN*

Plant maintenance cost

= *₹30000/year (fixed)*

= *₹40000/year (running)*

Coal used = *250000 kN/year*

Assume transmission and distribution costs are to be charged to generation

(i) Devise a two-part tariff.

(ii) Average cost of generation in paise/kWh.

Solution. (i) Two-part tariff :

S. No.	Items	Fixed cost per year (in ₹)	Running cost per year (in ₹)
1.	Interest, depreciation etc. of the plant	$\frac{10}{100} \times 10000 \times 800$ $= ₹\ 800 \times 10^3$	–
2.	Interest, depreciation etc. of the transmission and distribution	$\frac{5}{100} \times 350 \times 10^3$ $= 17.5 \times 10^3$	–
3.	Annual cost of coal	–	250000×6 $= 1500 \times 10^3$
4.	Operating cost	–	$= 350 \times 10^3$
5.	Plant maintenance cost	$= 30 \times 10^3$	$= 40 \times 10^3$
	Total cost	847.5×10^3	1890×10^3

$\therefore$ Grand total cost

$$= \text{Fixed cost + running cost}$$

$$= 847.5 \times 10^3 + 1890 \times 10^3$$

$$= ₹\ 2737.5 \times 10^3$$

Energy generated/year

$$= \text{Average load} \times (365 \times 24)$$

$$= (\text{Peak load} \times \text{load factor}) \times (365 \times 24)$$

$$= (8 \times 10^3 \times 0.72) \times (365 \times 24)$$

$$= 50.46 \times 10^6 \text{ kWh}$$

$\therefore$ *Two-part tariff*

$$= \frac{\text{Fixed cost}}{\text{Maximum load}} + \frac{\text{Running cost}}{\text{Energy generated}}$$

$$= \frac{847.5 \times 10^3}{8 \times 10^3} + \frac{1890 \times 10^3}{50.46 \times 10^6} \times 100$$

$$= \textbf{₹ 105.9/kW + paise 3.74/kWh.} \quad \textbf{(Ans.)}$$

(ii) Average cost generation in paise/kWh :

Average generation cost

$$= \frac{\text{Grand total cost}}{\text{Energy generated}}$$

$$= \frac{2737.5 \times 10^3}{50.46 \times 10^6} \times 100$$

$$= \textbf{5.42 paise/kWh.} \quad \textbf{(Ans.)}$$

Example 9.38. *Determine the load factor at which the cost of supplying a unit of electricity is same in Diesel station as in a steam station if the respective annual fixed and running charges are given below :*

Diesel : *₹(40/kW + 0.06/kWh)*

Steam : *₹(160/kW + 0.015/kWh).*

Solution. Let P = Maximum load in kW, and
x = Load factor (same for both the stations).
Then, Average load
$= P \times x$
Cost of diesel station,
$C_{diesel} = 40\,P + 0.06 \times P \times x \times (365 \times 24)$
Cost of steam station,
$C_{steam} = 160\,P + 0.015 \times P \times x \times (365 \times 24)$
As given in the problem,
Unit energy cost (diesel station) = Unit energy cost (steam station)

$$\therefore \quad \frac{40\,P + 0.06\,Px \times (365 \times 24)}{Px \times (365 \times 24)} = \frac{160\,P + 0.015\,Px \times (365 \times 24)}{Px \times (365 \times 24)}$$

$$\therefore \quad 40\,P + 0.06\,Px \times 8760 = 160\,P + 0.015\,Px \times 8760$$

or $$40\,P + 525.6\,Px = 160\,P + 131.4\,Px$$

or $$120\,P = 394.2\,Px$$

or $$x = \frac{120}{394.2} = 0.3$$

i.e., Load factor $= \mathbf{0.3.}$ **(Ans.)**

Example 9.39. *A motor of 25 H.P. connected to a condensate pump has been burnt beyond economical repairs. Two alternatives have been proposed to replace it by :*

	Cost	*η at full load*	*η at half load*
Motor A :	*₹ 5000*	*90%*	*85%*
Motor B :	*₹ 3500*	*86%*	*80%*

The life of each motor is 20 years and its salvage value is 12 per cent of the initial cost. The rate of interest is 5 per cent annually. The motor operates at full load for 30% of time and at half load for the remaining period. The annual maintenance cost of motor A is ₹ 400 and that of motor B is ₹ 200. The energy rate is 12 paise / kWh.

Which motor will be economical ?

Solution. Motor A :

Salvage value $= \frac{12}{100} \times 5000 =$ ₹ 600

Depreciation $= \frac{5000 - 600}{20} =$ ₹ 220/year

Interest $= \frac{5}{100} \times 5000 =$ ₹ 250/year

Maintenance = ₹ 400

Energy given to motor

$$= \frac{\text{Load on motor} \times \text{time in hours}}{\text{Efficiency of the motor}}$$

$\therefore$ Energy cost

$$= \left[\left(25 \times 0.7355 \times (365 \times 24) \times \frac{30}{100} \times \frac{1}{0.9}\right) + \left((25 \times 0.7355) \times \frac{1}{2} \times (365 \times 24) \times \frac{70}{100} \times \frac{1}{0.85}\right)\right] \times \frac{12}{100}$$

$$= (53691.5 + 66324.8) \times \frac{12}{100}$$

= ₹ 14402/year

$\therefore$ *Total cost of motor A*

$= 220 + 250 + 400 + 14402 =$ **₹ 15272/year.**

Motor B :

Salvage value $= \frac{12}{100} \times 3500 =$ ₹ 420

Depreciation $= \frac{3500 - 420}{20} =$ ₹ 154

Interest $= \frac{5}{100} \times 3500 =$ ₹ 175

Maintenance = ₹ 200

Energy cost

$$= \left[\left(25 \times 0.7355 \times (365 \times 24) \times \frac{30}{100} \times \frac{1}{0.86}\right) + \left(25 \times 0.7355 \times \frac{1}{2} \times (365 \times 24) \times \frac{70}{100} \times \frac{1}{0.8}\right)\right] \times \frac{12}{100}$$

$$= (56188.8 + 70470) \times \frac{12}{100} =$$ ₹ 15199

Total cost of motor B

$= 154 + 175 + 200 + 15199 =$ **₹ 15728/year.**

Hence motor A is economical since its annual cost is less than motor B.

☞Example 9.40. *The following proposals are under consideration for an industry which has a maximum demand of 45 MW and a load factor of 0.45 :*

(i) A steam plant having an initial cost of ₹ 1200 / kW and maintenance cost of 2.4 paise / kWh. The coal of C.V. of 2550 kJ / N is used. The overall efficiency of the plant is 24 per cent.

(ii) An hydro-plant having a capital cost of ₹ 3600 / kW and a running cost of 0.6 paise / kWh.

Assuming interest and depreciation rate of 10 per cent for steam plant and 8 per cent for hydro-plant, determine the price of coal above which steam station is uneconomical.

Solution. Energy required per year
= Peak load × load factor × (365 × 24)
$= 45 \times 10^3 \times 0.45 \times (365 \times 24)$
$= 177.39 \times 10^6$ kWh/year

(i) Steam plant :

Interest and depreciation

$$= \frac{10}{100} \times (45 \times 10^3) \times 1200 = ₹\ 5.4 \times 10^6$$

Maintenance cost

$$= \frac{2.4}{100} \times 177.39 \times 10^6 = ₹\ 4.257 \times 10^6$$

Let W_{coal} = Weight of coal in kN used/year, and

x = Cost of coal in rupees per kN

$\therefore$ $W_{coal} \times 10^3 \times$ C.V. $\times \eta_{overall}$

$= 177.39 \times 10^6 \times 3.6 \times 10^3$

($\because$ 1 kWh = 3.6×10^3 kJ)

or $$W_{coal} = \frac{177.39 \times 10^6 \times (3.6 \times 10^3)}{10^3 \times 2550 \times 0.24}$$

$= 1.043 \times 10^6$ kN/year

Now, total cost of steam plant

= Interest + maintenance cost + fuel cost

$= 5.4 \times 10^6 + 4.257 \times 10^6 + 1.043 \times 10^6 \times x$ ...(1)

(ii) Hydel plant :

Interest and depreciation

$$= 45 \times 10^3 \times 3600 \times \frac{8}{100} = ₹\ 12.96 \times 10^6$$

Running cost

$$= \frac{0.6}{100} \times 177.39 \times 10^6 = ₹\ 1.064 \times 10^6$$

Total cost of hydel plant

$= 12.96 \times 10^6 + 1.064 \times 10^6$

$= ₹\ 14.024 \times 10^6$ ...(2)

The steam and hydel station will be equally economical if the total cost/year remains same.

$\therefore$ Equating the values of (1) and (2), we get

$5.4 \times 10^6 + 4.257 \times 10^6 + 1.043 \times 10^6 \times x$

$= 14.024 \times 10^6$

or $5.4 + 4.257 + 1.043\ x$

$= 14.024$ (Dividing both sides by 10^6)

$\therefore$ $$x = \frac{14.024 - 5.4 - 4.257}{1.043} = ₹\ 4.19 \text{ per kN}$$

Hence price coal above which steam station is uneconomical = **₹ 4.19 per kN.** **(Ans.)**

Example 9.41. *An industrial consumer has a choice between low and high voltage supply available at the following rates :*

High voltage : *₹ 50/kW per year + paise 4/kWh*

Low voltage : *₹ 55/kW per year + paise 5/kWh*

In order to have high voltage supply, consumer has to install his own transformer which costs ₹ 110/kW. The losses in the transformer are 4 per cent of full load. Determine the number of working hours per week above which the high voltage supply will be economical.

Assume : interest and depreciation 12 per cent of capital, working weeks per year 50 and load of consumer as 1.5 MW.

Solution. Consumer load

= 1.5 MW = 1500 kW

Required rating of transformer

$$= \frac{1500}{(1 - 0.4)} = 1562 \text{ kW}$$

Cost of the transformer to the consumer

$= 1562 \times 110 = ₹\ 171820$

Annual interest and depreciation

$$= \frac{12}{100} \times 171820 = ₹\ 20618$$

Let the number of hours for which power is required by the consumer = x hours/week

$\therefore$ Number of hours for which power is used during the year = $50x$ hours

(*i*) Number of units consumed from low voltage side if the load is connected to low voltage

$= 1500 \times 50x = 75000x$ kWh/year

(*ii*) Number of units consumed from high voltage side if the load is connected to high voltage

$= 1562 \times 50x = 78100x$ kWh/year

Total cost from low voltage supply in rupees

$$= 1500 \times 55 + 75000x \times \frac{5}{100}$$

$= 82500 + 3750x$ ...(1)

Total cost from high voltage supply in rupees

$$= 1562 \times 50 + 78100x \times \frac{4}{100} + 20618$$

$= 98718 + 3124x$ ...(2)

It both the systems cost the same to the consumer, then equating (1) and (2), we get

$82500 + 3750x = 98718 + 3124x$

i.e., $$x = \frac{98718 - 82500}{(3750 - 3124)} = \frac{16218}{626} = 25.9 \text{ hours.}$$

Hence the number of working hours above which the high voltage supply will be economical

= 25.9 hours. **(Ans.)**

ADDITIONAL/TYPICAL EXAMPLES

Example 9.42. *A diesel electric station has 4-generating sets, each of 500 kW and 1 of 400 kW capacity.*

The other data is given below :

Maximum demand	*1500 kW*
Load factor	*0.5*
Capital cost	*₹ 10000/kW*
Annual cost (interest + depreciation + insurances and taxes)	*16% of capital cost*
Annual maintenance cost	*₹ 45000*
Operation cost	*₹ 8000*
Fuel used	*0.45 kg/kWh*
Cost of fuel	*₹ 8/kg*
Lubricating oil used	*0.0024 kg/kWh*
Cost of lubricating oil	*₹ 45/kg*
Calorific value of fuel used	*41000 kJ/kg*
Generator efficiency	*90%*

Determine the following :

(i) The rating of diesel engine,

(ii) Energy produced per year,

(iii) Cost of generation, ₹/kWh, and

(iv) Overall efficiency of the plant. **(N.U.)**

Solution. *(i)* **The rating of diesel engine :**

Rating of first 3-sets

$$= \frac{500}{0.9} = \mathbf{555\ kW.} \quad \textbf{(Ans.)}$$

Rating of last set

$$= \frac{400}{0.9} = \mathbf{445\ kW.} \quad \textbf{(Ans.)}$$

(ii) **Energy produced per year :**

Average demand

= Maximum demand × load factor

= 1500 × 0.5 = 750 kW

∴ Energy produced per year

= 750 × 8760 = $\mathbf{6.57 \times 10^6\ kWh.}$ **(Ans.)**

(iii) **Cost of generation, ₹/kWh :**

Fixed cost per year :

Capital cost = (3 × 500 + 1 × 400) × 10000

= ₹ 1.9×10^7

Annual fixed cost = $\frac{16}{100} \times 1.9 \times 10^7 = ₹\ 0.304 \times 10^7$

Maintenance cost = ₹ 45000 = ₹ 0.0045×10^7

Total fixed cost = ₹ $(0.304 + 0.0045) \times 10^7$

= ₹ 0.3085×10^7

Variable cost per year :

Fuel cost = $(6.57 \times 10^6 \times 0.45) \times 8$

= ₹ 23.65×10^6

Cost of lubricating oil

= $(6.57 \times 10^6 \times 0.0024) \times 45$

= ₹ 0.71×10^6

Total variable cost per year

= $(23.65 + 0.71) \times 10^6$ = ₹ 24.36×10^6

Total cost = Fixed cost + variable cost

= $3.085 \times 10^6 + 24.36 \times 10^6$

= ₹ 27.44×10^6

∴ **Cost per kWh generated**

$$= \frac{\text{Total cost}}{\text{Energy generated per year}}$$

$$= \frac{27.44 \times 10^6}{6.57 \times 10^6} \simeq ₹\ \mathbf{4.18.} \quad \textbf{(Ans.)}$$

(iv) **Overall efficiency of the plant, $\eta_{overall}$:**

$$\eta_{overall} = \frac{\text{Output}}{\text{Input}} = \frac{6.57 \times 10^6 \times 3600\ (kJ)}{6.57 \times 10^6 \times 0.45 \times 41000\ (kJ)}$$

= 0.195 or **19.5%.** **(Ans.)**

Example 9.43. *A load curve of a factory follows a parabola and it works for 8 hours a day from 10 A.M. to 6 P.M. The maximum and minimum loads of the factory are $\sqrt{3}$ MW and 1 MW. The capacity of the diesel power plant supplying the power to the factory is 2 MW. Determine the following :*

(i) Load factor and capacity factor of the plant supplying power to the factory.

(ii) Energy consumption of the factory per month assuming it works for 26 days per month and 8 hours per day.

(iii) Electrical charges to be paid by the factory if the charges are ₹ 60/kW for maximum load during a day and ₹ 2.75/kWh.

The time at 6 A.M. may be taken as zero. **(M.U.)**

Solution. *Given* : Working hours per day = 8 (10 A.M. to 6 P.M.) ; Maximum load = $\sqrt{3}$ MW ; Minimum load = 1 MW ; Capacity of diesel power plant = 2 MW ; Tariff : ₹ 60/kW (maximum load) ; ₹ 2.75/kWh.

The load curve is shown in Fig. 9.18.

The load curve is given by :

$$y^2 = ax,$$

where x and y represent hours and MW respectively.

The boundary conditions are :

At $x = 0$, $y = 0$; At $x = 4$, $y = 1$

∴ $1 = a \times 4$ or $a = \frac{1}{4}$

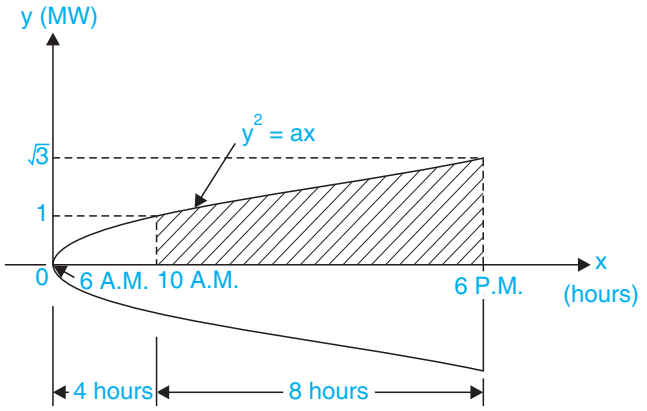


Fig. 9.18

$$\therefore \qquad y^2 = \frac{x}{4} \quad \text{or} \quad y = \frac{\sqrt{x}}{2} \text{ (load curve)}$$

The above load curve also fulfills the another condition which is :

At $x = 12$, $y = \sqrt{3}$

$$\therefore \qquad \left(\sqrt{3}\right)^2 = \frac{12}{4} \quad \therefore \quad 3 = 3$$

The average load of the factory on the diesel power plant is given by :

$$L_{av} = \frac{1}{8}\int_4^{12} y \, . \, dx = \frac{1}{8}\int_4^{12} \frac{\sqrt{x}}{2}\, dx$$

$$= \frac{1}{16}\left[\frac{2}{3}(x)^{1.5}\right]_4^{12} = \frac{1}{24}\left[(12)^{1.5} - (4)^{1.5}\right]$$

$$= 1.4 \text{ MW}$$

(*i*) Load factor and capacity factor :

$$\textit{Load factor} = \frac{L_{av}}{L_{\max}} = \frac{1.4}{\sqrt{3}} = \mathbf{0.808.} \quad \textbf{(Ans.)}$$

$$\textit{Capacity factor} = \frac{L_{\max}}{\text{Plant capacity}} = \frac{\sqrt{3}}{2}$$

$$= \mathbf{0.866.} \quad \textbf{(Ans.)}$$

(*ii*) Energy consumption per month :

Energy consumption per month,

$$E = (L_{av} \times 8) \times 26$$

$$= (1.4 \times 8 \times 1000) \times 26$$

$$= 291200 \text{ kWh}$$

(*iii*) Electrical charges to be paid by the factory :

Electrical charges to be paid by the factory

$$= L_{\max} \times 60 + E \times 2.75$$

$$= \sqrt{3} \times 60 + 291200 \times 2.75$$

$$= \mathbf{₹\ 800904.} \quad \textbf{(Ans.)}$$

Example 9.44. *The daily load curve for a power plant is given by the following equation :*

$$L = 350 + 10t - t^2$$

where t is time in hours from 0 to 24 hours and L is in MW calculate :

(i) Value of maximum load and when it occurs, and

(ii) Load factor of the plant.

Draw load curve and load duration curve. **(P.U.)**

Solution. Equation of the load curve,

$$L = 350 + 10t - t^2 \qquad \text{...(Given)}$$

(*i*) Value of maximum load and when it occurs :

The condition for finding the value of maximum load is $\frac{dL}{dt} = 0$

$$\therefore \qquad \frac{d}{dt}(350 + 10t - t^2) = 0 \quad \text{or} \quad 10 - 2t = 0$$

$$\therefore \qquad t = 5 \text{ hours.}$$

Thus, the *maximum load occurs at 5th hour during the day.* **(Ans.)**

$$\therefore \qquad L_{max} = 350 + 10 \times 5 - 5^2 = \mathbf{375\ MW.} \quad \textbf{(Ans.)}$$

(*ii*) Load factor of the plant :

The average load on the plant is given by

$$L_{av} = \frac{1}{24}\int_0^{24} L \, . \, dt = \frac{1}{24}\int_0^{24} (350 + 10t - t^2)\, dt$$

$$= \frac{1}{24}\left[350t + 10 \times \frac{t^2}{2} - \frac{t^3}{3}\right]_0^{24}$$

$$= \frac{1}{24}\left[350 \times 24 + 10 \times \frac{(24)^2}{2} - \frac{(24)^3}{3}\right]$$

$$= 278 \text{ MW}$$

$$\therefore \qquad \text{Load factor} = \frac{L_{av}}{L_{max}} = \frac{278}{375} = \mathbf{0.7413.} \quad \textbf{(Ans.)}$$

Load curve and load duration curve :

- The *'load curve is' the representation of load with respect to time.*
- The *'load duration curve' is the representation of load with respect to time in descending order.*

In order to draw these curves, we need to calculate the values of L when $t = 0, 1, 2, 3, \ldots . 24$ hours and these values are tabulated below :

(Eqn. of the load curve $L = 350 + 10t - t^2$), At $t \simeq 0$, $L = 350$ MW

t (h)	L (MW)	t (h)	L (MW)
1	359	13	311
2	366	14	294
3	371	15	275
4	374	16	254
5	375	17	231
6	374	18	206
7	371	19	179
8	366	20	150
9	359	21	119
10	350	22	86
11	339	23	51
12	326	24	14

From the above data the load curve and load duration curve are drawn as shown in Fig. 9.19 (*a*) and (*b*) respectively.

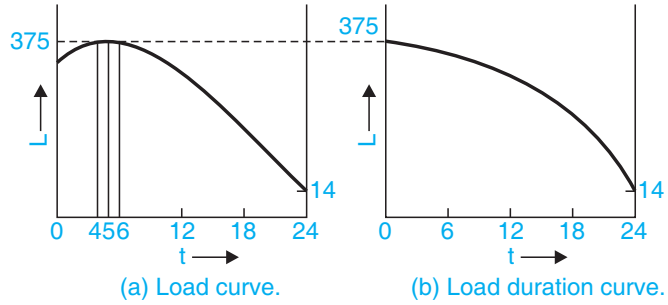


Fig. 9.19

HIGHLIGHTS

1. Types of loads : (*i*) Residential load, (*ii*) Commercial load, (*iii*) Industrial load, (*iv*) Municipal load, (*v*) Irrigation load, and (*vi*) Traction load.
2. A *load curve* is a graphic record showing the power demands for every instant during a certain time interval. The area under the load curve represents the energy generated in the period considered.
3. The cost of a power system includes the following :
   A. *Capital cost or fixed cost :*
   (*i*) Initial cost (*ii*) Interest
   (*iii*) Depreciation cost (*iv*) Taxes
   (*v*) Insurance
   B. *Operational cost :*
   (*i*) Fuel cost (*ii*) Operating labour cost
   (*iii*) Maintenance cost (*iv*) Supplies
   (*v*) Supervision (*vi*) Operating taxes.
4. The following methods are used to calculate the depreciation cost :
   (*i*) Straight line method. (*ii*) Percentage method.
   (*iii*) Sinking fund method. (*iv*) Unit method.
5. The economics of power plant is greatly influenced by :
   (*i*) Load factor (*ii*) Demand factor
   (*iii*) Utilisation factor.
6. The performance of a plant can be precisely represented by the *input-output* curve from the tests conducted on individual power plant. In general input-output may be represented as follows :
   $$I = a + bL + cL^2 + dL^3$$
   where I = input (in millions of kcal/h or kJ/h in case of thermal plants and m^3/s of water in case of hydro-plants)
   L = output (in MW or kW)
   a, b, c, d = constants.
7. For minimum combined input to carry a given combined output, the slopes of the input-output curves for each unit must be equal. If there are n units supplying a constant load, then the required condition for the minimum input or maximum system efficiency is
   $$\frac{dI_1}{dL_1} = \frac{dI_2}{dL_2} = \frac{dI_3}{dL_3} = \ldots\ldots \frac{dI_n}{dL_n}.$$
8. The general tariff form is given by :
   $$z = a.x + b.y + c$$
   where, z = Total amount of bill for the period considered.
   x = Maximum demand in kW.
   y = Energy consumed in kWh during the period considered.
   a = Rate per kW of maximum demand.
   b = Energy rate per kWh.
   c = Constant amount charged to the consumer during each billing period. This charge is independent of demand or total energy because a consumer that remains connected to the line incurs expenses even if he does not use energy.
9. Various types of *tariff* are :
   (*i*) Flat demand rate
   (*ii*) Straight meter rate
   (*iii*) Block meter rate
   (*iv*) Hopkinson demand rate (Two-part tariff)
   (*v*) Doherty rate (Three-part tariff)
   (*vi*) Wright demand rate.

THEORETICAL QUESTIONS

1. Define the following terms :
   (*i*) Connected load (*ii*) Demand
   (*iii*) Demand factor (*iv*) Load factor
   (*v*) Diversity factor (*vi*) Utilisation factor.
2. Explain briefly the following :
   (*i*) Load curve (*ii*) Load duration curve.
3. What is the significance of load curves ?
4. Enumerate various types of loads.
5. List the factors which should be considered while designing a power plant.
6. What are the considerations on which the location of a power plant depends ?
7. List the points which should be taken care of while deciding about power plant building and its layout.
8. List the various costs which go to form the total cost of a power system.
9. Explain briefly the following :
   (*i*) Capital or fixed cost (*ii*) Operational cost.
10. What do you mean by depreciation ?
11. Enumerate and explain briefly various methods used to calculate the depreciation cost.
12. Name the elements that make up the operating expenditure of a power plant.
13. What points should be considered while choosing the type of generation ?
14. Discuss the economic loading of combined steam and hydro-plants.
15. How can the power generation cost be reduced ?
16. What do you understand by the term tariff ?
17. What are the objectives and requirements of tariff ?
18. Enumerate various types of tariff and explain any two of them.
19. Explain briefly the following tariff :
   (*i*) Straight meter rate (*ii*) Block meter rate
   (*iii*) Doherty rate (three-part tariff).

UNSOLVED EXAMPLES

1. The maximum demand of a power station is 80000 kW and the load curve is defined as follows :

Time (hours) :	0–6	6–8	8–12	12–14	14–18	18–22	22–24
Load (MW) :	40	50	60	50	70	80	40

   (*i*) Determine the load factor of power station.
   (*ii*) What is the load factor of standby equipment rated at 25 MW that takes up all load in excess of 60 MW ? Also calculate its use factor.
   [**Ans.** (*i*) 0.71, (*ii*) 0.75, 0.6]
2. The following load is to be supplied by a power station :

Load (MW) :	30	90	60	100	50
Time (hours) :	0–6	6–12	12–14	14–18	18–24

   (*i*) Draw the load curve.
   (*ii*) Draw the load duration curve.
   (*iii*) Choose suitable generating units to supply the load.
   (*iv*) Calculate the load factor.
   (*v*) Calculate plant capacity factor.
   [**Ans.** (*iii*) 30 MW (4 units including standby unit), 10 MW (one unit), (*iv*) 0.64, (*v*) 0.49]
3. The yearly duration curve of a certain plant can be considered as a straight line from 150 MW to 40 MW. Power is supplied with one generating unit of 100 MW capacity and two units of 50 MW capacity each. Determine :
   (*i*) Installed capacity (*ii*) Load factor
   (*iii*) Plant factor (*iv*) Maximum demand
   (*v*) Utilization factor.
   [**Ans.** (*i*) 200 MW, (*ii*) 0.633, (*iii*) 0.475, (*iv*) 150 MW, (*v*) 0.75]
4. A generating station has a maximum demand of 20 MW, a load factor of 0.6, a plant capacity of 0.48 and a plant use factor of 0.80. Find :
   (*i*) The daily energy produced.
   (*ii*) The reserve capacity of the plant.
   (*iii*) The maximum energy that could be produced if the plant were running all the time.
   (*iv*) The maximum energy that could be produced daily, if the plant when running, according to operating schedule, were fully loaded.
   [**Ans.** (*i*) 2.88×10^5 kWh, (*ii*) 5000 kW, (*iii*) 2.88×10^5 kWh, (*iv*) 3.60×10^5 kWh]
5. A proposed power station has to supply load as follows :

Time (hours) :	01–08	08–12	12–17	17–20	20–23	23–01
Load (MW) :	10	20	25	18	35	20

   After drawing the load curve, find out the load factor. Also choose suitable generating units to supply this load, maintaining reliability of supply. Prepare operation schedule for the machine and calculate plant use factor.
   [**Ans.** 0.56, 0.92]
6. A generating station supplies the following loads :
   15 MW ; 12 MW ; 8 MW and 0.5 MW. The station has a maximum demand of 20 MW and the annual load factor is 0.5. Find :
   (*i*) Number of units supplied annually.
   (*ii*) Diversity factor.
   [**Ans.** (*i*) 876×10^5 kWh, (*ii*) 1.775]
7. A base load power station and standby power station share a common load as follows :

Base load station annual output = 150 × 10^6 kWh ; Base load station capacity = 35 MW ; Maximum demand on base load station = 30 MW ; Standby station capacity = 18 MW ; Standby station annual output = 140 × 10^6 kWh ; Maximum demand (peak load) on standby station = 15 MW. Determine the following for both power stations :

(*i*) Load factor

(*ii*) Capacity factor (plant factor).

[**Ans.** Base load station : (*i*) 0.57 (*ii*) 0.49
Standby power station : (*i*) 0.107 (*ii*) 0.09]

8. A power system has the following load particulars :

	Maximum demand	Load factor	Diversity between consumers
1. Residential load :	1000 kW	0.2	1.3
2. Commercial load :	2000 kW	0.3	1.1
3. Industrial load :	5000 kW	0.8	1.2

Overall diversity factor may be taken as 1.4.

Determine the following :

(*i*) Maximum demand on system.

(*ii*) Daily energy consumption (total).

(*iii*) Overall load factor.

(*iv*) Connected load (total) assuming that demand factor for each load is unity.

9. The following data is available for a steam power station : Maximum demand = 25000 kW ; Load factor = 0.4 ; Coal consumption = 0.86 kg/kWh ; Boiler efficiency = 85% ; Turbine efficiency = 90% ; Price of coal = ₹ 55 per tonne.

Determine the following :

(*i*) Thermal efficiency of the station.

(*ii*) Coal bill of the plant for one year.

[**Ans.** (*i*) 76.5%, (*ii*) ₹ 4143480]

10. The daily load curve of a power plant is given by the table below :

Time :	12	2	4	6	8	10	12	2	4	6	8	10	12
Load (MW) :	2	2.5	3	4	6	6.5	6.5	5	6	8	9	5	2

(*i*) Find the daily load factor.

(*ii*) All loads in excess of 400 kW are carried out by unit No. 2 rated at 600 kW. Find its use factor.

[**Ans.** (*i*) 0.814, (*ii*) 0.417]

11. The annual peak load on a 30 MW power station is 25 MW. The power station supplies load having maximum demands of 10 MW, 8.5 MW, 5 MW and 4.5 MW. The annual load factor is 0.45. Find :

(*i*) Average load (*ii*) Energy supplied per year

(*iii* Diversity factor (*iv*) Demand factor.

[**Ans.** (*i*) 11.25 MW, (*ii*) 98.55 × 10^6 kWh, (*iii*) 1.12, (*iv*) 0.9]

12. A generating station supplies the following loads : 15 MW, 12 MW, 8.5 MW, 6 MW and 0.45 MW. The station has a maximum demand of 22 MW. The annual load factor of the station is 0.48. Calculate :

(*i*) The number of units supplied annually,

(*ii*) The diversity factor. (*iii*) The demand factor.

[**Ans.** (*i*) 92.5 × 10^6 kWh, (*ii*) 1.907, (*iii*) 0.525]

13. A power station has a maximum demand of 15 MW, a load factor of 0.7, a plant capacity factor of 0.525 and a plant use factor of 0.85. Find :

(*i*) The daily energy produced.

(*ii*) The reserve capacity of the plant.

(*iii*) The maximum energy that could be produced daily if the plant operating schedule is fully loaded when in operation.

[**Ans.** (*i*) 252000 kWh, (*ii*) 5000 kW, (*iii*) 296470 kWh]

14. Determine the annual cost of a feed water softner from the following data :

Cost = ₹ 80000 ; Salvage value = 5% ; Life = 10 years ; Annual repair and maintenance cost = ₹ 2500 ; Annual cost of chemicals = ₹ 5000 ; Labour cost per month = ₹ 300 ; Interest on sinking fund = 5%. [**Ans.** ₹ 17,140]

15. Estimate the generating cost per kWh delivered from a generating station from the following data :

Plant capacity = 50 MW

Annual load factor = 0.4

Capital cost = ₹ 1.2 crores

Annual cost of wages, taxation etc. = ₹ 4 lacs

Cost of fuel, lubrication, maintenance etc. = 1.0 paise per kWh generated.

Interest 5% per annum, depreciation 5% per annum of initial value. [**Ans.** 1.91 paise/kWh delivered]

16. A 100 MW, steam power station is estimated to cost ₹ 20 crores. The operating expenses are estimated as follows :

Cost of fuel and oil = ₹ 140 lacs per annum

Transportation and storage = ₹ 20 lacs per annum

Salaries and wages = ₹ 20 lacs per annum

Miscellaneous = ₹ 20 lacs per annum

Reckoning interest and depreciation at 10% of the capital cost, calculate the cost of generation per unit, if the average load factor of the power station is 0.6.

What economics could be affected if the load factor was improved to 0.8, the operating expenses increasing by only 10% thereby.

[**Ans.** 6 p/kWh, 21% reduction in cost of generation]

17. A steam station has two 110 MW units. Following cost data are given :

Particulars	**Unit A**	**Unit B**
Capital cost	₹ 2000 per kW	₹ 2500 per kW
Fixed charge rate	10 per cent	10 per cent
Capacity factor	0.55	0.6
Fuel consumption	1 kg/kWh	0.9 kg/kWh
Fuel cost	₹ 80 per 1000 kg	₹ 80 per 1000 kg
Annual cost of operating, labour maintenance and supplies	20 per cent of annual cost	15 per cent of annual cost
Utilisation factor	1	1

Calculate the following :

(*i*) Annual plant cost and generation cost of unit A.

(*ii*) Annual plant cost and generation cost of unit B.

(*iii*) Overall generation cost of the station.

[**Ans.** (*i*) ₹ 7,28,78,080 ; 13.75 p/kWh, (*ii*) ₹ 75.371648 × 10^6 ; 13.036 p/kWh, (*iii*) 13.378 p/kWh]

18. The annual costs of operating a 15,000 kW thermal power station are as follows :

Cost of plant = ₹ 900 per kW

Interest, insurance, taxes on plant = 5 per cent

Depreciation = 5 per cent

Cost of primary distribution system = ₹ 500000

Interest, insurance, taxes and depreciation on primary distribution system = 5 per cent

Cost of secondary distribution system = ₹ 900000

Interest, taxes, insurance and depreciation on secondary distribution system = 5 per cent

Maintenance of secondary distribution system = ₹ 180000

Plant maintenance cost

(*i*) Fixed cost = ₹ 30000

(*ii*) Variable cost = ₹ 40000

Operating costs = ₹ 600000

Cost of coal = ₹ 60 per tonne

Consumption of coal = 30000 tonnes

Dividend to stock-holders = ₹ 1000000

Energy loss in transmission = 10 per cent

Maximum demand = 14000 kW

Diversity factor = 1.5

Load factor = 0.7

Determine : (*i*) Charge per kW per year, (*ii*) Rate per kWh.

[**Ans.** (*i*) ₹ 116.6, (*ii*) 3.4 p/kWh]

19. It is proposed to supply a load with a maximum demand of 100 MW and a load factor of 0.4. Choice is to be made from steam, hydro and nuclear power plants. Calculate the overall cost per kWh in case of each machine :

Cost	Steam power plant	Hydro power plant	Nuclear power plant
Capital cost per kW installed	₹ 1800	₹ 3600	₹ 5000
Interest	12%	10%	10%
Depreciation	12%	8%	10%
Operating cost per kWh	15 paise	5 paise	10 paise
Transmission and distribution cost/kWh	0.2 paise	0.8 paise	0.2 paise

[**Ans.** 27.52 p ; 23.57 p ; 38.73 p]

20. A power plant of 150 MW installed capacity has the following data :

Capital cost = ₹ 1800/kW installed ; Interest and depreciation = 12 per cent ;

Annual load factor = 0.6 ; Annual capacity factor = 0.5 ; Annual running charges = ₹ 30 × 10^6 ; Energy consumed by the power plant auxiliaries = 6 per cent. Calculate :

(*i*) Reserve capacity (*ii*) Generating cost.

[**Ans.** (*i*) 25 MW, (*ii*) 10.10 paise]

21. Compare the annual cost of supplying a factory load having a maximum demand of 1 MW at a load factor of 50% by energy obtained from

(*a*) Nuclear power plant (*b*) Public supply

Nuclear power plant

Capital cost = ₹ 50,000

Cost of fuel = ₹ 600 per 1000 kg

Fuel consumption = 30 g per kWh generated

Cost of maintenance etc. = ₹ 0.005 per kWh generated

Wages = ₹ 20000 per annum

Interest and depreciation = 10 per cent.

Public supply : ₹ 50 per kW + ₹ 0.03 per kWh generated.

[**Ans.** ₹ 170740 ; ₹ 181400]

22. A system with a maximum demand of 1,00,000 kW and a load factor of 30% is to be supplied by either (*a*) steam station alone or (*b*) a steam station in conjunction with a water storage scheme, the latter supplying 100 million units with a maximum output of 40000 kW. The capital cost of steam and storage stations are ₹ 600 per kW and ₹ 1,200 per kW respectively. The corresponding operating costs are 15 paise and 3 paise per kWh respectively. The interest on capital cost is 15% per annum. Calculate the overall generating cost per kWh and state which of the two projects will be economical.

[**Ans.** 18.425 p/kWh, 15.23 p/kWh]

23. A power station has the installed capacity of 120 MW. Calculate the cost of generation, other data pertaining to power station are given below :

Capital cost = ₹ 200 × 10^6

Rate of interest and depreciation = 18 per cent

Annual cost of fuel oil, salaries and taxation = ₹ 24 × 10^6

Load factor = 0.4

Also calculate the saving in cost per kWh if the annual load factor is raised to 0.5.

[**Ans.** 14.25 paise ; 2.84 paise]

24. A 50 MW generating station has the following data :

Capital cost = ₹ 15 × 10^6 ; Annual taxation = ₹ 0.4 × 10^6 ; Annual salaries and wages = ₹ 1.2 ×10^6 ; Cost of coal = ₹ 65 per tonne ; Calorific value of coal = 5500 kcal/kg ; Rate of interest and depreciation = 12 per cent ; plant heat rate = 33000 kcal/kWh at 100% capacity factor. Calculate the generating cost/kWh at 100% capacity factor.

[**Ans.** 39.77 p/kWh]

25. An input output curve of a 10 MW thermal station is given by an equation

$$I = 10^6(18 + 12L + 0.5L^2) \text{ kcal/hour}$$

where I is in kcal/hour and L is the load on power plant in MW.

Find : (*i*) The load at which the efficiency of the plant will be maximum.

(*ii*) The increase in output required to increase the station output from 5 MW to 7 MW by using the input-output equation and by incremental rate curve.

[**Ans.** (*i*) 6 MW, (*ii*) 36×10^6 kcal/hour]

26. The input-output curve of a 60 MW power station is given by :

$$I = 10^6(8 + 8L + 0.4L^2) \text{ kcal/hour}$$

where I is the input in kcal/hour and L is load in MW.

(*i*) Determine the heat input per day to the power station if it works for 20 hours at full load and remaining period at no load.

(*ii*) Also find the saving per kWh of energy produced if the plant works at full load for all 24 hours generating the same amount of energy.

[**Ans.** (*i*) 38592×10^6 kcal/day, (*ii*) 4000 kcal/kWh]

27. The incremental fuel costs for two generating units 1 and 2 of a power plant are given by the following equations :

$$\frac{dF_1}{dP_1} = 0.06P_1 + 11.4$$

$$\frac{dF_2}{dP_2} = 0.07P_2 + 10$$

where P is in megawatts and F is in rupees per hour.

(*i*) Find the economic loading of the two units when the total load to be supplied by the power station is 150 MW.

(*ii*) Find the loss in fuel costs per hour if the load is equally shared by the two units.

[**Ans.** (*i*) $P_1 = 70$ MW, $P_2 = 80$ MW, (*ii*) ₹ 1.63 per hour]

28. The incremental fuel costs for two generating units 1 and 2 of a power plant are given by the following equations :

$$\frac{dF_1}{dP_1} = 0.065P_1 + 25$$

$$\frac{dF_2}{dP_2} = 0.08P_2 + 20$$

where F is fuel cost in rupees per hour and P is power output in MW. Find :

(*i*) the economic loading of the two units when the total load supplied by the power plants is 160 MW.

(*ii*) the loss in fuel cost per hour if the load is equally shared by both units.

[**Ans.** (*i*) $P_1 = 53.5$ MW, $P_2 = 106.5$ MW, (*ii*) ₹ 35/hour]

29. Two steam turbines each of 20 MW capacity take a load of 30 MW. The steam consumption rates in kg per hour for both turbines are given by the following equations :

$$S_1 = 2000 + 10L_1 - 0.0001L_1^2$$

$$S_2 = 1000 + 7L_2 - 0.00005L_2^2$$

L represents the load in kW and S represents the steam consumption per hour.

Find the most economical loading when the load taken by both units is 30 MW. [**Ans.** $L_1 = 20$ MW, $L_2 = 10$ MW]

30. Two electrical units used for the same purpose are compared for their economical working :

(*i*) Cost of Unit-1 is ₹ 5000 and it takes 100 kW.

(*ii*) Cost of Unit-2 is ₹ 14000 and it takes 60 kW.

Each of them has a useful life of 40000 hours. Which unit will prove economical if the energy is charged at ₹ 80 per kW of maximum demand per year and 5 p. per kWh ?

Assume both units run at full load.

[**Ans.** Unit-1 : ₹ 6.039 ; Unit-2 : ₹ 3.898, Unit-2 is more economical]

31. A new industry requires maximum demand of 800 kW at 30% load factor. The following two power supplies are available :

(*i*) *Public supply* charges ₹ 50/kW of maximum demand and 4 p. per kWh.

Capital cost	= ₹ 80000
Interest and depreciation	= 10 per cent.

(*ii*) *Private oil engine generating station*.

Capital cost	= ₹ 30000
Interest and depreciation	= 12 per cent
Maintenance and labour charges	= 1 p. per kWh energy generated
Fuel consumption	= 0.35 kg/kWh
Cost of fuel	= 8 paise/kg.

Find which supply will be more economical ?

[**Ans.** (*i*) 6.3 p/kWh, (*ii*) 5.1 p/kWh ; oil engine generation is more preferable]

32. A load having a maximum demand of 80 MW and a load factor of 40% may be supplied by one of the following schemes :

(*i*) A steam station capable of supplying the whole load.

(*ii*) A steam station in conjunction with pump-storage plant which is capable of supplying 120×10^6 kWh energy per year with a maximum output of 30 MW.

Find out the cost of energy per unit in each of the two cases mentioned above. Use the following data :

Capital cost of steam station = ₹ 1800/kW of installed capacity ; Capital cost of pump storage plant = ₹ 1200/kW of installed capacity ; Operating cost of steam plant = 0.5 p/kWh ; Operating cost of pump storage plant = 0.4 p./kWh.

Interest and depreciation together on capital invested should be taken as 12 per cent.

Assume that no spare capacity is required.

[**Ans.** (*i*) 11.16 p./kWh, (*ii*) 8.42 p./kWh]

33. The monthly electricity consumption of a residence can be approximated as under :

Light load : 4 tube lights 40 watts each working for 3 hours daily ; *Fan load* : 4 fans 100 watts each working for 5 hours daily ; *Refrigerator load* : 1 kWh daily ; *Miscellaneous load* : 1 kW for one hour daily.

Find the monthly bill at the following tariff :

First 15 units : ₹ 0.50/kWh, Next 25 units : ₹ 0.40 per kWh ; Remaining units : ₹ 0.30 per kWh ; Constant charge : ₹ 2.50 per month. Discount for prompt payment = 5% .

[**Ans.** ₹ 45.20]

34. An industrial undertaking has a connected load of 110 kW. The maximum demand is 90 kW. On an average each machine works for 60 per cent time. Find the yearly expenditure on electricity if the tariff is :

₹ 1000 + ₹ 100 per kW of maximum demand per year + ₹ 0.10 per kWh. [**Ans.** ₹ 67186]

35. A Hopkinson demand rate is quoted as follows :

Demand rates

First 1 kW of maximum demand = ₹ 5/kW/month

Next 4 kW of maximum demand = ₹ 4/kW/month

Excess over 5 kW of maximum demand = ₹ 3/kW/month

Energy rates

First 50 kWh = 6 paise/kWh

Next 50 kWh = 4 paise/kWh

Next 200 kWh = 3 paise/kWh

Next 400 kWh = 2.5 paise/kWh

Excess over 700 kWh = 2 paise/kWh

Determine : (*i*) The monthly bill for a total consumption of 1500 kWh and a maximum demand of 12 kW. Also find the unit energy cost.

(*ii*) Lowest possible bill for a month and corresponding unit energy cost.

[**Ans.** (*i*) ₹ 79, 5.26 paise/kWh, (*ii*) ₹ 46.33, 3.09 paise/kWh]

36. Find the cost of generation per kWh from the following data :

Capacity of the plant = 120 MW

Capital cost = ₹ 1200 per kW installed

Interest and depreciation = 10 per cent on capital

Fuel consumption = 1.2 kg/kWh

Fuel cost = ₹ 40 per tonne

Salaries, wages, repairs and maintenance = ₹ 600000 per year

The maximum demand = 80 MW

Load factor = 40%.

[**Ans.** 10.18 paise/kWh]

37. The following data relate to a 2200 kW diesel power station :

The peak load on the plant = 1600 kW

Load factor = 45%

Capital cost per kW installed = ₹ 1000

Annual costs = 15 per cent of capital

Annual operating costs = ₹ 60000

Annual maintenance cost :

(*i*) Fixed = ₹ 10000

(*ii*) Variable = ₹ 20000

Cost of fuel = ₹ 0.4 per kg

Cost of lubricating oil = ₹ 1.25 per kg

C.V. of fuel = 10000 kcal/kg

Consumption of fuel = 0.5 kg/kWh

Consumption of lubricating oil = 0.0025 kg/kWh

Determine the following :

(*i*) The annual energy generated.

(*ii*) The cost of generation (per kWh).

[**Ans.** (*i*) 6.3×10^6 kWh/year, (*ii*) 27 paise/kWh]

38. The following data relate to a steam power station of 120 MW capacity which takes 100 MW peak demand at 80% load factor :

Annual cost towards interest and depreciation = ₹ 100/kW installed ; Operating costs = ₹ 1200×10^3/year ; Maintenance costs = ₹ 200×10^3/year (fixed) and = ₹ 400×10^3/year (variable) ; Miscellaneous costs = ₹ 100×10^3/year ; Cost of coal used = ₹ 32/ton ; C.V. of fuel used = 6400 kcal/kg ; Overall efficiency of the plant = 20 per cent ; Steam consumption in kg/kWh = (0.8 + 3.5 × load factor).

Determine the following :

(*i*) Coal cost per year.

(*ii*) Overall cost of generation (paise/kWh).

[**Ans.** (*i*) ₹ 15×10^6/year, (*ii*) 4.12 paise/kWh]

39. A power system requires a maximum load of 80 MW at 35% load factor. It can be supplied by any of the following schemes :

(*i*) A steam plant capable to supply whole load.

(*ii*) A steam plant with hydel plant where energy supplied by steam plant is 120×10^6 kWh/year with a maximum load of 50 MW.

Plant	Capital cost	Operating cost	Transmission cost
Steam plant	₹ 600/kW installed	4.8 paise/kWh	Negligible
Hydro plant	₹ 1400/kW installed	1.2 paise/kWh	0.3 paise/kWh

Assume interest and depreciation at 12 per cent of capital for steam plant and 10 per cent of capital for hydro plant. Calculate the overall cost per kWh.

(*iii*) If the whole load is supplied by a nuclear plant, determine annual cost. Take capital cost of ₹ 2500/kW and running cost of 2.5 paise/kWh. Assume interest and depreciation as 10 per cent per annum.

[**Ans.** (*i*) 7.05 paise/kWh, (*ii*) 5.98 paise/kWh, (*iii*) 10.67 paise/kWh]

40. The following data relate to a power plant of 120 MW capacity :

Capital cost = ₹ 1500/kW ; Interest and depreciation = 10 per cent on capital ; Annual running charges = ₹ 20×10^6 ; Profit to be gained = 10 per cent of the capital ; The energy consumed by the power plant auxiliaries = 5 per cent of generated ; The annual load factor = 0.6 ; Annual capacity factor = 0.5.

Calculate the following :

(*i*) The reserve capacity.

(*ii*) The cost of generation per kWh.

[**Ans.** (*i*) 20 MW, (*ii*) 9.3 paise/kWh]

41. A small generating unit of 5,000 kW capacity supplies the following loads :

(*i*) Street-light load with maximum demand of 200 kW at 0.3 load factor.

(*ii*) Small industrial load with maximum demand of 1800 kW at a load factor of 0.5.

(*iii*) Domestic consumers with a maximum demand of 3000 kW at a load factor of 0.2.

Find the overall energy rate for each type of consumer using the following data :

Capital cost of the plant = ₹ 1,800/kW of installed capacity

Total running cost = ₹ 6,20,000 per year

Annual rate of depreciation and interest on capital cost is 10%.

[**Ans.** (*i*) 11.4 paise/kWh, (*ii*) 8.65 paise/kWh, (*iii*) 14.8 p/kWh]

42. The following data relate to a 15 MW thermal plant :

Capital cost of plant = ₹ 1200/kW ; Interest, insurance and depreciation = 10% of the plant ; Capital cost of primary and secondary distribution = ₹ 15×10^5 ; Interest, insurance and depreciation on the capital cost of primary and secondary distribution = 5% of capital cost ; Plant maintenance cost = ₹ 80×10^3 per year ; Maintenance cost of primary and secondary equipments = ₹ 2×10^5 per year ; Salaries and wages = ₹ 6×10^5 per year ; Consumption of coal = 40×10^3 tonnes per year ; Cost of coal = ₹ 80 per tonne ; Dividend to stockholders = ₹ 12×10^5 per year ; Energy loss in transmission = 10% ; Diversity factor = 1.6 ; Load factor = 0.8 ; Maximum demand = 14 MW.

Devise a two-part tariff and find the average cost per kWh.

[**Ans.** Fixed charge per kW = 146, charge for energy consumption = 4.63 paise/kWh ; Average cost of supply = 8.1 paise/kWh]

43. The following data relate to a 12 MW capacity thermal plant :

Peak load = 10 MW

Annual load factor = 70%

Cost of the plant = ₹ 700/kW installed capacity

Interest, insurance and depreciation = 10 per cent of the capital cost

Cost of transmission and distribution system = ₹ 300×10^3

Interest, depreciation on distribution system = 5 per cent

Operating cost = ₹ 300×10^3 per year

Cost of coal = ₹ 50/ton

Plant maintenance cost = ₹ 25,000 per year (fixed) = ₹ 35,000 per year (running)

Coal used = 30,000 tons/year.

Assume transmission and distribution costs are to be charged to generation.

(*i*) Design a two-part tariff.

(*ii*) Determine overall cost of generation in paise/kWh.

[**Ans.** (*i*) ₹ 88/kW + 3 paise/kWh, (*ii*) 4.43 paise/kWh]

44. Determine the load factor at which the cost of supplying a unit of electricity is same in Diesel station as in a Steam station if the respective annual fixed and running charges are as given below :

Diesel : ₹ (30/kW + 0.05/kWh)

Steam : ₹ (120/kW + 0.0125/kWh). [**Ans.** 0.275]

45. A 30 H.P. motor connected to a condensate pump has been burnt beyond economical repairs. Two alternatives have been proposed to replace it by :

	Cost	**η at full load**	**η at half load**
Motor A	₹ 6000	90%	86%
Motor B	₹ 4000	85%	82%

The life of each motor is 20 years and its salvage value is 10 per cent of the initial value. The rate of interest is 5 per cent annually. The motor operates at full load for 25 per cent of the time and at half load for the remaining period. The annual maintenance cost of motor *A* is ₹ 420 and that of motor *B* is ₹ 240. The energy rate is 10 paise/kWh.

Which motor will be economical ?

[**Ans.** Motor A ; Total cost : Motor A = ₹ 14,777/year Motor B = ₹ 15135/year]

46. The following proposals are under consideration for an industry which has a maximum demand of 50 MW and a load factor of 0.4.

(*i*) A steam plant having an initial cost of ₹ 1000/kW and maintenance cost is 2 paise/kWh. The coal of C.V. of 6150 kcal/kg is used. The overall efficiency of the plant is 25 per cent.

(*ii*) A hydro-plant having a capital cost of ₹ 3000/kW and running cost of 0.5 paise/kWh.

Assuming interest and depreciation rate of 12 per cent for steam plant and 9 per cent for hydro-plant, determine the price of coal above which steam station is uneconomical. [**Ans.** ₹ 49.7/ton]

47. An industrial consumer has a choice between low and high voltage supply available at the following rates :

High voltage : ₹ 45/kW per year + paise 3.5/kWh

Low voltage : ₹ 47/kW per year + paise 4/kWh

In order to have high voltage supply, consumer has to install his own transformer which costs ₹ 100/kW. The losses in the transformer are 3 per cent of full load. Determine the number of working hours per week above which the high voltage supply will be economical. Assume interest and depreciation 10 per cent of capital and working weeks per year 50. Assume the load of the consumer as 1 MW. [**Ans.** 49 hours per week]

48. The expected annual cost of power system supplying the energy to 40,000 consumers is tabulated below :

Fixed charges = ₹ 2400×10^3

Energy charges = ₹ 1716×10^3

Consumer charges = ₹ 210×10^3

Profit = ₹ 168×10^3

Maximum demand = 5000 kW

Diversity factor = 4

Energy supplied = 17×10^6 kWh.

Devise a three-part tariff allowing 25% of the profit in fixed charges, 50% in energy charges and remaining 25% in customer charges.

[**Ans.** ₹ 122/kW per year + 11 paise/kWh + ₹ 6.3 per consumer per year]

COMPETITIVE EXAMINATIONS QUESTIONS

1. (*a*) Define 'connected load', 'maximum demand', 'demand factor' and 'load factor'. Explain the importance of each in total power system.

(*b*) What are the different methods of regulating voltage in a power supply system ?

2. (*a*) Define 'diversity factor' and state the advantages of diversity of load in a power system.

(*b*) What are the different methods used to meet the variable loads ? Explain in details.

3. Find the cost of generation per kWh from the following data :

Capacity of the plant	= 120 MW
Capital cost	= ₹ 1,200 per kW installed
Interest and depreciation	= 10% on capital
Fuel consumption	= 1.2 kg/kWh
Fuel cost	= ₹ 40 per tonne
Salaries, wages, repair and maintenance	= ₹ 6,00,000 per year

The maximum demand is 80 MW and load factor is 40%.

4. (*a*) State the advantages of combined working of different types of power plants.

(*b*) State the function of control board equipment.

(*c*) Describe earthing of a power system.

5. A power plant has the following annual load factors :

Load factor	= 70%
Capacity factor	= 50%
Use factor	= 60%
Maximum demand	= 20 MW

Find out :

(*a*) Annual energy production ;

(*b*) Reserve capacity over and above peak load ;

(*c*) Hours during which the plant is not in service per year.

6. The motor of a 30 H.P. condensate pump has been burnt beyond economical repairs. Two alternatives have been proposed to replace it by :

Motor A	Cost	= ₹ 6,000
	η at full load	= 90%
	η at half load	= 86%
Motor B	Cost	= ₹ 4,000
	η at full load	= 85%
	η at half load	= 82%

The life of each motor is 20 years, and its salvage value is 10% of the initial cost. The rate of interest is 5% annually. The motor operates at full load for 25% of the time and at half load for the remaining period.

The annual maintenance cost of motor *A* is ₹ 420 and that of motor *B* is ₹ 240. The energy rate is 10 paise per kWh.

Which motor would you recommend ?

7. (*a*) Discuss in detail how the load between two alternators can be divided for best economy. Explain the effect of load factor of a plant on the cost/kWh generated.

(*b*) What are the functions of switch gears ? Discuss the advantages of outdoor installations over indoor switch gear installations.

8. A new industry requires a maximum demand of 800 kW at 30% load factor. The following two supplies are available :

(*a*) Public supply charges ₹ 50/kW of maximum demand and 4 paise/kWh. The capital cost is ₹ 80,000 and interest and depreciation charges are 10%.

(*b*) A private oil engine station requires a capital of ₹ 3,00,000. The interest and depreciation on capital is 12%. The maintenance and labour charges are 1 p/kWh of energy generated. The fuel consumption is 0.35 kg/kWh and cost of fuel is 8 paise/kg.

Find out which supply is more economical.

9. (*a*) Explain the principle of economic distribution of load between generating stations.

(*b*) A small generating unit of 5,000 kW capacity supplies the following loads :

(*i*) Domestic consumers with a maximum demand of 3,000 kW at a load factor of 20 per cent ;

(*ii*) Small industrial load with a maximum demand of 2,000 kW at a load factor of 50 per cent.

Find the overall energy rate for both types of consumers.

Use the following data :

Capital cost of the plant = ₹ 2,000 per kW of installed capacity

Total running cost = ₹ 6,00,000 per year

Annual rate of depreciation and interest on capital cost is 10 per cent.

10. (*a*) What are the advantages of combined working of thermal power plant and hydro-electric plant ? Discuss briefly the need for coordination of these plants in power system.

(*b*) The maximum demand of a factor is 1000 kW at 30% load factor. The following two power supplies are available :

(*i*) **Public supply :** It charges ₹ 80/kW of maximum demand and 5 p/kWh. The capital cost is ₹ 1,00,000 and depreciation charges on the capital are 12%.

(*ii*) **Private oil engine station :** It requires ₹ 4,00,000 as capital and depreciation on capital is 10%. The maintenance and labour charges are 2 p/kWh energy generated. The fuel consumption is 0.3 kg/kWh and fuel cost is 20 p/kg.

Determine which supply is more economical.

11. (*a*) What is the effect of variable load on the power plant design and operation ?

(*b*) The loads on a power plant with respect to time for 24 hours are listed below :

Time (Hrs) :	0–6	6–10	10–12	12–16	16–20	20–24
Load (MW) :	30	50	60	70	80	40

Draw the load curve and find out the load factor of the power plant. If the load above 50 MW are taken by a stand-by unit of 30 MW capacity, find out the load factor of the stand by unit.

12. (*a*) Explain the principle of circuit interruption and its application in circuit brakers. Define the 'interruption capacity' and 'recovery voltage' of a circuit braker.

(*b*) What are the advantages of combined operation of power plants in a power system ? Explain with examples.

13. (*a*) Explain the effect of variable load on power plant operation and power plant design.

(*b*) The following data relate to a 10 MW thermal station :

Cost of plant = ₹ 3,000 per kW

Interest and taxes on cost of plant = 8% per annum

Depreciation of plant = 5% per annum

Cost of primary distribution = ₹ 800000

Interest, taxes, depreciation on cost of primary distribution system = 5%

Cost of coal with transportation = ₹ 100 per tonne

Operating cost = ₹ 800000 per annum

Plant maintenance cost (*i*) fixed = ₹ 40000 per annum

Plant maintenance cost (*ii*) variable = ₹ 50000 per annum

Installed capacity of plant = 10 MW

Maximum demand = 9 MW

Annual load factor = 70%

Consumption of coal per annum = 25000 tonnes.

Find : (*i*) the fixed cost of power generation per kW per annum ; (*ii*) the total cost of power generation per kWh. Cost of primary distribution is chargeable to generation.

14. (*a*) What is meant by powers plant economics ? What are the fixed and operating costs ?

(*b*) The following data relate to steam power station of 120 MW capacity which takes 100 MW peak demand at 80% load factor (L.F.).

Annual cost towards the interest and depreciation = ₹ 100/kW installed

Annual operating costs = ₹ 1200×10^3

Annual maintenance costs = ₹ 200×10^2 (fixed)

= ₹ 400×10^3 (variable)

Annual miscellaneous costs = ₹ 100×10^3

Cost of coal used = ₹ 32/tonne

Calorific value of fuel used = ₹ 6400 kcal/kg

Overall efficiency of the plant = 20%

Steam consumption in kg/kWh = (0.8 + 3.5 × L.F.)

Determine (*i*) costs per year, and (*ii*) overall cost of generation paise/kWh.

(*c*) Explain the different methods used for finding out the depreciation cost of the power plant.

15. (*a*) Discuss the methods of determining the depreciation of electrical power plant.

(*b*) The following data for a 2200 kW diesel power station is given. The peak load on the plant is 1600 kW and its load factor is 45% :

Capital cost/kW installed = ₹ 1000

Annual costs = ₹ 15% of capital

Annual operating costs = ₹ 60,000

Annual maintenance costs = Fixed ₹ 10,000

= Variable ₹ 20,000

Cost of fuel = ₹ 0.4 per kg

Cost of lubricating oil = ₹ 1.25 per kg

C.V. of fuel = 10,000 kcal/kg

Consumption of fuel = 0.5 kg/kWh

Consumption of lubricant oil = $\frac{1}{400}$ kg/kWh

Determine (*i*) the annual energy generated, and (*ii*) the cost of generation ₹/kWh.

16. (*a*) Explain with a neat sketch the water cooling system in diesel power plants using water softening plant and cooling tower.

(*b*) The annual costs of operating a 25 MW thermal plant are given below :

Capital cost of plant = ₹ 1200/kW

Interest + insurance + depreciation = 10% of plant cost

Capital cost of primary and secondary distribution = ₹ 15×10^5

Interest + insurance + depreciation on the capital cost of primary and secondary distribution = 5% of capital cost

Plant maintenance cost = ₹ 80×10^3 per year

Maintenance cost of primary and secondary equipment = ₹ 2×10^5 per year

Salaries and wages = ₹ 6×10^5 per year

Consumption of coal = 40×10^3 tonnes per year

Cost of coal = ₹ 80 per tonne

Dividend to stockholders = ₹ 12×10^5 per year

Energy loss in transmission = 10%

Diversity factor = 1.5

Load factor = 80%

Maximum demand = 14 MW.

Find the following :

(*i*) Total fixed cost ; (*ii*) Total variable charges ; (*iii*) Charges for energy consumption ; (*iv*) Average cost of supply.

17. (*a*) Explain load-duration curve. What are annual operating costs ? What are the factors that influence the depreciation of capital equipment ?

(*b*) The estimated total annual operating costs and capital charges for two power stations are given by the following expressions :

Annual cost for station *A* :

$$₹ (10^5 + 60 \text{ kW} + 0.01 \text{ kWh})$$

Annual cost for station *B* :

$$₹ (6 \times 10^4 + 35 \text{ kW} + 0.02 \text{ kWh})$$

where kW represents the capacity of the station and kWh represents the total annual energy generated.

The stations are to be used to supply a common load having annual load duration curve approximated by a straight line, maximum and minimum loads being 50 MW and zero respectively.

Find the following :

(*i*) Which station should be used to supply the peak load ?

(*ii*) What should be its installed capacity ?

(*iii*) For how many hours per year should it be in operation to give the minimum total cost per unit generated ?

Calculate also the total cost per unit generated under these conditions.

18. (*a*) What are fixed costs and operating costs ?

(*b*) Name the major items of fixed costs and operating costs.

(*c*) A new housing development is to be added to the lines of a public utility system. There are 1000 apartments, each having a connected load of 4 kW ; also stores and services are included as given below :

Stores or Services	Connected load in kW	Demand factor in per cent
Laundry, Drug stores, etc.	50	60
1 Restaurant	60	52
2 Churches	20 each	56
3 Theatre	100	50

The demand factor of the apartments is 45 per cent. The group diversity factor of the residential load for this system is 3.5 and the peak diversity factor is 1.4. The commercial load group diversity factor is 1.5 and the peak diversity factor is 1.1.

Find the increase in peak demand on the total system delivery from the station bus resulting from addition of this development on the distribution system. Assume line losses as 5 per cent of delivery energy.

19. (*a*) Define 'diversity factor' and state the advantages of the diversity load on a power supply system.

(*b*) A load having a maximum demand of 100 MW and a load factor of 30% may be supplied by one the following schemes :

Scheme A : A steam thermal plant capable of supplying the whole load.

Scheme B : A steam thermal plant in conjunction with a pump storage plant capable of supplying 108 kWh of energy per year with a maximum load of 40 MW.

Find the cost of energy per unit in each case.

Use the following data :

Capital cost of the steam plant

= ₹ 3000/kW of installed capacity

Capital cost of the pump storage plant

= ₹ 2000/kW of installed capacity

Operating cost of steam plant

= 20 p/kWh

Operating cost of pump storage plant = 2 p/kWh

Interest and depreciation together on capital cost for both schemes = 15%

Assume reserve capacity of 20 MW for the steam plant in each scheme.

20. How do you define load factor, plant use factor and capacity factor ? What is the importance of diversity factor in the design of a steam power plant ?

21. (*a*) Explain the terms 'Maximum Demand' and 'Load Factor' with reference to a 'Power System'.

(*b*) A load having a maximum demand of 100 MW at 30% load factor may be supplied by one of the following schemes :

(*i*) A steam plant capable of supplying the whole load ;

(*ii*) A steam plant in conjunction with a pumped storage plant capable of supplying 10^6 kWh energy per year with a maximum load of 40 MW.

Using the following data, find the most economic scheme among the two

Capital cost of steam station is ₹ 1000/kW of installed capacity.

Capital cost of pumped storage plant is ₹ 700/kW of installed capacity. Operating cost of steam station = 2.5 NP/kWh. Interest and depreciation together on capital cost is 15%. Assume no reserve capacity is required for both the schemes.

Non-Conventional Power Generation and Direct Energy Conversion

10

10.1. Introduction to energy and energy sources—Energy—Non-conventional energy sources. **10.2. Wind power plants**—Introduction—Characteristics of wind—Advantages and disadvantages of wind energy—Sources/origins of wind—Wind availability and measurement—Wind power—Terms and definitions—Types of wind mills—Wind-electric generating power plant—Types of wind machines—Utilisation aspects of wind energy—Generating systems—Wind-powered battery chargers—Wind electricity in small independent grids—Wind electricity economics—Problems in operating large wind power generators—Considerations for selection of site for wind energy conversion systems. **10.3. Tidal power plants—Ocean energy conversion**—Ocean energy sources—General aspects—Tidal power plants—Wave energy—Ocean thermal energy conversion (OTEC) plant. **10.4. Solar power plants**—Solar energy—General terms and introduction—Collectors in various ranges and applications—Flat plate collectors—Focusing (or concentrating) collectors—Solar pond technology—Low temperature thermal power generation—Medium temperature systems using focusing collectors—High temperature systems—Solar farm and solar power plant. **10.5. Geothermal power plants**—Geothermal energy—Geothermal sources—Geothermal power estimates—Environmental problems—Applications of geothermal energy—Advantages and disadvantages of geothermal energy over other energy forms—Geothermal energy in India and abroad. **10.6. Biogas plants-Biomass**—Introduction to biomass—Biomass conversion processes—Biogas plants. **10.7. Direct energy conversion systems**—Thermoelectric conversion system—Thermionic conversion system—Photovoltaic power system—Magnetohydrodynamics (MHD) system—Electrostatic mechanical generators—Electro gas-dynamic generators (EGD)—Fuel cells—Nuclear Batteries—*Highlights—Theoretical Questions—Competitive Examinations Questions.*

10.1. INTRODUCTION TO ENERGY AND ENERGY SOURCES

10.1.1. Energy

Energy *is the capability to produce motion ; force ; work ; change in shape ; change in form etc.*

Energy exists in several forms such as :

—Chemical energy

—Nuclear energy

—Mechanical energy

—Electrical energy

—Internal energy

—Bio-energy in vegetables and animal bodies

—Thermal energy etc.

Energy may be *classified* as follows :

Energy :

1. *Stored in earth :*
   - (*i*) Chemically bonded :
     - (*a*) Oil
     - (*b*) Gas
     - (*c*) Coal
   - (*ii*) Geotherm
   - (*iii*) Atomic :
     - (*a*) Fission
     - (*b*) Fusion (futuristic)
2. *Continually received by earth :*
   - ● Solar insolation
     - (*a*) Ocean temp. difference
     - (*b*) Tidal
     - (*c*) Hydro
       - —Irrigation
       - —Other benefits (flood control etc.)
       - —Hydroelectric (no thermal limits)
     - (*d*) Wind
       - —Wind mill generator
     - (*e*) Direct
       - —*PVC*
       - —Concentrator—Steam turbine

Water input

↓

Thermocycle
- —Steam turbo-generator
- —Gas turbo-generator-combined cycle
- —M.H.D combined cycle

Conservation
- —Cogeneration
- —High thermal generation
- —low trans. loss
- —High efficiency motors
- —Curb wasteful use

- **Energy science** focusses attention on the *'energy'* and *'energy transformations'* involved in the various other branches of science, to National economy and civilization.
- **Energy technology** *is the applied part of energy sciences for work and processes, useful to human society, nations and individuals.*

— Energy technologies deal with plants and processes involved in the energy transformation and *analysis* of the *useful energy* ***(exergy)*** and *worthless energy* ***(anergy)***

— Energy technology co-relates various sciences and technologies

Characteristics of energy. Energy has the following *characteristics* :

(*i*) It can be stored.

(*ii*) It can neither be created nor destroyed.

(*iii*) It is available in several forms

(*iv*) It does not have absolute value.

(*v*) It is associated with a potential. Free flow of energy takes place only from a higher potential to a lower potential.

(*vi*) It can be transported from one system to other system or from one place to another.

(*vii*) The energy is measured in Nm or in joules.

(*viii*) The forms of energy are graded as per their availability or energy content.

- The total mass and energy in the closed system remains unchanged (as per law of conservation of energy).

Energy and thermodynamics :

"Thermodynamics" is a branch of energy which deals with conversion of heat into work or vice versa :

— More than 30 per cent energy conversion processes involve *thermodynamics*, while more than 30 per cent energy conversion processes involve *electromagnetic energy* and more than 30 per cent involve *chemical energy.*

In most of the energy conversion processes, First law and Second law of thermodynamics are applicable :

- *First law* of thermodynamics relates to *conservation of energy* and throws light on concept of internal energy.
- *Second law* of thermodynamics indicates the limit of *converting heat into work* and introduces the principle of increase of entropy. Following statements are based on this law :

  — Spontaneous processes are irreversible.

— The internal energy of the environment is worthless for obtaining useful work.
— All forms of energy are not identical with reference to useful work.
— Every energy conversion process has certain 'losses'.

Energy resources :

The various sources of energy can be *classified* as follows :

1. *Commercial primary energy resources :*
   (*i*) Coal
   (*ii*) Lignite
   (*iii*) Oil and natural gas
   (*iv*) Hydroelectric
   (*v*) Nuclear fuels.
2. *Renewable energy sources :*
   (*i*) Solar photo-voltaic
   (*ii*) Wind
   (*iii*) Hydrogen fuel-cell.
3. *New sources of energy :*

Most prominent *new sources of energy* as identified by UN are :

(*i*) Tidal energy
(*ii*) Ocean waves
(*iii*) OTEC (Ocean Thermal Energy Conversion)
(*iv*) Geothermal energy
(*v*) Peat
(*vi*) Tar sand
(*vii*) Oil shales
(*viii*) Coal tar
(*ix*) Draught animals
(*x*) Agricultural residues etc.

— *Coal, oil, gas, uranium and hydro* are commonly known as ***commercial or conventional energy sources.*** These represent about 92% of the total energy used in the world.
— *Firewood, animal dung and agricultural waste* etc. are called as ***non-commercial energy sources.***

These represent about 8% of the total energy used in the world.

- Renewable energy sources include both '*direct*' solar radiation intercepted by collectors (*e.g.* solar and flat-plate thermal cells) and '*indirect*' solar energy such as *wind*, *hydropower*, *ocean energy* and *biomass resources* that can be managed in a sustainable manner. *Geothermal* is considered renewable because the resource is unlimited.

Advantages of renewable energy sources :

1. These energy sources recur in nature and are inexhaustible.
2. The power plants using renewable sources of energy do not have any fuel cost and hence their running cost is negligible.
3. As renewables have low energy density, there is more or less no pollution or ecological balance problem.
4. These energy sources can help to save foreign exchange and generate local employment (since most of the devices and plants used with these sources of energy are simple in design and construction, having being made from local materials, local skills and by local people).
5. These are more site specific and are employed for local processing and application, their economic and technological losses of transmission and distribution being nil.
6. Since conversion technology tends to be flexible and modular, renewable energy can usually be rapidly deployed.

Limitations/Demerits :

1. Owing to the low energy density of renewable energy sources large size plants are required, and as such the cost of delivered energy is increased.
2. These energy sources are intermittent and also lack dependability.
3. The user of these sources of energy has to make huge additional investment before deriving any benefit from it (whereas in case of conventional energy sources, the processing cost has traditionally been borne by large industries which borrow money from a bank and then charge the customer for each unit of energy used).
4. These energy sources, due to their low energy density, have low operating temperatures leading to low efficiencies.
5. Since the renewable energy plants have low operational efficiency, the heat rejections are large which cause thermal pollution.
6. These energy sources are energy intensive.

Note. Energy cannot be economically stored in electrical form in large quantities. Energy in large quantities is stored in conventional forms (Hydro-reservoirs, coal stocks, fuel stocks, nuclear fuel stocks). Electrical energy is generated, transmitted and utilised almost simultaneously without intermediate storage in electrical form. Hence a large *electrical network* is formed *to pool up electrical energy* available from various generating stations and to distribute to various consumers over the large geographical area. Consumers draw power as per their load requirement (*e.g.* lighting, heating, mechanical drives etc.)

10.1.2. Non-Conventional Energy Sources

A plenty of energy is needed to sustain industrial growth and agricultural production. The existing sources of energy such as coal, oil, uranium etc. may not be adequate to meet the ever increasing energy demands. These conventional sources of energy are also depleting and may be exhausted at the end of the century or beginning of the next century. Consequently sincere and untiring efforts shall have to be made by the scientists and engineers in exploring the possibilities of harnessing energy from several non-conventional energy sources. The various non-conventional energy sources are as follows :

(*i*) Solar energy (*ii*) Wind energy
(*iii*) Energy from biomass and biogas
(*iv*) Ocean thermal energy conversion
(*v*) Tidal energy (*vi*) Geothermal energy
(*vii*) Hydrogen energy (*viii*) Fuel cells
(*ix*) Magneto-hydrodynamics generator
(*x*) Thermionic converter
(*xi*) Thermo-electric power.

Advantages of non-conventional energy sources :

The leading advantages of non-conventional energy sources are :

1. They do not pollute the atmosphere.
2. They are available in large quantities.
3. They are well suited for decentralised use.

According to energy experts the non-conventional energy sources can be used with advantage for *power generation* as well as other applications in a large number of locations and situations in our country.

10.2. WIND POWER PLANTS

10.2.1. Introduction

- **Wind** *is air set in motion by small amount of insolation reaching the upper atmosphere of earth.*
  - — Nature generates about 1.67×10^5 kWh of wind energy annually over land area of earth and 10 times this figure over the entire globe.
  - — Wind contains *kinetic energy* which can easily be *converted to electrical energy.*
- The wind energy, which is an indirect source of energy, can be used to run a wind will which in turn drives a generator to produce electricity. Although wind mills have been used for more than a dozen centuries for grinding grain and pumping water, interest in large scale power generation has developed over the past 50 years. A largest wind generator built in the past was 800 kW unit operated in France from 1958–60. The flexible 3 blades propeller was about 35 m in diameter and produced the rated power in a 60 km/hour wind with a rotation speed of 47 r.p.m. The maximum power developed was 12 MW. In India the interest in the wind mills was shown in the last fifties and early sixties. Apart from importing a few from outside, new designs were also developed, but these were not sustained. It is only in last 15–20 years that development work is going on in many institutions. An important reason for this lack of interest in wind energy must be that wind, in India is *relatively low and vary appreciably with seasons. These low and seasonal winds imply a high cost of exploitation of wind energy. In our country high wind speeds are however available in coastal areas of Sourashtra, Western Rajasthan and some parts of central India. In these areas there could be a possibility of using medium and large sized wind mills for generation of electricity.*

Applications of wind plants :

Following are the main *applications* of wind plants :

1. Electrical generation.
2. Pumping.
3. Drainage.
4. Grinding grains.
5. Saw milling.

10.2.2. Characteristics of Wind

The main characteristics of wind are :

- *Wind speed increases roughly as* $\frac{1}{7}$*th power of height. Typical* tower heights are about 20–30 m.
- *Energy-pattern factor.* It is the ratio of the actual energy in varying wind to energy calculated from the cube of mean wind speed. This factor is always *greater than unity* which means that energy estimates based on mean (hourly) speed are pessimistic.

10.2.3. Advantages and Disadvantages of Wind Energy

Following are the *advantages* and *disadvantages* of wind energy :

Advantages :

1. It is a renewable energy source.
2. Wind power systems being non-polluting have no adverse effect on the environment.
3. Fuel provision and transport are not required in wind energy conversion systems.
4. Economically competitive.

5. Ideal choice for rural and remote areas and areas which lack other energy sources.

Disadvantages :

1. Owing to its irregularity, the wind energy needs storage.
2. Availability of energy is fluctuating in nature.
3. The overall weight of a wind power system is relatively high.
4. Wind energy conversion systems are noisy in operation.
5. Large areas are required for installation/ operation of wind energy systems.
6. Present systems are neither maintenance free, nor practically reliable.
7. Low energy density.
8. Favourable winds are available only in a few geographical locations, away from cities, forests.
9. Wind turbine design, manufacture and installation have proved to be most complex due to several variables and extreme stresses.
10. Requires energy storage batteries and/or stand by diesel generators for supply of continuous power to load.
11. Wind farms require flat, vacant land free from forests.
12. Only in kW and a few MW range ; it does not meet the energy needs of large cities and industry.

10.2.4. Sources/Origins of Wind

Following are the two sources/origins of wind (a natural phenomenon) :

1. Local winds.
2. Planetary winds.

1. **Local winds.** These winds are caused by *unequal heating and cooling of ground surfaces and ocean / lake surfaces during day and night.* During the day warmer air over land rises upwards and colder air from lakes, ocean, forest areas, shadow areas flows towards warmer zones.

2. **Planetary winds.** These winds are caused by *daily rotation of earth around its polar axis and unequal temperature between polar regions and equatorial regions.* The strength and direction of these planetary winds change with the seasons as the solar input varies.

- Despite the wind's intermittent nature, *wind patterns at any particular site remain remarkably constant year by year.*
- Average wind speeds are greater in hilly and coastal areas than they are well in land. The winds also tend to blow more consistently and with greater strength over the surface of the water where there is a less surface drag.
- *Wind speeds increase with height*. They have traditionally been measured at a standard height of 10 metres where they are found to be 20–25 per cent greater than close to the surface. At a height of 60 m they may be 30–60 per cent higher because of the reduction in the drag effect of the surface of the earth.

10.2.5. Wind Availability and Measurement

Wind energy can only be economical in areas of good wind availability. Wind energy differs with region and season and also, possibly to an even greater degree with local terrain and vegetation. Although wind speeds generally increase with height, varying speeds are found over different kinds of terrain. Observations of wind speed are carried out at meteorological stations, airports and lighthouses and are recorded regularly with ten minute mean values being taken every three hours at a height of 10 m. But airports, sometimes are in valleys and many wind speed meters are situated low and combinations of various, other factors mean that reading can be misleading. It is difficult, therefore, to determine the real wind speed of a certain place without actual in-situ measurements.

The World Meteorological Organization (WMO) has accepted four methods of wind recording :

(*i*) Human observation and log book.

(*ii*) Mechanical cup-counter anemometers.

(*iii*) Data logger.

(*iv*) Continuous record of velocity and direction.

1. **Human observation and log book.** This involves using the Beaufort Scale of wind strengths which defines visible "symptoms" attributable to different wind speeds. The method is *cheap* and *easily implemented* but is *often unreliable*. The best that can be said of such records is that they are better than nothing.

2. **Mechanical cup-counter anemometers.** The majority of meteorological stations use mechanical cup-counter anemometers. By taking the readings twice or three times a day, it is possible to estimate the mean wind speed. This is a *low cost method*, but is *only relatively reliable*. The instrument has to be in good working order, it has to be correctly sited and should be reliably read at least daily.

3. **Data logger.** The equipment summarizes velocity frequency and direction. It is *more expensive and prone to technical failures but gives accurate data*. The method is tailored to the production of readily interpretable data of relevance to wind energy assessment. It does not keep a time series record but *presents the data in processed form*.

4. **Continuous record of velocity and direction.** This is how data is recorded at major airports of

permanently manned meteorological stations. The *equipment is expensive and technically complex*, but it retains a detailed times-series record (second-by-second) of wind direction and wind speed. Results are given in copious quantities of data which require lengthy and expensive analysis.

10.2.6. Wind Power

The wind power can be computed by using the concept of kinetics. The mind mill works on the principle of *converting kinetic energy of the wind to mechanical energy.*

"Power density" in moving air is given by

$$P_w = KU_w^3 \, W/m^2 \qquad ...(10.1)$$

where, U_w = Wind speed in km/h, and

$K = 1.3687 \times 10^{-2}$

Theoretically a fraction $\frac{16}{27} = 0.5926$ of the power in the wind is recoverable. This is called *Gilbert's limit* or *Betz coefficient.* Aerodynamically efficiency for converting wind energy to mechanical energy can be reasonably assumed to be 70 per cent. So the mechanical energy available at the rotating shaft is limited to 40 per cent or at the most 45 per cent of wind energy.

- Available wind power (P_a) may be given as :

$$P_a = \frac{1}{2} mU_w^2 = \frac{1}{2} \cdot \rho.A.U_w U_w^2 = \frac{1}{2} \rho. \frac{\pi}{4} D^2.U_w^3$$

$$= \frac{1}{8} \rho \pi D^2 U_w^3 \text{ watts} \qquad ...(10.2)$$

where, ρ = Density of air (1.225 kg/m^3 at sea level), and

D = Diameter (in meters), in *horizontal axis* aeroturbines.

Eqn. (10.2) indicates that maximum power available from the wind *varies according to square of the diameter* of the intercept area (or square of the root diameter) normally taken to be swept area of the aeroturbine. The combined effects of wind speed and rotor diameter variations is shown in Fig. 10.1. Thus, *wind machines intended for generating substantial amounts of power should have large rotors and be located in areas of high wind speeds.*

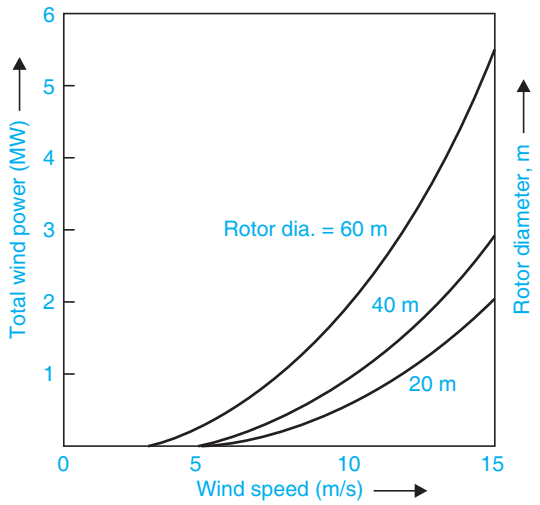


Fig. 10.1. The combined effects of variations of wind speed and diameter.

- State-wise wind power potential and wind power addition capacity (as on 31-12-2004) are given in Table 10.1 and Table 10.2 respectively.

Table 10.1. Wind Power Potential

State	*Gross potential(MW) (a)*	*Technical potential (MW) (b)*
Andhra Pradesh	8275	1750
Gujarat	9675	1780
Karnataka	6620	1120
Kerala	875	605
Medhya Pradesh	5500	825
Maharashtra	3650	3020
Odisha	1700	680
Rajasthan	5400	895
Tamil Nadu	3050	1750
West Bengal	450	450
Total	**45195**	**12875**

Table 10.2. State-wise Wind Power Capacity Addition (As on 31-12-2004)

State	*Demonstration projects (MW) (a)*	*Private sector projects (MW) (b)*	*MW (Total) capacity (MW) (a) + (b)*
Andhra Pradesh	5.4	95.9	101.3
Gujarat	17.3	202.6	219.9
Karnataka	7.1	268.9	276.0
Kerala	2.0	0.0	2.0
Madhya Pradesh	0.6	27.0	27.6
Maharashtra	8.4	402.8	411.2
Rajasthan	6.4	256.8	263.2
Tamil Nadu	19.4	1658.0	1677.4
West Bengal	1.1	0.0	1.1
Others	0.5	0.0	0.5
Total	**68.2**	**2912.0**	**2980.2**

Characteristics of a good wind power site :

A good wind power site should have the following *characteristics* :

1. High annual wind speed.
2. An open plain or an open shore line.
3. A mountain gap.
4. The top of a smooth, well rounded hill with gentle slopes lying on a flat plain or located on an island in a lake or sea.
5. There should be no full obstructions within a radius of 3 km.

10.2.7. Terms and Definitions

1. **Aerodynamics.** It is the branch of science which deals with air and gases in motion and their mechanical effects.
2. **Wind.** Air in motion.
3. **Windmill.** It is the machinery driven by the wind acting upon sails used chiefly in flat districts for grinding of corn, pumping of water etc.
4. **Wind turbine (Aeroturbine, wind machine).** It is a machine which converts wind power into rotary mechanical power. A wind turbine has aerofoil blades mounted on the rotor. The wind drives the rotor and produces rotary mechanical energy.
5. **Wind turbine generator unit.** It is an assemblage of a wind turbine, gear chain, electrical generator, associated civil works and auxiliaries.
6. **Wind farm (wind energy park).** It is a zone comprising several turbine-generator units, electrical and mechanical auxiliaries, substation, control room etc.

   Wind farms are located in areas having continuous favourable wind. Such locations are on-shore or off-shore away from cities and forests.
7. **Nacelle.** It is an assemblage comprising of the wind turbine, gears, generator, bearings, control gear etc. mounted in a housing.
8. **Propeller (wheel).** It is a revolving shaft with blades. The blades are set at an angle and twisted (like thread of a screw).
9. **Hub.** It is control solid part of the wheel (propeller).
10. **Pitch angle.** It is the angle between the direction of wind and the direction perpendicular to the planes of blades.
11. **Pitch control.** It is the control of pitch angle by turning the blades or blade tips [Fig. 10.2 (*a*)].
12. **Yaw control.** It is the control for orienting (steering) the axis of wind turbine in the direction of wind [Fig. 10.2 (*b*)].
13. **Teethering.** It is see-saw like swinging motion with hesitation between two alternatives. The plane of wind turbine wheel is swung in inclined position at higher wind speeds by teethering control [Fig. 10.2 (*b*)].

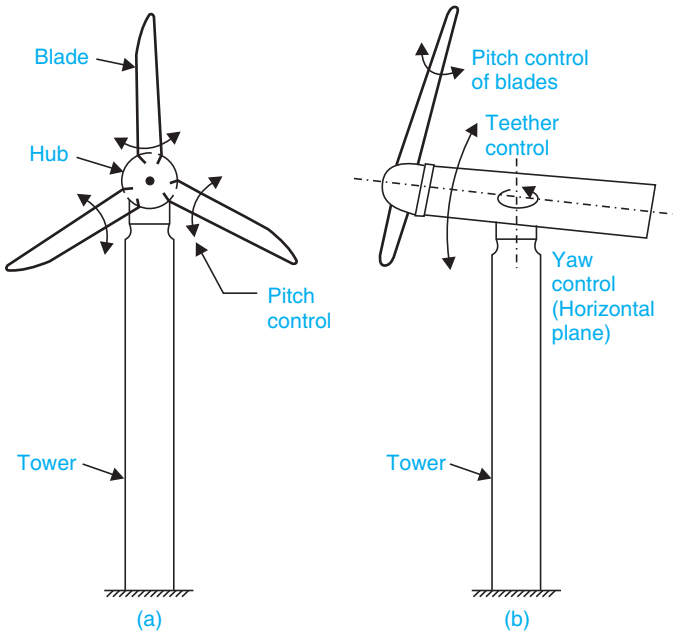


Fig. 10.2. Controls in wind-turbines: Pitch control; Yaw control ; Teether control.

14. **Wind speeds for turbines :**

(*i*) ***Cut-in-speed.*** It is the wind speed at which wind-turbine starts delivering shaft power. For a typical horizontal shaft propeller turbine it may be around 7 m/s.

(*ii*) ***Mean wind speed.***

$$U_{wm} = \frac{U_{w_1} + U_{w_2} + \cdots\cdots + U_{w_n}}{n}$$

(*iii*) ***Rated wind speed.*** It is the velocity at which the wind-turbine generator delivers rated power.

(*iv*) ***Cut-out wind velocity (furling wind velocity).*** It is the speed at which power conversion is cut-out.

10.2.8. Types of Wind Mills

The various types of wind mills (Fig. 10.3) are :

1. Multiple blade type.
2. Savonius type.
3. Darrieus type.

1. **Multiple blade type.** It is the *most widely used* wind mill.

- It has 15 to 20 blades made from metal sheets. The *sail type* has three blades made by stitching out triangular pieces of convass cloth. Both these types run at low speeds of 60 to 80 r.p.m.

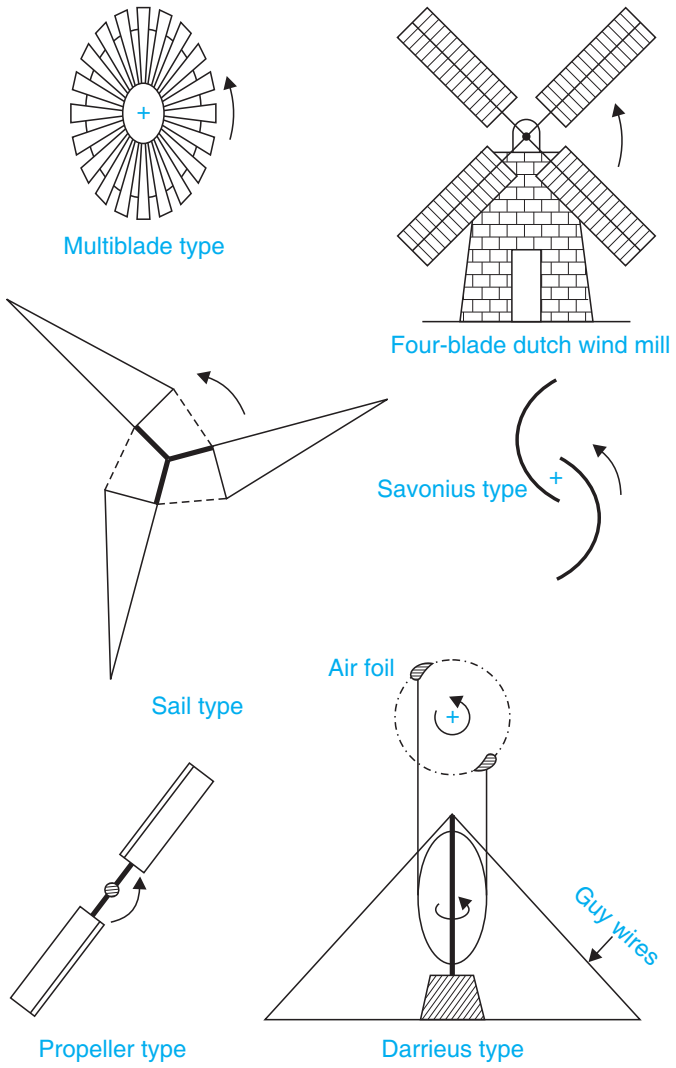


Fig. 10.3. Types of wind mills.

2. **Savonius type.** This type of windmill has hollow circular cylinder sliced in half and the halves are mounted on vertical shaft with a gap in between.

- Torque is produced by the pressure difference between the two sides of the half facing the wind.
- This is quite efficient but needs a large surface area.

Characteristics of savonius rotor :

(*i*) Self starting.

(*ii*) Low speed.

(*iii*) Low efficiency.

3. **Darrieus type.** This wind mill needs *much less surface area.*

- It is shaped like an egg beater and has two or three blades shaped like aerofoils.

Characteristics of Darrieus rotor :

(*i*) Not self starting.

(*ii*) High speed.

(*iii*) High efficiency.

(*iv*) Potentially low capital cost.

It may be noted that :

- Both the Savonius and Darrieus types are mounted on a *vertical axis* and hence they *can run independently of the direction of wind*.
- The horizontal axis mills *have to face the direction of the wind* in order to generate power.

Performance of Wind mills :

The performance of a wind mill is defined as *'Co-efficient of performance' (K_p).*

$$K_p = \frac{\text{Power delivered by the rotor}}{\text{Maximum power available in the wind}}$$

or $$K_p = \frac{P}{P_{max}} = \frac{P}{\frac{1}{2}\rho A U_w^3}$$

where, ρ = Density of air,

A = Swept area, and

U_w = Velocity of wind.

Fig. 10.4 shows a plot between K_p and tip speed ratio U_{bt}/U_w

where, U_{bt} = Speed of blade tip.

It can be seen that K_p is the *lowest of Savonius* and *Dutch types* whereas the *propeller types have the highest value*.

In the designing of wind mills, it is upper most to keep the *power to weight ratio at the lowest possible level.*

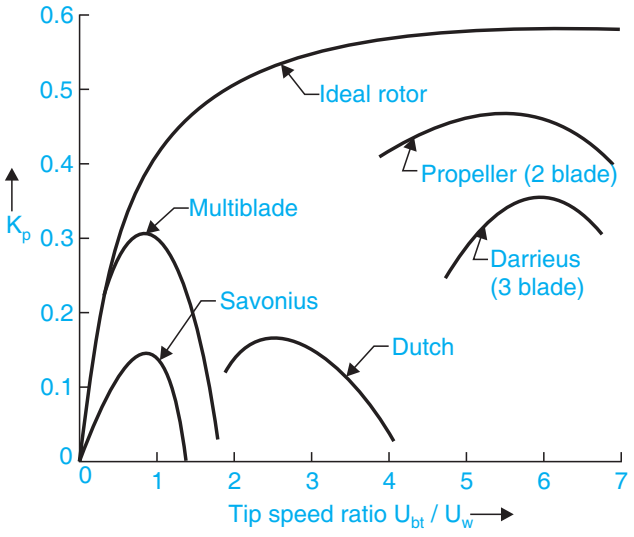


Fig. 10.4. K_p of wind mills.

10.2.9. Wind-electric Generating Power Plant

Fig. 10.5 shows the various parts of a wind-electric generating power plant. These are :

1. Wind turbine or rotor
2. Wind mill head—it houses speed increaser, drive shaft, clutch, coupling etc.
3. Electrical generator
4. Supporting structure

— The most important component is the **rotor.** For an effective utilisation, all components should be properly designed and matched with the rest of the components.

— The wind mill head performs the following functions :

(*i*) It supports the rotor housing and the rotor bearings.

(*ii*) It also houses any control mechanism incorporated like changing the pitch of the blades for safety devices and tail vane to orient the rotor to face the wind, the latter is facilitated by mounting it on the top of the supporting structure on suitable bearings.

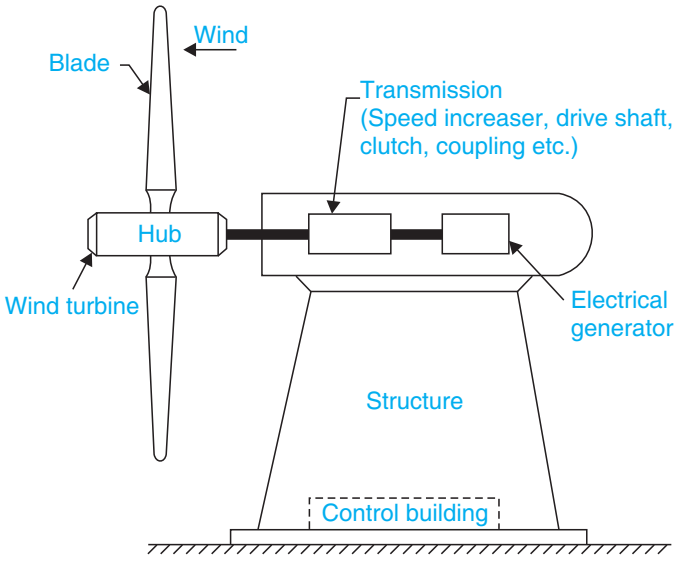


Fig. 10.5. Wind-electric generating power plant.

— The wind turbine may be located either *unwind* or *downwind* of the power. In the unwind location the wind encounters the turbine before reaching the tower. *Downwind rotors are generally preferred especially for the large aerogenerators*.

— The **supporting structure** is designed to withstand the wind load during gusts. Its type and height is related to cost and transmission

system incorporated. Horizontal axis wind turbines are mounted on towers so as to be above the level of turbulence and other ground related effects.

10.2.10. Types of Wind Machines

Wind machines (***aerogenerators***) are generally *classified* as follows :

1. Horizontal axis wind machines
2. Vertical axis wind machines.

1. **Horizontal axis wind machines.** Fig. 10.6 shows a schematic arrangement of a horizontal axis machine. Although the common wind turbine with a horizontal axis is simple in principle, yet the design of a complete system, especially a large one that would produce electric power economically, is complex. It is of paramount importance that the components like rotor, transmission, generator and tower should not only be as efficient as possible but they must also function effectively in combination.

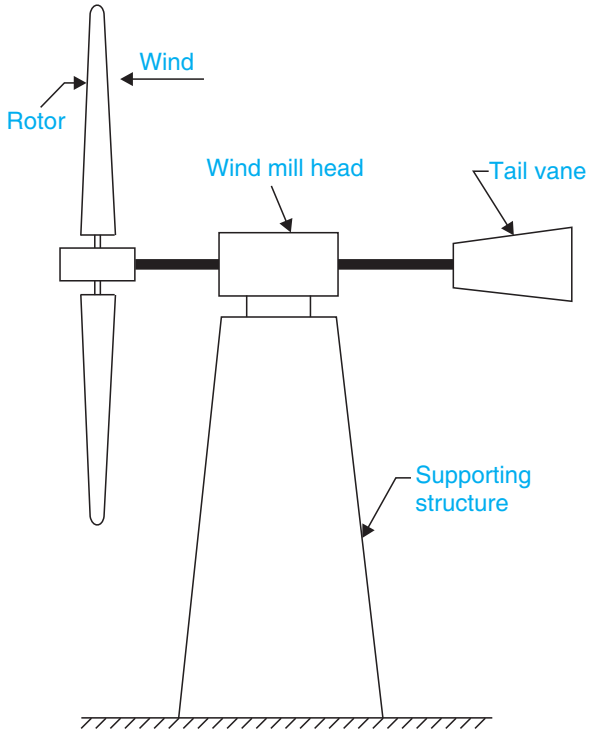


Fig. 10.6. Horizontal axis wind machine.

2. **Vertical axis wind machines.** Fig. 10.7 shows vertical axis type wind machine. One of the main advantages of vertical axis rotors is that they do not have to be turned into the windstream as the wind direction changes. Because their operation is independent of wind direction, vertical axis machines are called *panemones*.

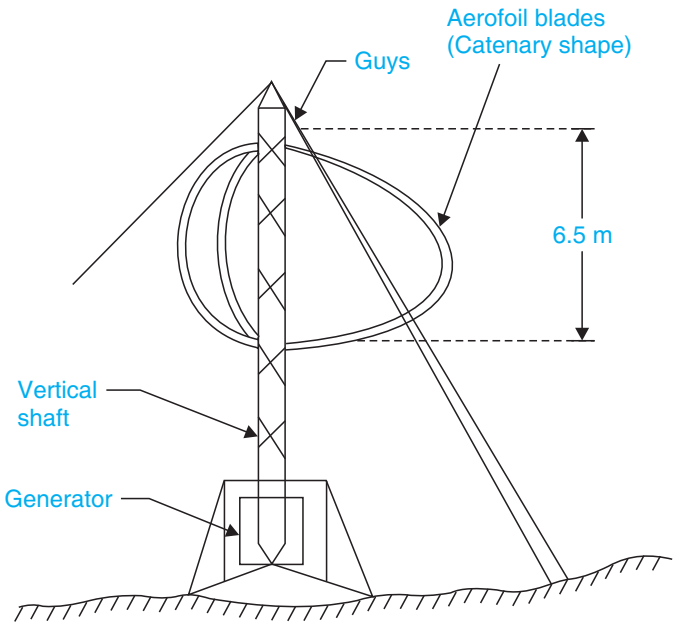


Fig. 10.7. Vertical axis wind machine.

Advantages of vertical axis wind machines :

1. The rotor is not subjected to continuous cyclic gravity loads since the blades do not turn end over end (Fatigue induced by such action is a major consideration in the design of large horizontal axis machines).
2. Since these machines would react to wind from any direction, therefore, they do not need yawing equipment to turn the rotor into the wind.
3. As heavy components (*e.g.* gear box, generator) can be located at ground level these machines may need less structural support.
4. The installation and maintenance are easy in this type of configuration.

10.2.11. Utilisation Aspects of Wind Energy

Utilisation aspects of wind energy fall into the following three broad categories :

1. Isolated continuous duty systems which need suitable energy storage and reconversion systems.
2. Fuel-supplement systems in conjunction with power grid or isolated conventional generating units.
   - This utilisation aspect of wind energy is the *most predominant in use as it saves fuel and is fast growing particularly in energy deficient grids.*

3. Small rural systems which can use energy when wind is available.
   - This category has application in *developing countries with large isolated rural areas.*

10.2.12. Generating Systems

The wind turbine-generator unit comprising wind turbine, gears and generator, converts wind power into electrical power. Several identical units are installed in a wind farm. The total electrical power produced by the wind farm is fed into the distribution network or stand alone electrical load.

The choice of electrical system for an aeroturbine is guided by *three* factors :

(*i*) ***Type of electrical output*** **:**
- — D.C.
- — Variable-frequency A.C.
- — Constant-frequency A.C.

(*ii*) ***Aeroturbine rotational speed*** **:**
- — Constant speed with variable blade pitch.
- — Nearly constant speed with simpler pitch-changing mechanism.
- — Variable speed with fixed pitch blades.

(*iii*) ***Utilisation of electrical energy output*** **:**
- — In conjunction with battery or other form of storage.
- — Interconnection with power grid.

10.2.12.1. Constant speed-constant frequency (CSCF) system

Large scale electrical energy generated from wind is expected to be fed to the power grid to displace fuel generated kWh. For this application present economics and technological developments are heavily weighted in favour of CSCF system with alternator as the generating unit. It must be reminded here that to obtain high efficiencies the blade pitch varying mechanism and controls have to be installed.

- — Wind turbines of electrical rating of *100 kW and above* are of constant-speed type and are coupled to synchronous generators (conventional type). The turbine rated at *less than 100 kW* is coupled to fairly constant speed induction generators connected to grid and so operating at constant frequency having their excitation VARs from the grid or capacitor compensators.

10.2.12.2. Variable speed-constant frequency (VSCF) system

Variable-speed drive is *typical for small wind generators* used in autonomous applications, generally producing variable frequency and variable voltage output.

The variable speed operation of wind electric system *yields higher outputs* for both low and high wind speeds. This results in higher annual energy yields per rated installed kW capacity. Both horizontal axis and vertical axis turbines will exhibit this gain under variable speed operation.

The following schemes are used *to obtain constant frequency output* :

(*i*) A.C.—D.C.—A.C. link.

(*ii*) Double output induction generator.

(*iii*) A.C. commutation generator.

With the advent of power switching technology (*viz* high power diodes and thyristors) and chip-based associated control circuitry, it has now become possible to use VSCF systems. VSCF and wind electrical systems and its associated power conditioning system operate as shown in Fig. 10.8.

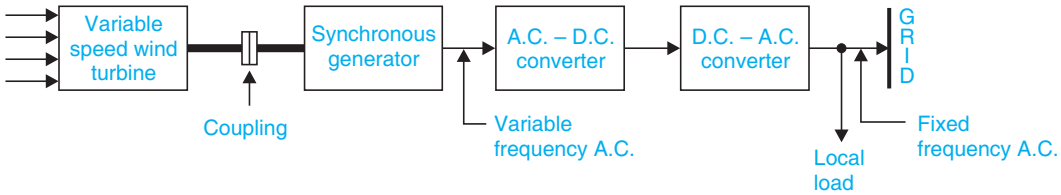


Fig. 10.8. Block schematic of VSCF wind electrical system.

VSCF wind electrical systems claim the following ***advantages*** :

1. Significant reduction in aerodynamic stresses, which are associated with constant-speed operation.
2. It is possible to extract extra energy in the high wind region of the speed-duration curve.
3. Complex pitch changing mechanism is not required.
4. Wind turbine/Aeroturbine always operates at maximum efficiency point (constant tip-speed ratio).

10.2.12.3. Variable speed-variable frequency (VSVF) system

The generator output is affected by the variable speed. The frequency of the induced voltage depends on the impedance of the load and speed of the prime mover. The variable

voltage can be converted to constant D.C. using choppers or rectifier and then to constant A.C. by the inverters.

10.2.13. Wind-Powered Battery Chargers

One application of wind energy systems which is of considerable potential importance (to developing countries) is the use of small wind generators to charge batteries for powering lighting, radio communication and hospital equipment. Wind generators have been in use in Europe and North America since the 1920s, although their use declined considerably.

A battery charging system has to include the following :

(*i*) A wind powered generator

(*ii*) A converter

(*iii*) A container for the batteries.

Fig. 10.9 shows a set-up of wind powered battery charging system. It is worthnoting that 12 volt batteries, which are rechargeable using wind generators, can be used to power fluorescent tube lighting which is six times more efficient than tungsten filament lamps. Such lighting opens up a number of important development opportunities in areas which normally have no lighting.

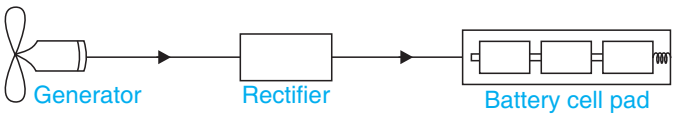


Fig. 10.9. Wind powered battery charging system.

For small wind generators the total system efficiency is made up as follows :

Wind regime matching efficiency	60% (approx.)
Rotor efficiency	35% (approx.)
Generator and wiring efficiency	70% (approx.)
Battery charge/discharge efficiency	70% (approx.)

Cumulatively, a total energy capture efficiency of about 10% is generally obtained from small wind generators utilized for battery charging.

Battery charging wind generators are produced in several countries, notably Australia, France, Sweden, Switzerland, the U.K., the U.S.A. and West Germany. In developing countries production is underway in China and has started in India.

10.2.14. Wind Electricity in Small Independent Grids

Refer to Fig. 10.10. In such systems electricity consumption fluctuates constantly as does the availability of wind energy. The degree of coincidence of supply and demand can be calculated by statistical means and it has been found that electricity supply with an acceptable degrees of reliability cannot be based solely on wind energy. If an extensive grid does not exist, electricity storage (batteries) or a back-up system (diesel) is required. Loads for remote systems of upto 6 kWh/day equivalent to an average power consumption of 250 W with a duty cycle of 24 hours, can be provided with battery storage.

If a diesel and wind generator are used in conjunction with a grid, the *diesel generator should only be used when wind energy is absent*. Problems can occur, however, when the diesel generator is called on to change its output frequently as wind energy availability fluctuates. Besides decreasing the oil saving, diesel generation on this basis leads to more frequent overhauls of the generator. Both factors will increase costs. Several methods of overcoming these problems have been tried but there is not yet an established solution. Some development work has still to be done before wind generators can be run in parallel with diesel on a routine basis.

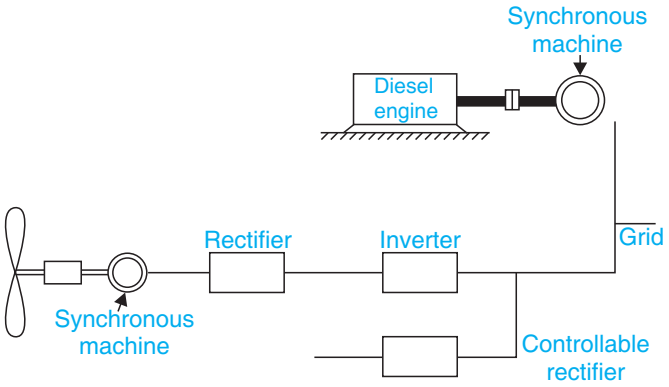


Fig. 10.10. Principle of combined wind/diesel power generation.

10.2.15. Wind Electricity Economics

Wind generator power costs are heavily linked to the characteristics of a wind resource in a specific location. The cost of supplied power declines as wind speeds increase, and the power supplied increases in proportion to the *cube of the wind speed.*

Matching available energy and load requirements is also important in wind energy economics. The correct size of wind generator must be chosen together with some kind of storage or co-generation with an engine or a grid to obtain the best economy. The ideal application is a task that can utilize a variable power supply, *e.g.* ice making or water purification.

Regarding the *economics*, the choice of interest rate obviously has a major effect on the overall energy cost. With low interest rates, capital intensive power sources such as solar and wind are favoured. Other factors bearing a strong influence on the economics of wind electricity are the standard of maintenance and service facilities and the cost of alternative energy supplies in the particular area.

10.2.16. Problems in Operating Large Wind Power Generators

The operation of large wind power generators entails the following *problems* :

1. **Location of site.** The most important factor is locating a site big enough which has a reasonable average high wind velocity.

Sourashtra and Coastal Regions in India are promising areas.

2. **Constant angular velocity.** A constant angular velocity is a must for generating A.C. (alternating current) power and this means very sensitive governing.

3. **Variation in wind velocity.** The wind velocity varies with time and varies in direction and also varies from the bottom to top of a large rotor (some rotors are as long as 50 metres). This causes fatigue in blades.

4. **Need of a storage system.** At zero velocity conditions, the power generated will be zero and this means some storage system will have to be incorporated along with the wind mill.

5. **Strong supporting structure.** Since the wind mill generator will have to be located at a height, the supporting structure will have to be designed to withstand high wind velocity and impacts. This will add to the initial costs of the wind mill.

6. **Occupation of large areas of land.** Large areas of land will become unavailable due to wind mill gardens (places where many wind mills are located). The whole area will have to be protected to avoid accidents.

Inspite of all these difficulties, interest to develop wind mills is there since this is a clean source of energy.

10.2.17. Considerations for Selection of Site for Wind Energy Conversion Systems

Following factors should be given due considerations while selecting the site for wind energy conversion systems :

1. Availability of anemometry data.
2. High annual average wind speed.
3. Availability of wind curve at the proposed site.
4. Wind structure at the proposed site.
5. Altitude of the proposed site.
6. Terrain and its aerodynamic.
7. Local ecology.
8. Distance to roads or railways.
9. Nearness of site to local centre/users.
10. Favourable land cost.
11. Nature of ground.

10.3. TIDAL POWER PLANTS—OCEAN ENERGY CONVERSION

10.3.1. Ocean Energy Sources—General Aspects

Ocean energy sources may be broadly divided into the following *four* categories :

1. Tidal energy.
2. Wave energy.
3. *Ocean thermal energy conversion (OTEC).
4. Energy emanated from the sun-ocean system from the mechanism of surface water evaporation by solar heating *i.e.*, hydrological cycle.

10.3.2. Tidal Power Plants

10.3.2.1. Introduction

The periodic rise and fall of the water level of sea which are carried by the action of the sun and moon on water of the earth is called the ***'tide'.***

- Tidal energy can furnish a significant portion of all such energies which are renewable in nature. The large scale up and down movement of sea water represents an unlimited source of energy. If some part of this vast energy can be converted into electrical energy, it would be an important source of hydropower.
- The *main feature of the tidal cycle is the difference in water surface elevations at the high tide and at the low tide.* If this differential head could be utilized in operating a hydraulic turbine, the tidal energy could be converted into electrical energy by means of an attached generator.

Tidal power :

When a basin exists along the shores with high tides, the power in the tide can be hydro-electrically utilised. This can be realised by having a long dam across the basin and locating two sets of turbines underneath the dam. As the tide comes in water flows into the basin one set of turbines. At low tide the water flows out of the basin operating another set of turbines.

Let,

h = Tidal range from high to low (in m), and

A = Area of water stored in the basin (in m^2).

Then, *energy stored* in the full basin is given as :

$$E = \rho g A \int_0^h x.dx$$

or,
$$E = \frac{1}{2} \rho g h^2 A \qquad ...(10.3)$$

*The ocean thermal energy concept was proposed as early as 1881 by the French physicist Jacques d' Arsonval.

Average power,

$$P_{av.} = \frac{1}{2}\rho g h^2 A \Big/ \left(\frac{T}{2}\right) = \rho g h^2 \Big/ \left(\frac{A}{T}\right) \quad ...(10.4)$$

where, T = Period of tidal cycle = 14 h 44 min, usually.

- Following are a few places which have been surveyed in the *world* as sites for tidal power :
  - (*i*) San Jose (S. America) : 10.7 m, 777 km^2, 19,900 MW ;
  - (*ii*) Sever (UK) : 9.8 m, 70 km^2, 8,000 MW ;
  - (*iii*) Passanaquoddy Bay (N. America) : 5.5 m, 262 km^2, 1,800 MW.

In *India*, following are the major sites where preliminary investigations have been carried out :

(*i*) Bhavanagar ;

(*ii*) Navalakh (Kutch) ;

(*iii*) Diamond harbour ;

(*iv*) Ganga Sagar.

The basin in Kandla in Gujarat has been estimated to have a capacity of 600 MW.

— The total potential of Indian coast is around 9000 MW, which does not compare favourably with the sites in the American continent stated above. The technical and economic difficulties still prevail.

10.3.2.2. Components of tidal power plants

The following are the components of a tidal power plant :

1. The dam or dyke (low wall) to form the pool or basin.
2. Sluice ways from the basins to the sea and *vice versa*.
3. The power house.

Dam or dyke. The function of dam or dyke is to form a barrier between the sea and the basin or between one basin and the other in case of multiple basins.

Sluice ways. These are used to fill the basin during the high tide or empty the basin during the low tide, as per operational requirement. These devices are controlled through gates.

Power house. A power house has turbines, electric generators and other auxiliary equipment. As far as possible the power house and sluice ways should be in *alignment* with the dam or dyke.

10.3.2.3. Classification and operation of tidal power plants

Tidal power plants are classified as follows :

1. Single basin arrangement

(*i*) Single ebb-cycle system

(*ii*) Single tide-cycle system

(*iii*) Double cycle system.

2. Double basin arrangement.

In a *single basin arrangement* power can be generated only *intermittently*. In this arrangement only one basin interacts with the sea. The two are separated by a dam or dyke and the flow between them is through sluice ways located conveniently along the dam. The rise and fall of tidal water levels provide the potential head.

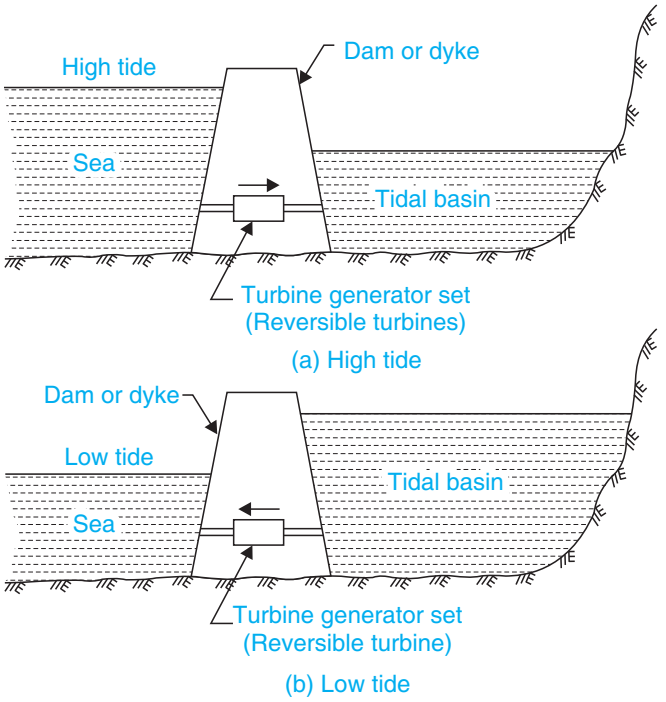


Fig. 10.11. General arrangement of tidal power plant.

Fig. 10.11 shows a general arrangement of single basin tidal power plant (double cycle system). Such plants generally use *reversible water turbines* so that power is generated on low tide as well high tide. The operation of the plant is as follows :

When the incoming tide sea level and tidal-basin level are equal, the turbine conduit is closed. When the sea level rises, and about half way to high tide the turbine valves are opened and the sea water flows into the basin through the turbine runner generating power. This also raises the level of water in the basin. The turbine continues to generate power until the tide passes through its high point and begins to drop. The water head then quickly diminishes till it is not enough to supply the no-load losses. By pass valve then quickly opens to let water into the basin to gain maximum water level. When sea and basin water level are again equal, the valves are closed as well as the turbine conduit. The basin level then stays constant while the tide continues to go out. After sufficient head has developed, the turbine valves are again opened and water

now flows from basin to the sea, thereby generating power. The plant continues to generate power till the tide reaches its lowest level.

A *single basin plant cannot generate power continuously, though it might do so by using a pumped storage plant if the load it supplies fluctuates considerably*. A ***double basin scheme*** can provide power *continuously* or on demand, which is a *great advantage*. The drawback is that the civil works become more extensive. In the simplest *double-basin scheme* there must be a dam between each basin and the sea and also a dam between the basins, containing the power house. One basin is maintained always at a lower level than the other. The lower reservoir empties at low tide, the upper reservoir is replinshed at high tide. If the generating capacity is to be large, the reservoirs must be large which means that long dams would be required.

Fig. 10.12 shows a *tidal power plant-double basin operation*.

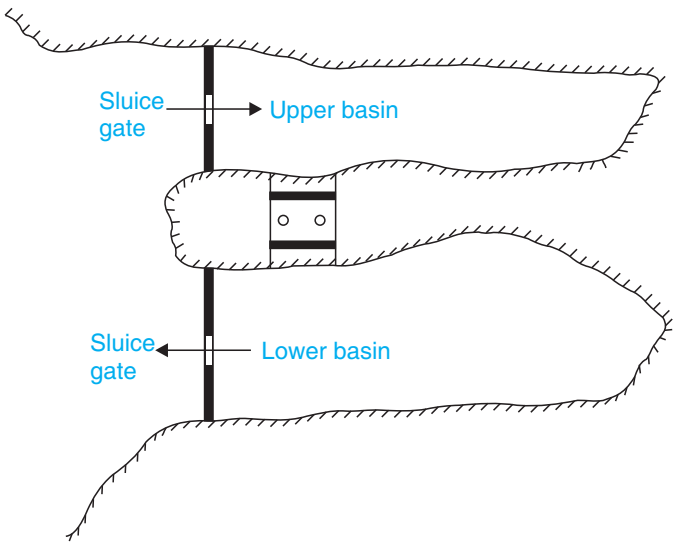


Fig. 10.12. Tidal power plant-double basin operation.

10.3.2.4. Advantages and limitations of tidal power generation

Advantages :

1. Tidal power is completely independent of the precipitation (rain) and its uncertainty, besides being inexhaustible.
2. Large area of valuable land is not required.
3. When a tidal power plant works in combination with thermal or hydro-electric system peak power demand can be effectively met with.
4. Tidal power generation is free from pollution.

Limitations :

1. Due to variation in tidal range the output is not uniform.
2. Since the turbines have to work on a wide range of head variation (due to variable tidal range) the plant efficiency is affected.
3. There is a fear of machinery being corroded due to corrosive sea water.
4. It is difficult to carry out construction in sea.
5. As compared to other sources of energy, the tidal power plant is costly.
6. Sedimentation and silteration of basins are the problems associated with tidal power plants.
7. The power transmission cost is high because the tidal power plants are located away from load centres.

— The first commercial tidal power station in the World was constructed in France in 1965 across the mouth of La Rance Estuary. It has a high capacity of 240 MW. The average tidal range at La Rance is 8.4 m and the dam built across the estuary encloses an area of 22 km^2.

10.3.3. Wave Energy

Wave energy *comes from the interaction between the winds and the surfaces of oceans.* The energy available varies with the size and frequency of waves. It is estimated that about 10 kW of power is available for every metre width of the wave front.

Wave energy when active is very concentrated, therefore, wave energy conversion into useful energy can be carried out at high power densities. A large variety of devices (*e.g. hydraulic accumulator wave machine ; high-level reservoir machine ; Dolphin-type wave-power machine ; Dam-Atoll wave machine*) have been developed for harvesting of energy but these are complicated and fragile in face of gigantic power of ocean storms.

Advantages and Disadvantages :

Following are the *advantages* and *disadvantages* of wave energy :

Advantages :

1. It is relatively pollution free.
2. It is a free and renewable energy source.
3. After removal of power, the waves are in placed state.
4. Wave-power devices do not require large land masses.
5. Whenever there is a large wave activity, a string of devices have to be used. The system not only produces electricity but also protects coast lines from the destructive action of large waves, minimises erosion and help create artificial harbour.

Disadvantages :

1. Lack of dependability.

2. Relative scarcity of accessible sites of large wave activity.
3. The construction of conversion devices is relatively complicated.
4. The devices have to withstand enormous power of stormy seas.
5. There are unfavourable economic factors such as large capital investment and costs of repair, replacement and maintenance.

Problems associated with wave energy collection :

The collection of wave energy entails the following *problems* :

1. The variation of frequency and amplitude makes it an unsteady source.
2. Devices, installed to collect and to transfer wave energy from far off oceans, will have to with stand adverse weather conditions.

- Uptil now no major development programme for taming wave energy has been carried but successfully through any country. Small devices are available, however, and are in limited use as power supplies for buoys and navigational aids. From the engineering development point of view, wave energy development is not nearly as far long as wind and tidal energy.

10.3.4. Ocean Thermal Energy Conversion (OTEC) Plant

The oceans cover about 70% of the global surface and are particularly extensive in the tropical zones. Therefore, most of the sun's radiations is absorbed by sea water. Thus warm water on the ocean's surface flows from the tropics towards poles. Cold water circulates at the ocean bottom from the poles to the tropics. Hence, in the tropical regions the water temperature is around **5°C** at a depth of 1000 m, whereas at the surface, it remains almost constant at **25°C** (for the first few metres because of mixing ; subsequently it decreases and asymptotically approaches the value at the lower level).

Thus, we can employ a *carnot-type process to generate power between these two steady temperatures.* Such plants are called **Ocean Thermal Energy Conversion Plants OTEC.**

All the systems being proposed for construction, now work on a *'Closed Rankine cycle'* (*Anderson cycle, vapour cycle) and use low boiling point working fluids like *ammonia, propane, R-12, R-22* etc. These systems would be located off shore on large floating platforms or inside floating hulls. The warm surface water is used for supplying the heat input in the boiler, while the cold water brought up from the ocean depths is used for extracting the heat in the condenser.

Fig. 10.13 shows a schematic diagram of an Ocean Thermal Energy Conversion plant—OTEC.

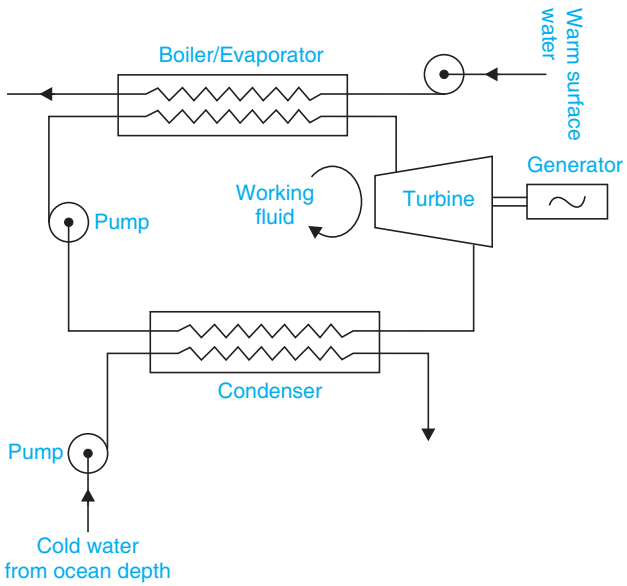


Fig. 10.13. Schematic layout of OTEC.

It is obvious that the efficiency of the Rankine cycle will be *low* because of *small temperature difference* between the hot and cold streams. Allowing for very small temperature drops of 4 to 5°C across the boiler and the condenser, it can be shown that the Rankine cycle efficiency for most of the fluids under consideration will range *between 2 and 3 per cent only*. Inspite of this, the concept of an OTEC system seems to be economically attractive because both the *collection and storage of solar energy is being done free by nature.*

- In *"Open cycle"* (*Claude cycle, steam cycle*), the warm water is converted into steam in an evaporator. The steam drives steam-turbine generator to deliver electrical energy.
- *Cogeneration OTEC plants deliver electrical energy and fresh water.*

The following points about OTEC are worth noting :

1. Each of the possible working fluids *i.e., ammonia* and *propane* has *advantages* and *disadvantages.*
   - *"Ammonia"* has better operating characteristics than propane and it is much less inflammable. On the other hand ammonia forms *irritating* vapour and probably could not be used with copper heat exchanger.
   - *"Propane"* is compatible with most heat-exchanger materials, but is highly flammable and forms an explosive mixture with air.

*The closed cycle OTEC concept was proposed by Barjot in 1926. The concept was further developed by Anderson in 1992.

- Ammonia has been used as the working fluid in successful tests of the OTEC concept with closed cycle systems.

2. Because of the low cycle efficiency the heat to be transferred in the boiler and condenser is large. In addition, the temperature difference between the sea water and the working fluid in these heat exchangers has to be restricted to very small values. For these reasons, very high flow rates are required for the sea water both in the boiler evaporator and the condenser. This results in high pumping power requirements and is reflected in the gross power outputs which are 20–50 per cent higher than net power outputs.

   A second important consequence is that both the evaporator and condenser are much larger in size than similar components in conventional practice.

   The materials suggested for these heat exchangers are *titanium* or an *alloy of copper and nickel.* This is necessitated because of the corrosive nature of the sea water.

3. An examination of the break up of the OTEC system costs shows that the cost of heat exchangers plays an important role in costing ; they contribute about 30 to 40 per cent of the total.

Merits and Limitations of OTEC :

Following are the *merits and demerits* of OTEC :

Merits :

1. It is clean form of energy conversion.
2. It does not occupy land areas.
3. No payment for the energy required.
4. It can be a steady source of energy since the temperatures are almost steady.

Limitations :

1. About 30 per cent of the power generated would be used to pump water.
2. The system would have to withstand strong convective effect of sea water ; hurricanes and presence of debris and fish contribute additional hazard.
3. The materials used will have to withstand the highly corrosive atmosphere and working fluid.
4. Construction of floating power plants is difficult.
5. Plant size is limited to about 100 MW due to large size of components.
6. Very heavy investment is required.

As an **example** for a 150 MW plant :

— A flow of 500 m^3/s would be required ;

— The heat exchangers area required will be about 0.5 km^2 ;

— A cold duct of 700 m length with a dia. of 25 m would be required.

10.4. SOLAR POWER PLANTS

10.4.1. Solar Energy—General Terms and Introduction

General Terms

Solar Constant. Solar constant is the energy from the sun, per unit time, received on a unit area of surface perpendicular to the radiation, in space, at the earth's mean distance from the sun. According to Thekaekara and Drummond (1971) the value of the solar constant is 1353 W/m^2 (1.940 Cal/cm^2 min, or 4871 kJ/m^2 hr.).

Beam Radiation. The solar radiation received from the sun without change of direction is called beam radiation.

Diffuse Radiation. It is the solar radiation received from the sun after its direction has been changed by reflection and scattering by the atmosphere.

Air Mass. It is the path length of radiation through the atmosphere, considering the vertical path at sea level as unity.

Zenith Angle. It is the angle between the beam from the sun and the vertical.

Solar Altitude. It is the angle between the beam from the sun and horizontal *i.e.*, (90-zenith angle).

Solar or Short-wave Radiation. It is the radiation originating from the sun, at a source temperature of about 6000 K and in the wavelength range of 0.3 to 3.0 μm.

Long-wave Radiation. Radiation originating from sources at temperatures near ordinary ambient temperatures and thus substantially all at wavelength greater than 3 μm.

Declination. It is the angular position of the sun at solar noon with respect to the plane of the equator (north positive).

Solar Energy—Introduction

The surface of the earth receives from the sun about 10^{14} kW of solar energy which is approximately five order of magnitude greater than currently being consumed from all resources. It is evident that sun will last for 10^{11} years. Even though the sun light is filtered by the atmosphere one square metre of the land exposed to direct sun light-receives the energy equivalent of about 1 H.P or 1 kW. However, this vast amount of solar energy reaching earth is not easily convertible and certainly is not "free".

There are two obvious obstacles to harnessing solar energy. *Firstly* it is not constantly available on earth. Thus some form of storage is needed to sustain a solar power system through the night and during periods when local weather conditions obscure the sun. *Second* the solar energy is diffused. Although the total amount of energy is enormous, the collection and conservation of solar energy

into useful forms must be carried out over a large area which entails a large capital investment for the conversion apparatus.

Solar energy, therefore, most likely will be developed not because it is cheaper than alternative energy sources but because these alternative sources sooner or later (*i*) will be exhausted, (*ii*) will become increasingly move expensive, (*iii*) will continue to political and economical control by the nations possessing them, and (*iv*) will produce undesirable yet incompletely understood environmental consequences, especially on large scale that will be required to meet projected demands even with controlled growth.

Solar energy has some good advantages in comparison to the other sources of power. Solar radiation does not contaminate environment or endanger ecological balance. It avoids major problems like exploration, extraction and transportation.

10.4.2. Collectors in Various Ranges and Applications

Following list gives the thermal applications of solar energy and possible temperature ranges :

1. **Long temperature**
   (t = 100°C)
   - (*i*) Water heating
   - (*ii*) Space heating
   - (*iii*) Space cooling
   - (*iv*) Drying

   ... Flat plate

2. **Medium temperature**
   (100 to 200°C)
   - (*i*) Vapour engines and turbines
   - (*ii*) Process heating
   - (*iii*) Refrigeration
   - (*iv*) Cooking

   ... Cylindrical Parabola

3. **High temperature**
   (> 200°C)
   - (*i*) Steam engines and turbines
   - (*ii*) Stirling engine
   - (*iii*) Thermo-electric generator

   ... Paraboloid Mirror arrays

The above classification of low, medium and high temperature ranges is some what arbitrary. Heating water for domestic applications, space heating and cooling and drying of agricultural products (and industrial products) is generally at temperature below 100°C, achieved using flat plate collectors with one or two glass plate covers. Refrigeration for preservation of food products, heating for certain industrial processes, and operation of engines and turbines using low boiling organic vapours is possible at some what higher temperature of 100 to 200°C and may be achieved using focusing collectors with cylindrical-parabola reflectors requiring only one directional diurnal tracking. Conventional steam engines and turbines, stirling hot air engines, and thermoelectric generators require the solar collectors to operate at high temperatures. Solar collectors operating at temperature above 200°C generally consist of parabolloid reflector as an array of mirrors reflecting to a central target, and requiring two directional diurnal tracking.

The concentrators or focusing type collectors can give high temperatures than flat plate collectors, but they entail the following shortcomings/limitations.

1. Non-availability and high cost of materials required. These materials must be easily shapeable, yet have a long life ; they must be light weight and capable of retaining their brightness in tropical weather. Anodised aluminium and stainless steel are two such materials but they are expensive and not readily available in sufficient quantities.

2. They require direct light and are not operative when the sun is even partly covered with clouds.

3. They need tracking systems and reflecting surfaces undergo deterioration with the passage of time.

4. These devices are also subject to similar vibration and movement problems as radar antenna dishes.

Comparison between Flat plate and Focusing collectors :

1. The absorber area of a concentrator system is smaller than that of a flat-plate system of the same solar energy collection area and the *insolation intensity is therefore greater.*

2. Because the area from which heat is lost to the surroundings per unit of the solar energy collecting area is less than that for a flat plate collector and because the insolation on the absorber is more concentrated, the working fluid can attain higher temperatures in a concentrating system than in a flat-plate collector of the same solar energy collecting surface.

3. Owing to the small area of absorber per unit of solar energy collecting area, selective surface treatment and/or vacuum insulation to reduce heat losses and *improve collector efficiency are economically feasible.*

4. Since higher temperatures can be achieved, the focusing collector *can be used for power generation*.

5. *Little or no anti-freeze is required* to protect the absorber in a concentrator system whereas the entire solar energy collection surface requires anti-freeze protection in a flat-plate collector.

6. Out of the beam and diffuse solar radiation components, only beam component is collected in case of focusing collectors because diffuse component cannot be reflected and is thus lost.

7. *Costly orienting systems* have to be used to track the sun.

8. Non-uniform flux on the absorber whereas flux in flat-plate collectors is uniform.

10.4.3. Flat Plate Collectors

10.4.3.1. Description

Fig. 10.14 shows a Flat Plate Collector which consists of four essential components :

1. **An absorber plate.** It intercepts and absorbs solar radiation. This plate is usually metallic (Copper, aluminium or steel), although plastics have been used in some low temperature applications. In most cases it is coated with a material to enhance the absorption of solar radiation. The coating may also be tailored to minimise the amount of infrared radiation emitted.

A heat transport fluid (usually air or water) is used to extract the energy collected and passes over, under or through passages which form an integral part of the plate.

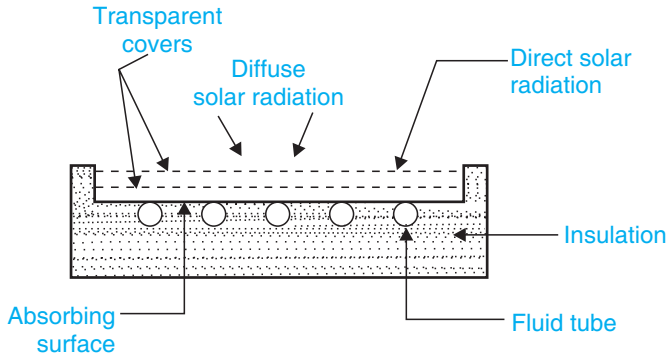


Fig. 10.14. Flat plate solar collector.

2. **Transparent covers.** These are one or more sheets of solar radiation transmitting materials and are placed above the absorber plate. They allow solar energy to reach the absorber plate while reducing convection, conduction and re-radiation heat losses.

3. **Insulation beneath the absorber plate.** It minimises and protects the absorbing surface from heat losses.

4. **Box like structure.** It contains the above components and keeps them in position.

Various types of flat plate collectors have been designed and studied. These include tube in plate, corrugated type, spiral wound type etc. Other criteria is single exposure, double exposure or exposure and reflector type. The collector utilizes sheets of any of the highly conducting material *viz*. copper, aluminium, or galvanized iron. The sheets are painted dead black for increasing the absorbtivity. The sheets are provided with one or more glass or plastic covers with air gap in between to reduce the heat transfer losses. The sides which are not exposed to solar radiation are well insulated. The whole assembly is fixed in air tight wooden box which is mounted on simple device to give the desired angle of inclination. The dimensions of collectors should be such as to make their handling easy. The collector will absorb the sun energy (direct as well as diffused) and transfer it to the fluid (air, water or oil) flowing within the collector. Basically, a flat plate collector is *effective* most of time, *reliable* for good many years and also *inexpensive*.

Use of flat mirrors in the flat plate collectors improves the output, permitting higher temperatures of operation. Side mirrors are used either at north and south edges or at east and west edges of the collector or a combination of both. The mirrors may be of reversible or non-reversible type.

10.4.3.2. Analysis

Consider an object exposed to sun radiations of intensity P, per unit area at the surface of the body. These radiations, will partly be absorbed by the body, while the remaining will be partly transmitted and rest reflected. If we take the incident radiations equal to unity, then, the absorbed, reflected, and transmitted parts of energy will add up to unity. There parts are called *absorption* co-efficient, *reflection* co-efficient and *transmission* co-efficient and represented by the symbols α, ρ and τ respectively.

Using the above symbols we can write

$$\alpha + \rho + \tau = 1 \qquad ...(i)$$

The absorbed part of the solar radiations, which is equal to α is responsible for increasing the temperature of the body. However, the body also loses energy by conduction, convection and radiation. The equilibrium temperature of the body will be that at which the heat loses from the body are equal to the absorbed radiations. For analysis purposes, if we represent the body by a flat plate and assume that the convection and conduction loses are negligible to begin with, then at equilibrium temperature, the absorbed solar radiations should be equal to the radiation losses from the flat plate. The radiation losses are equal to $\varepsilon\sigma T^4$, where ε and T are the emission co-efficient and absolute temperature respectively of flat plate and σ is the Boltzman's constant.

Therefore, at equilibrium,

$$\alpha P = \varepsilon\sigma T^4 \qquad ...(ii)$$

or

$$\frac{\alpha P}{\varepsilon} = \sigma T^4 \qquad ...(iii)$$

From equation (*iii*), it is evident that comparatively higher equilibrium temperature will be obtained where the quantity $\frac{\alpha}{\varepsilon}$ *i.e.*, the ratio of absorption co-efficient to emission co-efficient of the flat plate is more. However, this has been demonstrated by an equation obtained under idealised condition. In the realistic conditions too, its nature will remain the same, but it will get modified by other influencing factors.

The collectors for which ratio is equal to unity are called **'Neutral collectors'** and those for which the ratio is greater than unity are called **'Selective collectors'.**

The amount of energy collected, however, does not depend on $\frac{\alpha}{\varepsilon}$ ratio. It primarily depends on higher value of α. So to obtain higher energy collection, one should use such flat plate where absorption co-efficient is as high as possible.

A flat plate painted black is placed on a well insulated base. If it is exposed to solar radiations where P = 800 W/m^2, a typical summer value for a tropical region, we obtain from equation (*iii*) the equilibrium temperature as 70°C. Inspite of the simplifications here, it is a fair estimate of the temperature reached by a black plate left for a time in the tropical sun.

This method can be refined by including the convection losses and the energy gain as a result of absorption of diffused radiations by the flat plate.

If P' is the intensity of the diffused radiations and α' the absorption co-efficient, then equation (*ii*) becomes

$$\alpha P + \alpha' P' = h_c(T - T_a) + \varepsilon\sigma T^4 \qquad ...(iv)$$

This is valid, where the base is insulated, hence conduction losses are neglected. Here T_a is the atmospheric temperature and h_c is the convection heat transfer co-efficient.

10.4.4. Focusing (or Concentrating) Collectors

The main types of focusing or concentrating collectors are as follows :

1. Parabolic trough collector
2. Mirror strip collector
3. Fresnel less collector
4. Flat plate collector with adjustable mirrors
5. Compound parabolic concentrator.

Fig. 10.15 (*a*) shows the principle of the parabolic trough collector which is often used in focusing collectors. Solar radiation coming from the particular direction is collected over the area of reflecting surface and is concentrated at the focus of the parabola, if the reflector is in the form of a trough with parabolic cross-section, the solar radiation is focused along a line. Mostly *cylindrical parabolic concentrators* are used in which absorber is placed along focus axis [Fig. 10.15 (*b*)].

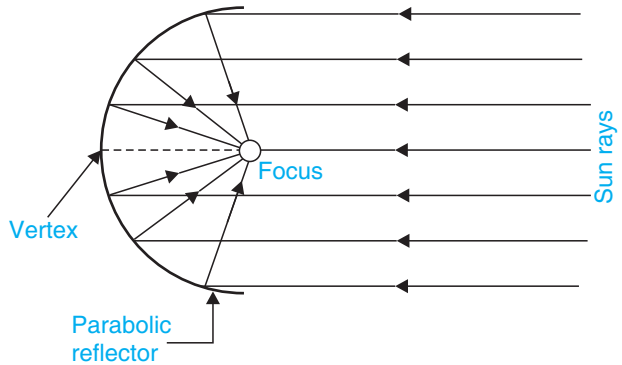


Fig. 10.15. (*a*) Cross-section of parabolic trough collector.

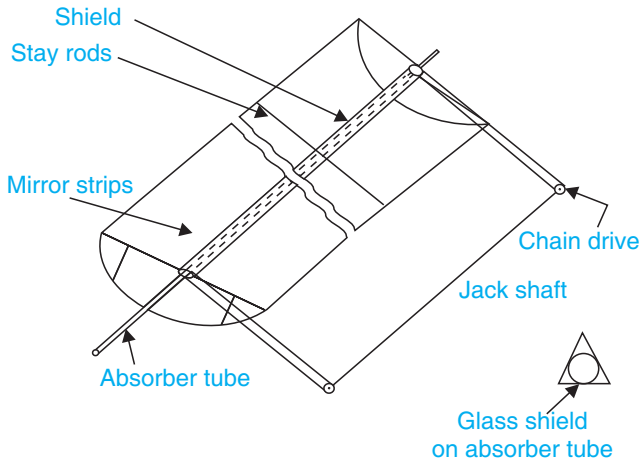


Fig. 10.15. (*b*) Cylindrical parabolic system.

10.4.5. Solar Pond Technology

Refer to Fig. 10.16.

The vertical configuration of salt-gradient solar pond normally consists of following *three zones* :

1. Adjacent the surface there is a *homogeneous convective zone* that serves as a buffer zone between environmental fluctuations at the surface and conductive heat transport from the layer below. This is the *upper convective zone* (UCZ).

2. At the bottom of the pond there is another convective zone, the lower convective zone or LCZ. This is the layer with the *highest salt concentration* and where the high temperatures are built up.

3. For given salinites and temperatures in the upper and lower convective zones, there exists a stable *intermediate gradient zone*. This zone keeps the two convective zones apart and gives the solar pond its unique thermal performance. This intermediate zone provides excellent insulation for the storage layer, while simultaneously transmitting the solar radiation. To maintain a solar pond in this non-equilibrium stationary state, it is necessary to replace the amount of salt that is transported by molecular diffusion from the LCZ to the UCZ. This means that salt must be added to the LCZ, and fresh water to the UCZ whilst-brine is removed. The brine can be recycled, divided into water and salt (by solar distillation) and returned to the pond.

The major heat loss occurs from the surface of the solar pond. This heat loss can be prevented by spreading a plastic grid over the pond's surface to prevent disturbance by the wind. Disturbed water tends to lose heat transfer faster than when calm.

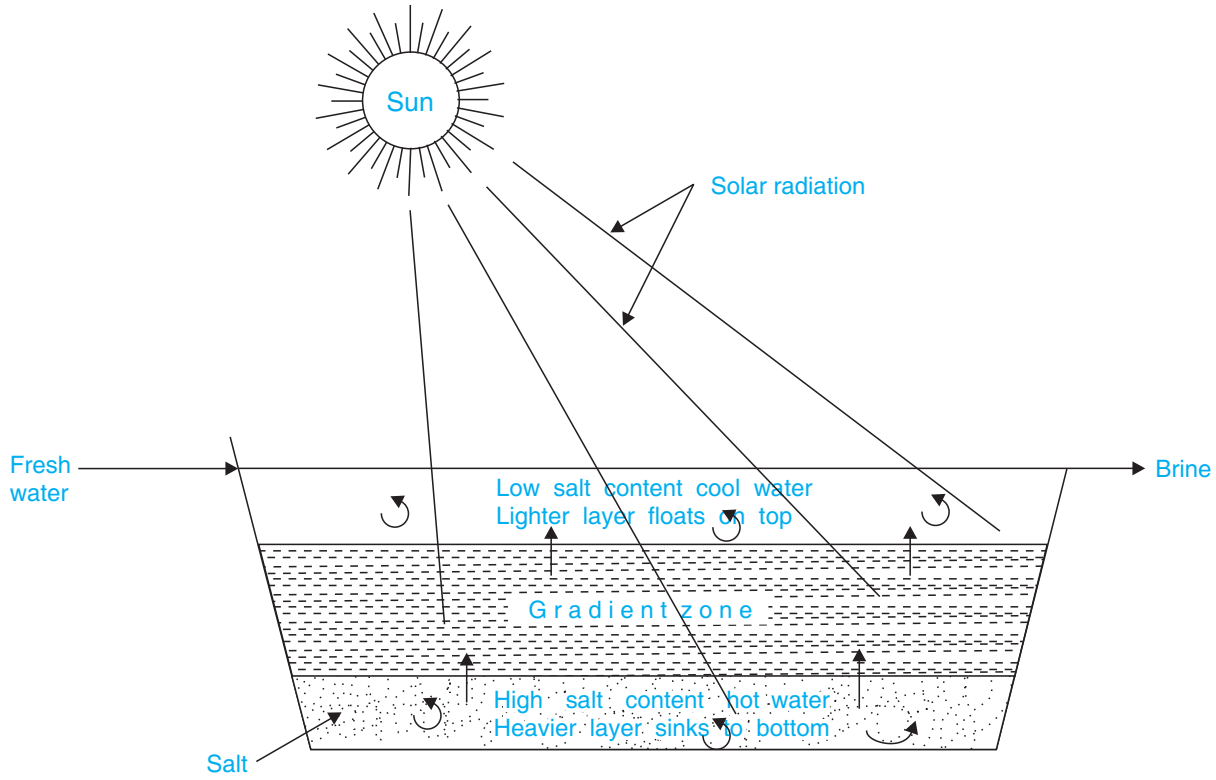


Fig. 10.16. Principle of solar pond.

Due to the excessively high salt concentration of the LCZ, a *plastic liner* or impermeable soil must be used to *prevent infiltration* into the nearby ground water or soil. The liner is a factor that increases the *cost* of a solar pond. A site where the soil is naturally impermeable, such as the base of a natural pond or lake, or can be made impermeable by compaction or other means, will allow considerably lower power costs.

The optical transmission properties and related collection efficiency vary greatly and depend on the following :

(*i*) Salt concentration.

(*ii*) The quantity of suspended dust or other particles.

(*iii*) Surface impurities like leaves or debris, biological material like bacteria and algae.

(*iv*) The type of salt.

It becomes obvious that much higher efficiencies and storage can be achieved *through the utilization of refined or pure salt* whenever possible, as this *maximizes optical transmission*.

The solar pond is an effective collector of diffuse, as well as direct radiation, and will gather useful heat even on cloudy or overcast days. Under ideal conditions, the pond's absorption efficiency can reach 50% of incoming solar radiation, although actual efficiencies average about 20% due to heat losses. Once the lower layer of the pond reaches over 60°C the heat generated can be drawn off through a heat exchanger and used to drive a low temperature organic Rankine cycle (ORC) turbine. This harnesses the pressure differentials created when a low boiling point organic fluid (or gas) is boiled by heat from the pond *via* a heat exchanger and cooled by a condenser to drive a turbine to generate electricity. The conversion efficiency of an organic Rankine cycle turbine driving an electric generator is 5–8% (which mean 1–3% from insolation to electricity output).

10.4.6. Low Temperature Thermal Power Generation

10.4.6.1. Solar pond electric power plant

A low temperature thermal electric power production scheme using solar pond is shown schematically in Fig. 10.17. The energy obtained from a solar pond is used to drive a Rankine cycle heat engine. Hot water from the bottom level of the pond is pumped to the evaporator where the organic working fluid is vapourized. The vapour then flows under high pressure to the turbine where it expands and work thus obtained runs an electric generator producing electricity. The exhaust vapour is then condensed in a condenser and the liquid is pumped back to the evaporator and the cycle is repeated.

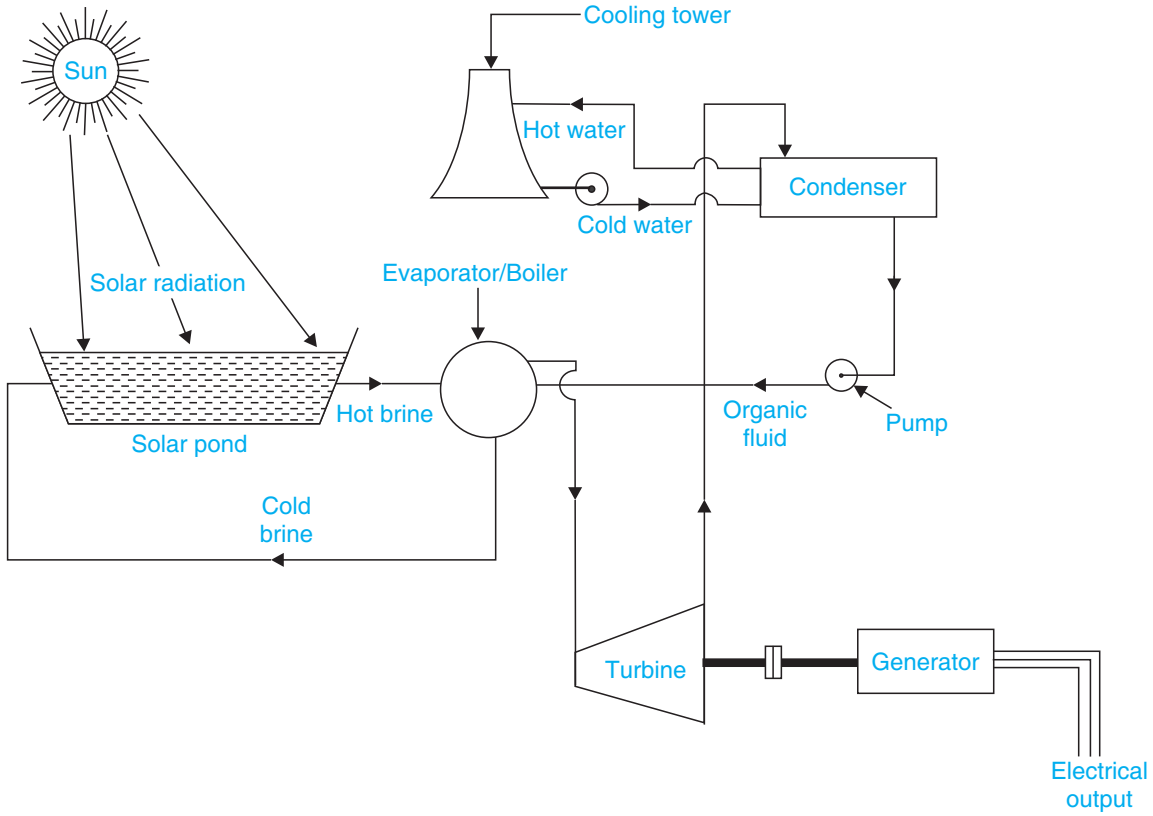


Fig. 10.17. Solar pond electric power plant.

In Australia a 2000 sq m solar pond equipped with a 20 kW engine has been installed.

10.4.6.2. Low temperature solar power plant

Fig. 10.18 shows a schematic diagram of a low temperature solar power plant. In this system an array of flat plate collectors is used to heat water to about 70°C and then this heat is used to boil butane in a heat exchanger. The high pressure butane vapour thus obtained runs a butane turbine which in tern operates a hydraulic pump. The pump pumps the water from well which is used for irrigation purposes. The exhaust butane vapour (from butane turbine) is condensed with the help of water which is pumped by the pump and the condensate is returned to the heat exchanger (or boiler).

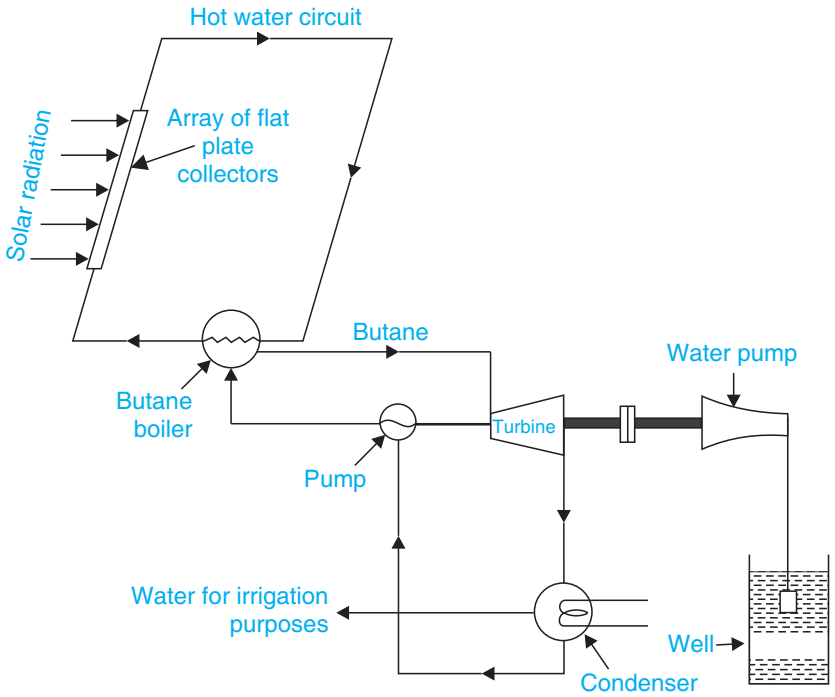


Fig. 10.18. Low temperature solar power plant.

10.4.7. Medium Temperature Systems Using Focusing Collectors

A circular or rectangular parabolic mirror can collect the radiation and focus it on to a small area, a mechanism for moving the collector to follow the sun being necessary. Such devices are used for *metallurgical research* where *high purity and high temperatures are essential*, an example being a 55 m diameter collector giving about 1 MW (th) at Mont Louis in Pyrenees. Smaller units having 20 m diameter reflector can give temperatures of 300°C over an area of about 50 m^2. The collector efficiency is about 50%. On a small scale, units about 1 m diameter giving temperatures of about 300°C have been used for cooking purposes.

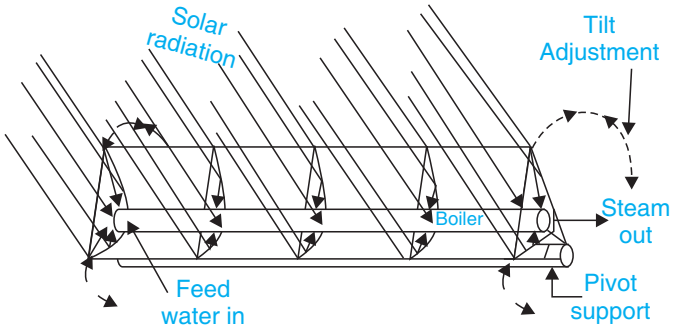


Fig. 10.19. Concave solar energy collector focuses sun's rays on boiler at focal point.

Fig. 10.19 shows a concave solar energy collector focusing sun's rays on boiler at a focal point. Generation of steam at 250°C could give turbine efficiencies up to 20–25 per cent.

10.4.8. High Temperature Systems—Solar Farm and Solar Power Plant

For a large scale production of process-heat the following two concepts are available :

1. **The solar farm.** It consists of a whole field covered with parabolic trough concentrators.

2. **The solar tower.** It consists of a central receiver on a tower and a whole field of tracking.

In case of a '*solar farm*' temperature at the point of focus can reach several hundred degrees celsius. Fig. 10.20 shows a solar tower system.

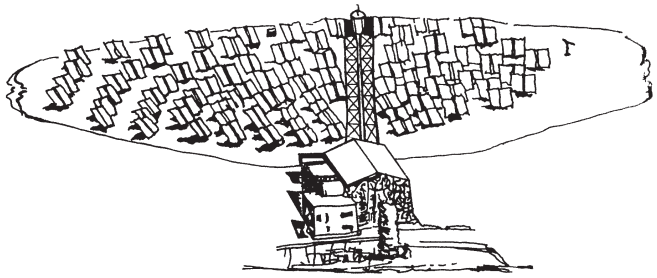


Fig. 10.20. Solar tower system.

In case of central receiver "*solar tower*" concentrators, temperature can reach thousands of degrees celsius, since a field of reflectors (heliostats) are arranged separately on sun-tracking frames to reflect the sun on to a boiler mounted on a central tower (Figs. 10.21, 10.22).

With both systems ('solar farm' and 'solar tower'), *a heat transfer fluid or gas is passed through the point or line of insolation concentration to collect the heat and transfer it to the point of use. Such heat can be used either directly in industrial or commercial processes or indirectly in electricity production via. steam and a turbine.*

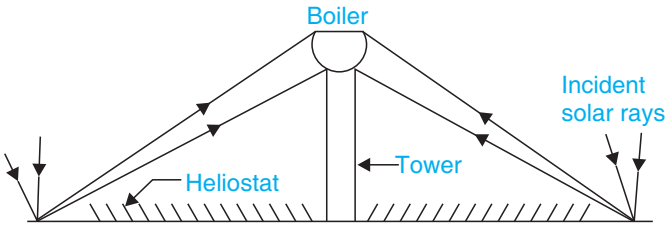


Fig. 10.21

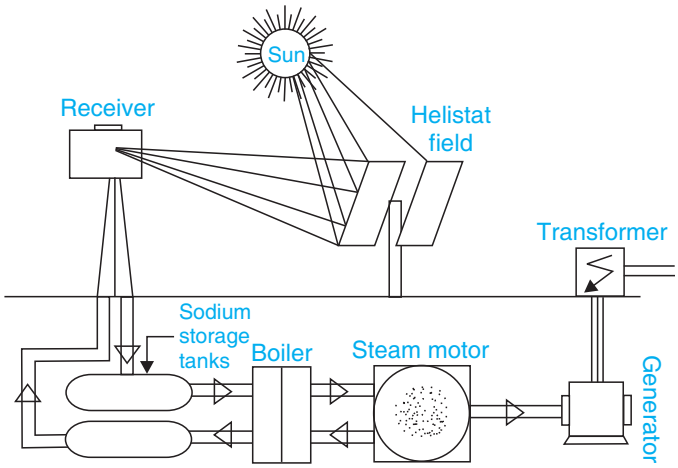


Fig. 10.22. Diagram of solar tower power plant.

The solar technologies such as the above two systems that produce very hot water or steam are currently still under development and, in general, these technologies are not cost competitive with conventional power sources such as oil or gas.

10.5. GEOTHERMAL POWER PLANTS

10.5.1. Geothermal Energy

As we travel down earth's surface radially, there exists a temperature gradient of 0.03°C per metre. Thus a 30°C increase in temperature can be obtained per kilometre depth from the earth's crust. *There are many local hot spots just below the surface where the temperatures are much higher than expected.* Ground water, when comes into

contact with these hot spots, either dry or wet steam is formed. By drilling holes to these locations, hot water and steam can be tapped and these can be used for power generation or space heating.

Geothermal energy is primarily energy from the earth's own interior, it is classified as *renewable* because the earth's interior is and will continue in the process of cooling for the indefinite future. Hence, geothermal energy from the earth's interior is almost inexhaustible as solar or wind energy, so long as its sources are actively sought and economically tapped. Geothermal energy can be used for *heat* and *power generation.* Geothermal energy is present over the entire extent of earth's surface except that it is nearer to the surface in the volcanic areas. Heat transfer from the earth's interior is by *three primary means* :

(*i*) Direct heat conduction ;

(*ii*) Rapid injection of ballistic magma along natural rifts penetrating deep into earth's mantle ; and

(*iii*) Bubble like magma that buoys upwards towards the surface.

Fig. 10.23 shows a schematic diagram depicting how hot springs are produced through hot magma (molten mass), the fractured crystalline rocks, the permeable rocks and percolating ground water.

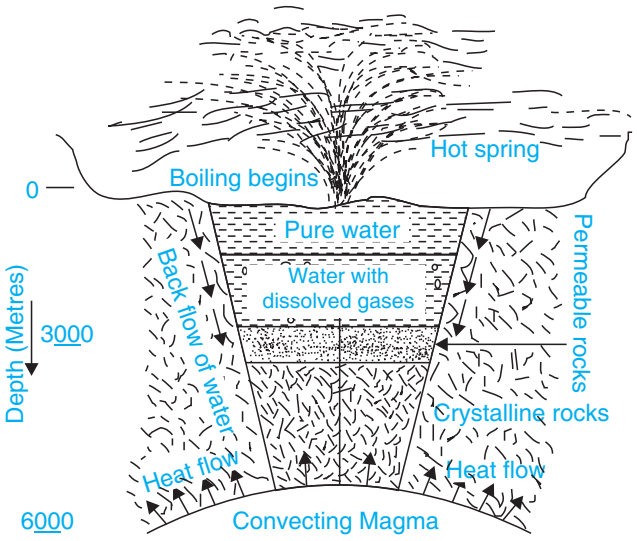


Fig. 10.23. Hot spring system structure.

10.5.2. Geothermal Sources

The following five general categories of geothermal sources have been identified :

1. Hydrothermal convective systems

(*i*) Vapour-dominated or dry steam fields.

(*ii*) Liquid-dominated system or wet steam fields.

(*iii*) Hot-water fields.

2. Geopressure resources.

3. Petro-thermal or hot dry rocks (HDR).

4. Magma resources.

5. Volcanoes.

The hydro-thermal convective systems are best resources for geothermal energy exploitation at present. Hot dry rock is also being considered.

Fig. 10.24 shows a dry-steam open system used in Larderello (Italy) and Greyser (U.S.A.).

Fig. 10.25 shows a flash steam open type system used in Cerro Prietol Mexico, Otake (Japan).

Fig. 10.26 shows a hot water closed (Binary) system under development in U.S.S.R. and U.S.A.

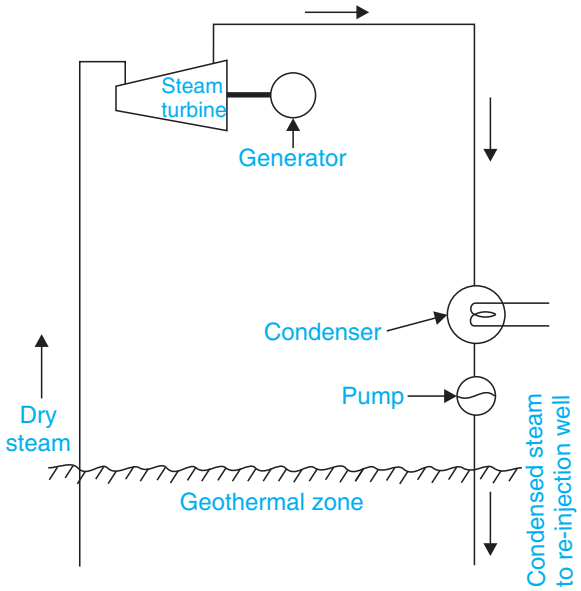


Fig. 10.24. Dry-steam open system.

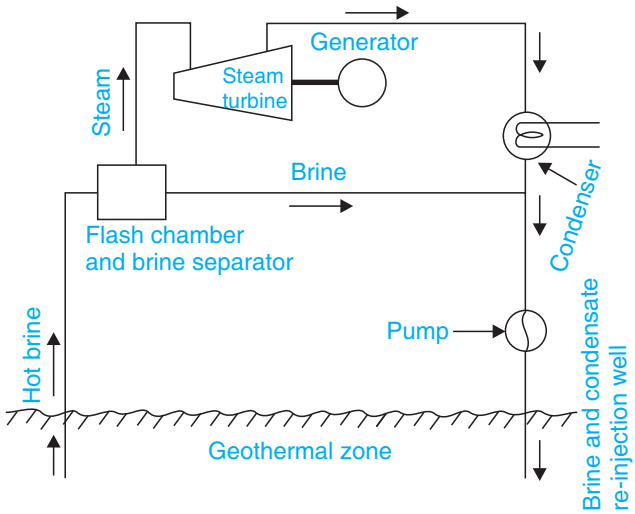


Fig. 10.25. Flash steam open type system.

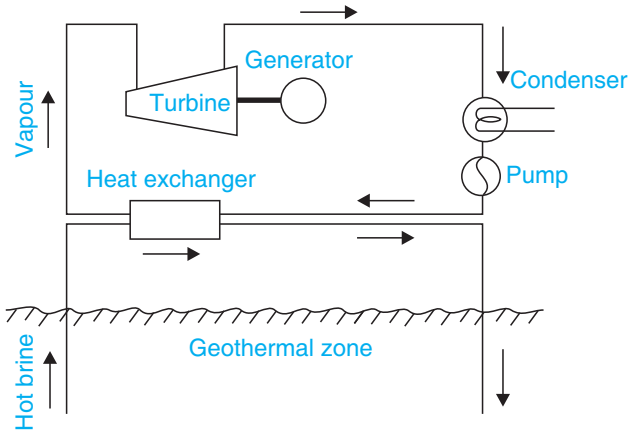


Fig. 10.26. Hot water closed (Binary) system.

10.5.3. Geothermal Power Estimates

Although geothermal power estimates vary very widely yet rough estimate is given below :

Depth	*Total stored energy* (approximately)
3 km	8×10^{21} joules
10 km	4×10^{22} joules

— The energy stored in hot springs = 10 per cent of the above quantities.

— If the above energy is extracted from a 3 km belt, with 1% thermal energy recovery factor, at a uniform rate of over 50 years period, thermal power of 50 GW is obtained. With a thermal electric conversion efficiency of 20% only 10 GW of electric power will be obtained.

10.5.4. Environmental Problems

Geothermal power plants create some environmental problems which are peculiar to them alone. The effluent will be salty and may contain sodium and potassium compounds. Additionally, in some cases lithium, fluorine, boron and arsenic compounds may be present. Such effluents cannot be discharged into the existing water courses unless properly treated without risking severe pollution problems. Some effluents contain boron, fluorine and arsenic. All these are *very harmful to plants and animal life in concentrations as low as two parts per million. Suitable waste treatment plants to prevent degradation of water quality will have to be installed to treat these new and increased sources of pollution*.

10.5.5. Applications of Geothermal Energy

The following are the three main applications of the steam and hot water from the wet geothermal reservoirs :

1. Generation of electric power.
2. Space heating for buildings.
3. Industrial process heat.

The major benefit of geothermal energy is its *varied application and versatility*.

- **Geothermal plants** *have proved useful for "base-load power plants". These kind of plants are primarily entering the market where modest sized plants are needed with low capital cost, short construction period and life-long fuel (i.e. geothermal heat).*

10.5.6. Advantages and Disadvantages of Geothermal Energy over Other Energy Forms

Advantages of Geothermal Energy :

1. Geothermal energy is cheaper.
2. It is versatile in its use.
3. It is the least polluting as compared to other conventional energy sources.
4. It is amenable for multiple uses from a single resource.
5. Geothermal power plants have the highest annual load factors of 85 per cent to 90 per cent compared to 45 per cent to 50 per cent for fossil fuel plants.
6. It delivers greater amount of net energy from its system as compared to other alternative or conventional systems.
7. Geothermal energy from the earth's interior is almost as inexhaustible as solar or wind energy, so long as its sources are actively sought and economically tapped.

Disadvantages :

1. Low overall power production efficiency (about 15% as compared to 35 to 40% for fossil fuel plants).
2. Drilling operation is noisy.
3. Large areas are needed for exploitation of geothermal energy.
4. The withdrawal of large amounts of steam or water from a hydro-thermal reservoir may result in surface subsidence or settlement.

10.5.7. Geothermal Energy in India and Abroad

Some progress is being made in India on tapping geothermal energy on a commercial scale. Engineers from the Geological Survey of India have drilled about 50 shallow wells for steam in the Puga valley of the Ladakh region in Jammu and Kashmir. It may be possible to operate a 5 MW power station at the site. The Puga valley at an altitude of 4500 metres above sea level has the most promising geothermal field. The area extends to about 40 square kilometres out of which 5 sq. km is active. A combination of wet and dry steam to the tune of 170 tonnes

of hot water per hour and 20 tonnes/hour of dry steam (superheated steam suitable for running steam turbines) is available. This is enough to run a small power station to light the homes of local population. The geothermal heat can also be used for space heating in the Puga valley as the temperature in this area, especially during winter months, goes down to 35 degrees below freezing point. There are no other energy sources in Ladakh region and coal, petroleum etc. have to be transported from Srinagar. It can also be used for poultry farming, mushroom cultivation and pashmina wool processing which need a warmer climate. In addition, there are good deposits of borax and sulphur in this area. Sulphur in elemental form is found only in this region in the whole of India.

There are many *hot water springs* in India. Hot water springs represent heat energy coming out of the earth from a large body of molten rock that has been pushed up into upper crust of the earth by geological forces. In North they occur in Ladakh and Himachal Pradesh. In western parts they are found in the Cambay region of Gujrat and Maharashtra. They are also found in the Singhbhum region of Bihar while there are some in Assam. The water from a hot spring at Garampani, near Jawai, in Assam is so hot is summer that rice kept in muslin bag gets worked in no time.

The Geological Survey of India has so far identified about 350 hot spring sites which can be explored as sources of geothermal energy. The engineers have commissioned an experimental 1 kW generator running on geothermal energy in the Puga area. This is the first production of electricity from a hot water spring in India.

Many countries with hot springs in their territories have realised their potential for power and heat production. Countries like Italy, Iceland, New Zealand, the USA and the USSR have achieved remarkable progress in the application of geothermal energy.

The Italian power plant at Landerello was started in 1904 on a small scale but now it produces 540 MW of electricity. This is equivalent to burning 1.5 million tonnes of oil in a year. New Zealand started exploration in 1950 and the Wairakei power station now produces 175 MW, which is equal to 0.7 million tonnes of oil per year. The power production in California, the USA, began in 1960 and has already touched 50 MW. In the Philippines the drillers struck high pressure, high temperature steam at about 200 m only at Tiwi, a tiny sleepy village nestled at the base of the volcano Malino, in 1967. By January, 1976, the first geothermal power plant at Tiwi began producing 55 MW. A geothermal plant with a capacity of 11 MW has been in operation for nearly 20 years in USSR. The construction of another power plant at Mutnovsky with a capacity of 200 MW is in progress.

10.6. BIOGAS PLANTS-BIOMASS

10.6.1. Introduction to Biomass

Biomass *is an organic matter from plants, animals and micro-organism grown on land and water and their derivatives*. The energy obtained from biomass is called **biomass energy**.

Biomass is considered as a renewable source of energy because the organic matter is generated every day. Coal, petroleum oil and natural gas do not come in the category of 'biomass', because they are produced from dead, burried biomass under pressure and temperature during millions of year. Biomass can also be considered a form of solar energy as the latter is used indirectly to grow these plants by *photosynthesis'*.

Biomass resources :

In our country, there is a great potential for application of biomass as an alternate source of energy. We have plenty of agricultural and forest resources for reproduction of biomass.

The following are the biomass resources:

1. *Concentrated wastes :*
   - (*i*) Municipal solid
   - (*ii*) Sewage wood products
   - (*iii*) Industrial waste
   - (*iv*) Manure at large lots.
2. *Dispersed waste residue :*
   - (*i*) Crop residue
   - (*ii*) Logging residue
   - (*iii*) Disposed manure.
3. *Harvested biomass :*
   - (*i*) Standing biomass
   - (*ii*) Biomass energy plantations.

The biomass sources are highly dispersed and bulky and contain large amount of water (50 to 90%). Thus, it is not economical to transport them over long distances, and as such conversion into usable energy must take place close to the source, which is limited to particular regions. However, biomass can be converted to liquid or gaseous fuels thereby increasing its energy density and making transportation feasible over long distances.

10.6.2. Biomass Conversion Processes

The following processes are used for the biomass conversion to energy or to biofuels :

1. Direct combustion.
2. Thermochemical conversion.
3. Biochemical conversion.

1. Direct combustion :

Combustion *is the process of burning in presence of oxygen to produce heat, light and byproducts.* Complete combustion to ashes is called ***incineration.***

— Wood, dung, vegetable waste can be dried and burnt to provide heat or converted into low calorific value gas by ***pyrolysis.*** In the pyrolysis process, the organic material is converted to gases, solids and liquids by heating to 500 to 900°C in the *absence of oxygen.*

— The combustion of biomass is more difficult than other fuels, since it contains relatively higher moisture content. Biomass is free from toxic metals and its ash.

- The technology of *"fluidised bed combustion"* may be used for the efficient combustion of forestry and agricultural waste material such as sawdust, wood chips, hog fuel, rice husks, straws, nutshells and chips.

— In fluidised bed combustion of biomass, the *biomass is fed into a bed of hot inert particles*, such us sand kept in fluidised state with air at sufficient velocity from below. The operating temperature is normally controlled within the range 750–950°C ; ideally it is kept as high as possible in order to maximise the rate of combustion and heat transfer but low enough to avoid the problem of sintering of the bed particles. *The rapid mixing and turbulence within the fluidised bed enables efficient combustion to be achieved with high heat releases, as well as effective transfer*, than in a conventional boiler. This can result in more compact boiler with less number of tubes.

2. Thermochemical conversion :

- Biomass is decomposed in thermochemical processes having various combinations of temperatures and pressures.
- Thermochemical conversion takes two forms : *Gasification* and *liquefaction.*
- *"Gasification"* takes place by heating the biomass with limited oxygen to produce low heating value gas or by reacting it with steam and oxygen at high pressure and temperature to produce medium heating value gas. The latter may be used as fuel directly or used in *"liquefaction"* by converting it to methanol (methyl alcohol), or ethanol (ethyl alcohol) or it may be converted to high heating value gas.

3. Biochemical conversion. In biochemical conversion there are two principal conversion processes :

(*i*) Anaerobic digestion ; (*ii*) Fermentation.

(*i*) ***Anaerobic digestion.*** This process involves microbial digestion of biomass.

- The process and end products depend upon the microorganisms cultivated and culture conditions. (An *anaerobe* is a microscopic organism that can live and grow without external oxygen or air ; it extracts oxygen by decomposing the biomass at low temperatures upto 65°C, in presence of moisture).
- This process generates mostly *methane* (CH_4) and CO_2 gas with small impurities such as hydrogen sulphide.
- The output gas obtained from anaerobic digestion can be directly burnt, or upgraded to superior fuel gas (methane) by removal of CO_2 and other impurities. The residue may consist of protein-rich sludge and liquid effluents which can be used as annual feed or for soil treatment after certain processing.

(*ii*) ***Fermentation.*** *It is the process of decomposition of organic matter by micro-organisms especially bacteria and yeasts.*

- It is a well established and widely used technology for the conversion of grains and sugar crops into ethanol (ethyl alcohol). Ethanol can be blended with gasoline (petrol) to produce gasohol (90% petrol and 10% ethanol). Processes have been developed to produce various fuels from various types of fermentations.

10.6.3. Biogas Plants

10.6.3.1. Biogas

The main source for production of biogas is wet cow-dung. Some of the other sources are :

(*i*) Sewage (*ii*) Crop residue
(*iii*) Vegetable wastes (*iv*) Water hyacinth
(*v*) Alga (*vi*) Poultry droppings
(*vii*) Pig-manure (*viii*) Ocean kelp.

Biogas, a mixture containing 55–65% methane, 30–40% carbon dioxide and the rest being the impurities hydrogen (hydrogen sulphide and some nitrogen), can be produced from the decomposition of animal, plant and human waste. It is a clean but slow-burning gas and usually has a heating value about 18 kJ/m^3. It can be used directly in cooking, reducing the demand for firewood. Moreover, the material from which the biogas is produced retains its value as fertilizer and can be returned to soil.

Biogas is produced by digestion, pyrolysis or hydrogasification. **Digestion** is a biological process that occurs in the absence of oxygen and in the presence of anaerobic organisms at ambient pressures and temperatures of 35–70°C. The container in which this digestion takes place is known as the *digester.*

10.6.3.2. Biogas applications

Biogas is a flammable fuel gas with 60% CH_4 and rest CO_2. The gas can be upgraded by removal of CO_2 with water scrubbing and the gas with high heating value can be used in I.C. engine. The main *applications of biogas* are:

(*i*) Cooking.

(*ii*) Domestic lighting and heating.

(*iii*) I.C. engines.

(*iv*) Fuel cells–electricity can be produced by using biogas in a fuel cell with air as oxidant. The electrolyte is usually potassium hydroxide (KOH).

10.6.3.3. Types of biogas plants

Biogas plant *converts wet biomass into biogas (methane) by the process of anaerobic fermentation.* The bacteria called *anaerobe* carries out digestion of biomass without oxygen and produces methane (CH_4) and carbondioxide (CO_2). Biogas plants are very popular in India particularly in rural areas. Cow dung, agricultural waste etc. is converted to methane.

A typical biogas plant has :

— Digester ; — Inlet tank ;

— Outlet tank ; — Stirrer etc.

The biogas plants are built in several sizes, small (0.5 m^3)/day) to very large (2500 m^3/day). Accordingly, the configurations are simpler to complex.

Biogas plants are *classified* as follows :

1. *Continuous type :*
   - Single stage type
   - Two stage type.
2. *Batch type*
3. *Fixed dome type* (Janata model or chinese model)
4. *Modified fixed dome type.* This type of plant has an additional displacement tank and water seal gas tank.
5. *Flexible bag type.*
6. *Floating dome type.*

10.6.3.4. Janata model gobar gas plant

Constructional features. This plant consists of the following parts :

Refer to Fig. 10.27.

1. Foundation
2. Digester
3. Dome
4. Inlet chamber
5. Outlet chamber
6. Mixing tank
7. Gas outlet pipe.

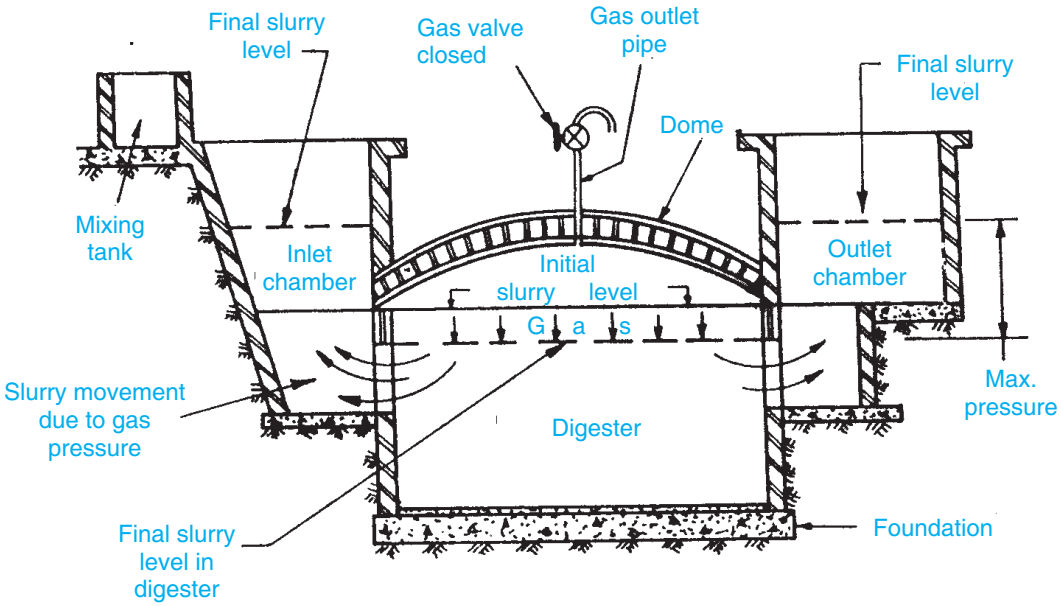


Fig. 10.27. Janata model gobar gas plant.

Foundation. The foundation is the amply compacted base of the digester made of cement concrete and brick ballast. Its construction is so carried out that it may provide a stable foundation to the digester walls and bear full load of slurry filled in the digester. It should be waterproof so that no percolation or water leakage takes place.

Digester. It is underground cylindrical wall portion made of bricks, sand and cement. It is this place where fermentation of dung takes place. It is also sometimes called 'fermentation tank'. Two rectangular openings facing each other are provided for inflow and outflow at almost middle of its height.

Dome. It is a hemispherical roof of the digester ; has a fixed height and forms the *critical part* in the construction of Janata gobar gas plant. The gas gets collected in the space of the dome and exerts pressure on the slurry in the digester.

Inlet chamber. An inlet chamber has a bell mouth shape and is made of bricks, cement and sand. It has its top opening at the ground level. Its outlet wall is made inclined/slopy to enable the daily cattle dung feed to move easily into the digester.

Outlet chamber. It is that part of the plant through which digested slurry moves out of the digester at a predetermined height. It has a small rectangular cross-section and above this it becomes larger to a defined height. For easy cleaning of the digester two steps are provided in it which enable a man to climb down. Its top opening is also at the ground level. Just near the top opening is provided a small outlet through which the digested/spent slurry flows to a compost pit.

***Mixing tank*.** It is this tank where gobar and water are mixed properly in the ratio of 1 : 1 to make slurry which is then poured into the inlet chamber.

***Gas outlet pipe*.** It is a small piece of G.I. Pipe which is fitted at the top of the dome for conveying the gas to the points of use. A valve is fitted at its end to regulate the flow of gas to the gas connections.

Site selection. While selecting the construction of Janata gobar gas plant the following points should be given due consideration.

— The surface should be plane/even and be at a higher elevation so that during rainy season the water level is at least at 3 m depth. The higher level will discourage water logging and ensure easy discharge of spent slurry from the outlet chamber. Preferably this place should be beyond the reach of children.

— The site should be as far as possible near the cattle shed and points of gas utilisation.

— It should be at least 2 metres away from the foundation of the house/building.

— The sun light should be available during whole of the day round the year.

— The site should be at least 10–15 metres away from the any water drinking source.

— There should not be any big tree near the plant whose roots may cause any harm with the passage of time.

— There should be an easy availability of water near the plant.

— To avoid carrying spent slurry to a very far distance there should be some space for making compost pit.

— The earth should have adequate bearing stress to avoid any possibility of caving in or collapse of the plant.

Nature of soil and corresponding precautions :

1. ***Soil formed of clay :***

— Related problem — Easy expansion and contraction of soil as the moisture content increases and decreases.

— Precautions — Do not disturb the primitive soil ; Or Take measures for excess or less of water ; Or Drain the surface water.

2. ***Non-uniform soil structure :***

e.g. partly soft soil and partly rocky

— Related problem — Crack may appear in digester wall due to uneven settlement.

— Precautions — Provide a uniform kind of soil under the digester ; Or

— Remove a portion of the soft, soil and put lime concrete and rubble in its place ; Or

— Remove a part of the rock and add medium and coarse sand, cinders, clay or clay gravel.

3. ***Soil with high water table :***

— Related problem — There is an upward force on the digester due to pressure of ground water.

— Precautions — Construct the plant in low water seasons.

— Dig a trench around the digester to collect the water ; this water may be occassionally pumped out.

— Divert the ground water, if possible, to other places *e.g.*, well points.

— Increase the strength of the base of the digester by increasing its thickness. It will counter act the buoyancy force of ground water.

Initial loading of the plant. After completion of the plant it is to be charged with cattle dung and water in the ratio of 1 : 1. Since Janata Plant is designed for 50 days retention period, therefore initial loading will comprise of 50 times of gobar needed for daily feed. Naturally to arrange such a large quantity of gobar by farmers who have a few cattle is a problem. This difficulty

can be overcome if the gobar is collected regularly during the period of construction of plant and by the time the plant is completed the large quantity of gobar collected can be then fed.

— Before feeding into the digester the dung should be properly mixed with water in the ratio of 1 : 1 in the mixing tank to get the slurry.
— The slurry is then fed to the digester upto the step provided on the Outlet chamber. Thereafter the fermentation starts.
— Initially allow the gas which comprises of large percentage of a carbondioxide, oxygen and hydrogen sulphide to escape since it will not burn.
— The gas obtained after this release will have a right combination of methane (60%) and carbon dioxide (40%) and burn with odourless blue flame in the gas chulha/burner/stove.
— Now, at this stage start feeding the plant with dung slurry.
— Regular, proper and careful feeding will ensure flawless gas service.

How does the plant function ?

— The cattle dung and water are mixed properly in the ratio 1 : 1 to form slurry which is then filled in the digester upto the height of its cylindrical portion.
— As soon as the fermentation of dung picks up the generated gas starts accumulating in the dome. This gas then exerts pressure on the slurry and displaces it into the Inlet and Outlet chambers. Consequently the slurry level in the digester falls and rises in the Outlet chamber.
— This fall in the level of slurry continues (if the outlet pipe valve is closed) till the slurry level reaches the upper ends/edges of the Inlet and Outlet gates.
— After this stage any further accumulation of gas would exert pressure and start escaping through these gates into the atmosphere. This condition is indicated by *bubbling* and froth formation on the surface of the slurry in the inlet and outlet chambers.
— The quantity of usable gas can be determined by calculating the increase in slurry volume in the inlet and outlet chambers.
— In the event of using gas the slurry level in the digester rises while that in the inlet and outlet comes down.
— The increase in gas pressure due to increased generation in comparison to its utilisation will push/displace the slurry up in the inlet and outlet chambers while the decrease in pressure is balanced by the return flow of slurry back in the digester.
— During the process approximately equivalent quantity of spent/digested slurry (top layer slurry) is discharged from the outlet chamber through the outlet opening ; this is so because fresh/undigested slurry which is fed into the inlet chamber is heavier than the digested/spent slurry and settles down in the digester.

Chemistry of gas generation. In gober gas plant the feed which comprises mainly of cattle dung is subjected to anaerobic fermentation as a result of which is produced combustible gas and fully matured organic manure which is superior to green manure available from dung otherwise. The whole process of feeding fresh slurry of dung and water and extraction of spent slurry in gobar gas plant is continuous one.

The cattle dung (and other fermentable materials like night soil, poultry or piggery droppings etc.) when confined in a place where there is no air gives rise to mainly two types of bacteria *viz. Acid forming bacteria* and *Gasifying bacteria*.

Acid forming bacteria convert carbohydrates, proteins, fats into volatile acids and carbon dioxide is produced during the process. This phase is also known as liquification phase and is brought about by a set of *saprophytic bacteria* of means of extracellular enzyme. These bacteria are less sensitive and can exist, develop and multiply in wide range of conditions.

Liquification phase is followed by gasification phase which is actively carried out by *methane bacteria*. They work upon volatile acid produced during the previous phase, with the help of intracellular enzyme and convert it into methane and carbon dioxide.

The whole process of gobar generation is governed by the factors *viz*. temperature of substrate. Loading rate, Solid concentration, Detention period, pH value, Nutrients concentration and Toxic substance etc.

The composition of the gas produced varies with the type of fermentable material used. In case of cattle dung on an average the gas produced consists of 55 to 60% methane and 40 to 45% corbon dioxide with little quantity of hydrogen, hydrogen sulphide. With night soil the percentage may be : Methane = 65%, carbon dioxide 34%, hydrogen sulphide = 0.6% and other gas 0.4%.

Diphasic anaerobic digestion. To tide over the problems generally associated with maintaining optimum fermentation conditions inside the digester, diphasic

anaerobic digestion seems to be probable solution. In this system two separate digesters are used which separate the hydrogen and acid formation phases from methane formation phase ; this separation of phases is brought out by kinetic control. The acid phase is operated at low retention times so that only the fast growing acidogens of first hydrolysis and acid forming stages are retained in the digester and methogens are washed out. The methane phase takes place in a separate digester with the acid phase effluent as the feed material.

This system facilitates provision of optimum environment conditions for growth of two physiologically different types of bacteria which in turn ensures *higher efficiency of the process with subsequent reduction in the size of digester and their cost*. In this process system monitoring is also rendered easier.

How to accelerate gas generation. The gas production is usually satisfactory during summer season but it falls considerably during coldest months of the year. *The gas production can be enhanced/accelerated by following the tips given below :*

— Add about 1 litre of cattle urine daily for every 5 kg slurry fed to the plant. It will augment the fermentation process and eventually increase gas production. The urine can be collected in the sump connected through a drain to the animal shed.

— Feed back about 10% of the fresh spent/digested slurry to the plant. The micro-organisms available in the spent slurry will stimulate fermentation.

— Prepare the dung slurry with hot water. Water may be kept exposed to Sun during the day and be used in the evening to produce slurry. This process will prove helpful in increasing the temperature of slurry in the digester and subsequently actify the bacteria to generate more gas.

— Cover the plant with rice straw or gunny bags during late evenings and nights ; it will check fall of temperature and keep the bacteria active in gas generation.

— Add 1 kg of powdered leaves for every 50 kg dung fed to the plant ; it will help creating warmer environment suitable to bacteria for actified fermentation.

— Addition of poultry droppings (5 to 10%) and piggery waste helps to bring about increase in gas generation.

— Provision of a compost pit around the plant assists in keeping the plant warm due to which gas generation is improved.

10.6.3.5. Advantages and disadvantages of 'Fixed dome type' and 'Movable drum type' plants

A. Fixed dome type plants :

Advantages :

1. No maintenance problems due to absence of moving parts.
2. Low cost.
3. Low operating cost.
4. Longer working life.
5. Due to underground construction, heat insulation is better and therefore, rate of gas production is uniform during night and day.
6. Quantity of gas produced is higher than movable drum type plants.
7. No corrosion problem.
8. Space above the plant can be used for other purposes.

Disadvantages :

1. Variable gas pressure.
2. Problem of scum formation.
3. For construction work skilled masons are required.

B. Movable drum type plants :

Advantages :

1. Gas pressure is constant.
2. Less scum problem.
3. No danger of explosion since there is no possibility of mixing of biogas and external air.
4. No gas leakage problem.

Disadvantages :

1. High cost.
2. High maintenance cost.
3. There is a loss of heat through gas holder.
4. The outlet pipe, which should be flexible, requires regular attention.

10.6.3.6. Guidlines for fixing optimum size of a biogas plant

The following *guidline* may be used to fix optimum size of biogas plant :

1. Type of waste.
2. Daily rate of waste to be digested.
3. Digestion period.
4. Method of stirring, if any.
5. Arrangement for raw waste feeding and discharge of digested slurry.
6. Climatic conditions.
7. Mix of raw waste.
8. Water table and sub-soil conditions.
9. Type of dome.

10.7. DIRECT ENERGY CONVERSION SYSTEMS

The energy conversion devices that have been in use for a long time are those that accept energy as heat and produce mechanical work, which is transformed into electric power distribution at large. *Direct energy conversion devices convert naturally available energy into electricity without an intermediate conversion into mechanical energy*. (The energy source may be thermal, solar or chemical). Until now, their use has been confined to small scale, special purpose applications, since the voltage output available with them is rather small and no inexpensive device that is reliable like a turbine or alternator has been built.

Under this topic the following systems will be discussed :

1. Thermoelectric conversion system
2. Thermionic conversion system
3. Photovoltaic power system
4. Magnetohydrodynamic system
5. Electrostatic mechanical generators
6. Electro Gas-Dynamic Generators (EGD)
7. Fuel cells
8. Nuclear batteries.

10.7.1. Thermoelectric Conversion System

The quest for a reliable, silent, energy converter with no moving parts that transforms heat to electrical power has led engineers to reconsider a set of phenomena called the *Thermoelectric effects*. These effects, known for over a hundred years, have permitted the development of small, self contained electrical power sources.

Seebeck (thermoelectric) effect. The German Scientist Seebeck (in 1822) discovered that *if two dissimilar materials* are joined to form a loop and the two junctions maintained at different temperatures, an e.m.f. will be set up around the loop. The magnitude of e.m.f. will be $E = \alpha\Delta T$ where ΔT is the temperature difference between the two junctions and α is the *Seebeck co-efficient*. This effect has long been used in *thermocouples to measure temperatures*.

This phenomenon offers one method of producing electrical energy directly from the heat of combustion, but its *thermal efficiency* is very low, of the order of 1 to 3 per cent. In any heat engine, the efficiency of thermoelectric generator depends upon the temperature of hot and cold junctions.

Thermoelectric Power Generator

Fig. 10.28 shows a schematic diagram of a thermo-electric power generator. The thermocouple material A and B are joined at the hot end, but the other ends are kept cold ; an electric voltage or electromotive force is then generated between the cold ends. A D.C. (Direct Current) will flow in a circuit or load connected between these ends. The flow of current will continue as long as the heat is supplied to the hot junction and removed from the cold ends. For a given thermocouple, the voltage and electric power output are increased by increasing the temperature difference between the hot and cold ends.

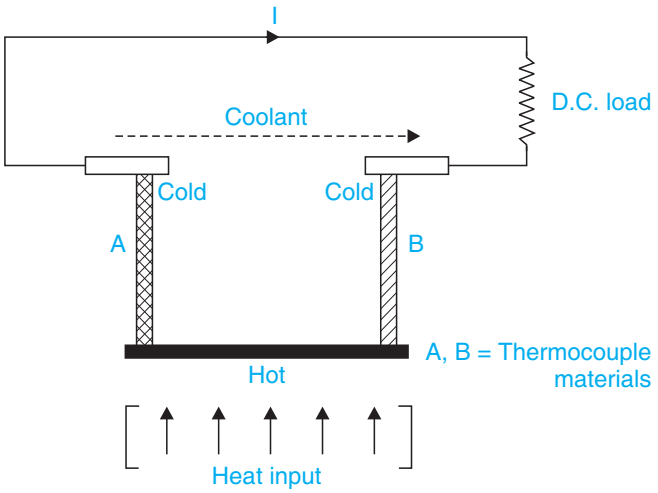


Fig. 10.28. Thermoelectric generator.

In a practical thermoelectric converter, several thermocouples are convected in series to *increases both voltage and power* as shown in Fig. 10.29. If the output voltage is insufficient to operate a particular device or equipment, it can be increased, with little loss of power, by an inverter transformers combination. The direct current generated by the thermocouples is first changed into alternating current of essentially the same average by means of an inverter. The alternating current and voltage in then increased to the desired value with the help of a transformer. The high voltage alternating current can be reconverted into direct current if required, by the use of a rectifier.

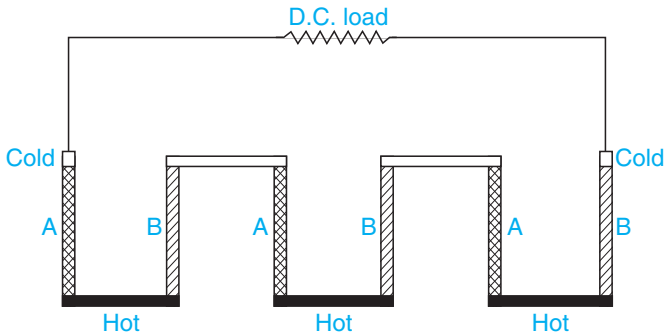


Fig. 10.29. Thermocouples in series (to increase voltage).

The source of heat for a thermoelectric generator may be a small oil or gas burner, a radio-isotope or direct solar radiation.

A typical couple operating with hot and cold junction temperatures of 600°C and 200°C could be designed to give about 0.1 V and 2 A *i.e.*, about 0.5 W, so that a 1 kW device could require about 5000 couples in series.

Taking into account mechanical characteristics, stability under operating conditions and ease of fabrication, Bismuth telluride appears to be most suitable material. It can be alloyed with such materials as Bismuth selenide, Antimony telluride, lead selenide and tin telluride to give improved properties.

Research is being carried out on the possibility of using thermoelectric devices within the core of a nuclear reactor. The hot junction would be located on the fuel element and the cold junctions in contact with the coolants.

Note. A thermoelectric converter is a form of *heat engine* which takes up heat at an *upper temperature* (hot junction) converts it partly into electrical energy and discharges the remaining part at a *lower temperature* (cold junction). The efficiency of a thermocouple, as is the case with other heat engines, increases by increasing the upper temperature and decreasing the lower temperature. Since the lower temperature is usually that of environment the efficiency of a thermocouple, practically, depends upon the *hot junction temperature*.

Thermoelectric materials and their selection :

The following materials find use in the making of thermoelectric elements :

Material	*Formula*	*Figure of merit, Z* (K^{-1})
Lead telluride	PbTe	1.5×10^{-3}
Bismuth telluride (doped with Sb or Se)	$Bi_2 Te_3$	4×10^{-3}
Germanium telluride (with bismuth)	Ge Te	1.5×10^{-3}
Cesium sulphide	Ce S	1.0×10^{-3}
Zinc antimonide (doped with silver)	Zn Sb	1.5×10^{-3}

where Z is an *index used in rating thermoelectric converters*. It depends on the properties of thermoelectric materials used. A high value of Z is obtained by using materials of :

(*i*) *Large Seebeck co-efficient*
(*ii*) *Small thermal conductivity*
(*iii*) *Small electrical resistivity.*

In recent times, the most commonly used material for thermoelectric converters is *lead telluride* [a compound of lead and tellurim, containing small amounts of either bismuth (*N*-type) or sodium (*P*-type)]. The efficiency of such a thermoelectric converter is, however, only about 5 to 7 per cent.

Taking into account mechanical characteristics, stability under operating conditions and ease of fabrication, Bismuth telluride appears to be amply suitable material. It can be alloyed with such materials as Bismuth selenide, Antimony telluride, Lead selenide and tin telluride to give improved properties.

Research is being made to find more efficient thermocouple materials. For high temperature applications, semiconductors based on silicon-germanium and compounds of selenium appear to be promising.

To achieve higher efficiency, thermoelectric material should have a high value of Z and be able to operate upto very high temperature. The following points are worthnothing in this regard :

1. The component thermal conductivity of semiconductor should be as low as possible.
2. The mobility of current carriers (electrons or holes, should be as high as is compatible with condition 1).
3. One of the arms should consist of a purely hole type and the other of a purely electronic type semiconductor.
4. In the low temperature zone the impurity concentration should be lower than in the higher temperature zone.
5. So that the thermoelectric material may not crack under the effect of stresses it should possess the following properties :
   (*i*) It should be able to resist chemical influences such as oxidation etc.
   (*ii*) It should have good mechanical strength.
   (*iii*) It should be amply elastic.

10.7.2. Thermionic Conversion System

Introduction

A thermionic converter can be analyzed from at least three different points of view :

1. In terms of *thermodynamics*, it may be viewed as a heat-engine that uses an electron gas as a working substance.

2. In terms of *electronics*, it may be viewed as a *diode* that transforms heat to electricity by the law of thermionic emission.

3. In terms of *thermoelectricity*, it may be viewed as a thermocouple in which an evacuated space or a plasma has been substituted for one of the conductors.

Regardless of the point of view adopted in analysis, a *thermionic converter works because of the phenomenon of 'thermionic emission'. Thermionic emission implies emission of electrons from the metal when it is heated.*

Work function (ϕ)

It is defined as *the energy required to extract an electron from the metal*. It is measured in *electron volts*. The value of work function varies with the *nature of the metal and its surface condition*.

A thermionic converter, in principle, consists of two metals or electrodes with different work functions sealed into an evacuated vessel. The electrode with a large work function is maintained at a higher temperature than one with the smaller work function.

Thermionic generators. Refer to Fig. 10.30.

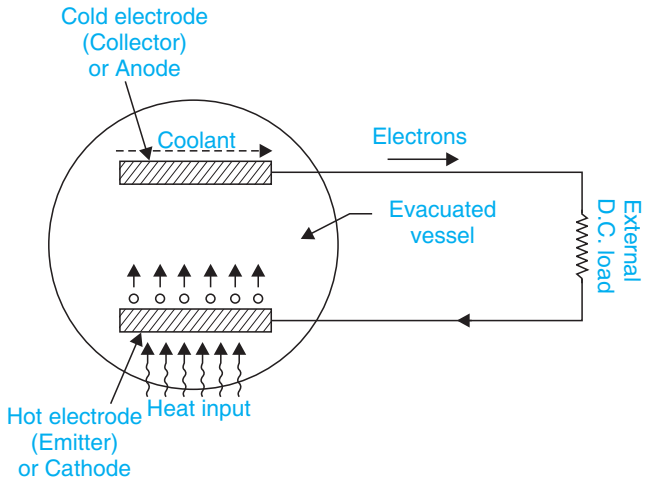


Fig. 10.30. Thermionic generator.

A thermionic converter/generator comprises a *heated cathode* (electron *emitter*) and an *anode* (electron *collector*) separated by a *vacuum*, the electrical output circuit being connected between the two as shown in Fig. 10.30. The heat which is supplied to the cathode raises the energy of its electrons to such a level that it enables them to escape from the surface and flow to the anode. *At the anode the energy of electrons appears partially as heat, removed by cooling and partially as electrical energy delivered to the circuit*. Although the distance between anode and cathode is only about *one millimetre*, the negative space charge with such an arrangement hinders the passage of the electrons and *must be reduced*, this can be achieved by introducing positive ions into the interelectrode space, cesium vapour being valuable source of such ions.

In order to materialise a substantial electron emission rate (per unit area of emitter), and hence a significant current output as well as a high efficiency, the emitter temperature in a thermionic converter containing cesium should be *at least 1000°C,* the efficiency is then 10 per cent. Efficiency as high as 40 per cent can be obtained by operating at still higher temperatures. Although temperature has little effect on the voltage generated, the increase in current (per unit emitter area) associated with a temperature increase results in increase in power. Electric power (P) is the product of voltage (E) and current (I) *i.e.*, $P = EI$.

Anode materials should have a *low work function e.g. barium and strontium oxides* while that of the *cathode* should be *considerably higher, tungsten impregnated with a barium compound* being a suitable material. Even with these materials temperatures upto 2000°C will be required to secure for the generator itself, efficiencies of 30–35 per cent. Electrical outputs of about 6 W/cm^2 of anode surface are envisaged with about 13 W/cm^2 removed by coolant.

A thermionic generator, in principal can make use of any fuel (may be fossil fuel, a nuclear fuel or solar energy) subject to the condition that sufficiently high temperatures are obtainable. The thermionic conversion can be utilized in several different situations-remote locations on the earth and in space.

Thermionic converter materials. The problem of developing materials suitable for use in thermionic converters ranks next to the space charge control problem in the development of efficient thermionic generators. Following properties are desirable in materials suitable for converters :

Emitter. A good emitter will :

(*i*) have high-electron emission capability coupled with a low rate of deterioration.

(*ii*) have *low emissivity*, to reduce heat transfer by radiation from the emitter.

(*iii*) be such that in the event some of it vapourizes and subsequently condenses on the collector it will not poison the collector (that is, change the collector properties, thereby making it less effective).

The relative importance of these properties is dependent upon the type of converter being designed. It should be noted that efficiency is a much slower rising function of electron emission capability if space charge is present than if there is no space charge.

The work function may be reduced considerably by an absorbed single layer of foreign atoms. This comes about by the establishment of a dipole layer at the surface. The layer can be formed by atoms or molecules. This is essentially what happens in a cesium converter, which is designed so that cesium condenses on the emitter or collector.

Collector. The *main criteria for choosing a collector material is that it should have as low a work function as possible*. Because the collector temperature is held below any temperature that will cause significant electron emission, its actual emission characteristics are of no consequence. The lower the collector work function (ϕ_c), however the less energy the electron will have to give up as it enters the collector surface. In practice the lowest value of ϕ_c that can be maintained stably is about 1.5 eV. For applications in which it is desirable to maintain the collector at elevated temperatures (greater than 900 K) such as space applications, an optimum value of ϕ_c may be determined. Molybdenum has been widely used as a collector ; it is frequently assumed to have a work function of 1.7 eV.

10.7.3. Photovoltaic Power System

Photovoltaic generators–Historical background. Edmond Becquerel in 1839 noted that a voltage was developed when light was directed onto one of the electrodes

in an electrolytic solution. The effect was first observed in a solid in 1877 by W.G. Adams and R.E. Day, who conducted experiments with selenium. Other early workers with solids included Schottky, Lange and Grandahl, who did pioneering work in producing photovoltaic cells with selenium and cuprous oxide. This work led to the development of photoelectric exposure metres. 1954 researchers turned to the problem of utilizing the photovoltaic effect as a source of power. In that year several groups including the workers at Bell Telephone Laboratories achieved conversion efficiencies of about 6 per cent by means of junctions of *P*-type and *N*-type semiconductors. These early junctions, commonly called *P-N* junctions, were made of cadmium sulphide and silicon. Later workers in the area have achieved efficiencies more than 20 per cent by using improved silicon *P-N* junctions.

Photovoltaic cell. Solar energy can be directly converted to electrical energy by means of *photovoltaic effect* which is defined as the *generation of an electromotive force as a result of the absorption of ionizing radiation*. Energy conversion devices which are employed to convert sunlight into electricity by the use of the photovoltaic effect are called *solar cells*. A single converter cell is called a solar cell or a *photovoltaic cell*. To increase the electrical power output a number of such cells are combined and the combination is called a *solar array* (or solar module).

In a photovoltaic cell sensitive element is a *semiconductor* (not metal) which generates voltage in proportion to the light or any radiant energy incident on it. The most commonly used photovoltaic cells are barrier layer type like iron-selenium cells or Cu—CuO_2 cells.

Fig. 10.31 shows a typical widely used photo-voltaic cell—"*Selenium cell*". It consists of a metal electrode on which a layer of selenium is deposited ; on the top of this a barrier layer is formed which is coated with a very thin layer of gold. The latter serves as a translucent electrode through which light can impinge on the layer below. Under the influence of this light, a negative charge will build up on the gold electrode and a positive charge on the bottom electrode.

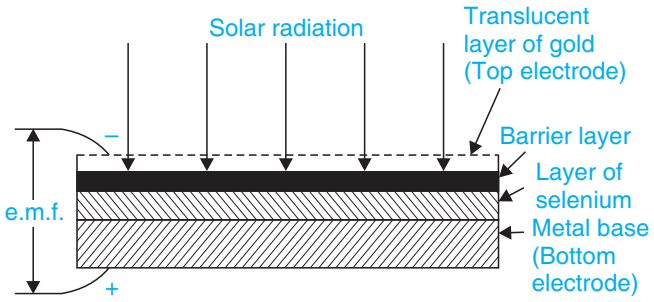


Fig. 10.31. Photovoltaic cell.

Photovoltaic cells are widely used in the following fields :

(*i*) Automatic control systems ;

(*ii*) Television circuits ;

(*iii*) Sound motion picture and reproducing equipment.

Basic photovoltaic system for power generation

Fig. 10.32 shows a basic photovoltaic system integrated with the utility grid. With the help of this system the generated electrical power can be delivered to the local load.

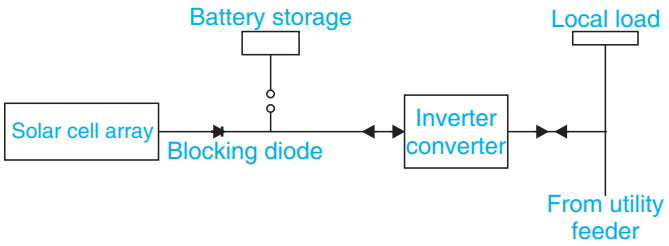


Fig. 10.32. Basic photovoltaic system integrated with power grid.

This system consists of the following :

1. Solar array
2. Blocking diode
3. Battery storage
4. Inverter converter
5. Switches and circuit breakers.

— The *solar array* (large or small) converts the insolation to useful D.C. electrical power.

— The *blocking diode* confines the electrical power generated by the solar array to flow towards the battery or grid only. In the absence of blocking diode the battery would discharge back (through the solar array) during the period when there is no insolation.

— *Battery storage* stores the electrical power generated through solar array.

— *Inverter / converter* (usually solid state) converts the battery bus voltage to A.C. of frequency and phase to match that needed to integrate with the utility grid. Thus it is typically a D.C., A.C. inverter.

— *Switches and circuit breakers* permit isolating parts of the system, as the battery.

Limitations of photovoltaic energy converters

The major factors which prohibit real photovoltaic converters from achieving the higher efficiencies are :

1. Reflection losses on the surface.
2. Incomplete absorption.

3. Utilization of only part of the photon energy for creation of electron hole pairs.
4. Incomplete collection of electron-hole pairs.
5. A voltage factor.
6. A curve factor related to the operating unit at maximum power.
7. Additional delegation of the curve due to internal series resistance.

Fabrication of Cells :

A. *Silicon cells*

Silicon cells are most widely used. Next to oxygen, silicon is the most abundant element on earth, the pure silicon used in cell manufacture is extracted from sand which is mostly silicon dioxide (SiO_2). The silicon required for solar cell use, because of its high purity, is expensive.

The fabrication of silicon cells include the following steps :

(*i*) The pure silicon is placed in an induction furnace where boron is added to melt. This turns the crystal resulting from the melt into *P*-type material.

(*ii*) A small seed of single crystal silicon is dipped into the melt and withdrawn at a rate slower than 10 cm per hour, the resulting inset looks like a medium sized carrot. The rate of growth and other conditions are adjusted so that the crystal that is pulled is a single crystal.

(*iii*) Wafers are then sliced from the grown crystal by the use of a diamond cutting wheel. The slices are then lapped, generally by hand, to remove the saw marks and strained regions.

(*iv*) After a fine lap the slabs are etched in hydrofluoric acid or nitric acid to complete the first phase of preparation of the cells. We now have thin slices of *P*-type silicon with a carefully finished surface.

(*v*) The wafers are then sealed in a quartz tube partly filled with phosphorous pentoxide and the arrangement is placed in a diffusion furnace where temperature is carefully controlled ; this process causes the phosphorous to diffuse into the *P*-type silicon to a depth of about 10^{-4} cm to 10^{-5} cm.

(*vi*) The cells are then etched in a concentrated acid to remove unwanted coatings that formed during manufacture. Wax or Teflon masking tape is used to protect the surfaces not to be etched.

B. *Thin film solar cells*

These cells have the following advantages :

(*i*) The material cost is low.

(*ii*) The manufacturing cost is low (possibly avoiding the need for single crystal growth).

(*iii*) High power-to-weight ratios.

(*iv*) Low array costs, because the number of connections needed will be greatly reduced.

The example of this type of cell is cadmium sulphide (CdS) cells. CdS cells having areas of 50 cm^2 have been made by evaporating the semiconductor on to a flexible substrate such as kapton, a metallized plastic substrate. A barrier layer of copper sulphide is then deposited on top of the CdS. Power to weight ratios of 200 watts/kg are claimed for such cells. These cells have low efficiency and instability.

Advantages and disadvantages of Photovoltaic solar energy conversion

Advantages :

(*i*) There are no moving parts.

(*ii*) Solar cells are easy to operate and need little maintenance.

(*iii*) They have longer life.

(*iv*) They are highly reliable.

(*v*) They do not create pollution problem.

(*vi*) Their energy source is unlimited.

(*vii*) They can be fabricated easily.

(*viii*) They have high power to weight ratio.

(*ix*) They can be used with or without sun tracking, making possible a wide range of application possibilities.

(*x*) They have ability to function unattended for long periods as evident in space programme.

Disadvantages :

(*i*) The cost of a solar cell is quite high.

(*ii*) The output of a solar cell is not constant, it varies with the time of day and weather.

(*iii*) Amount of power generated is small.

10.7.4. Magnetohydrodynamics (MHD) System

Introduction. Magnetohydrodynamics (MHD), as the name implies, is concerned with the flow of a conducting fluid in the presence of magnetic and electric field. The fluid may be gas at elevated temperature or liquid like sodium or potassium.

MHD generator is a device *which converts heat energy of a fuel directly into electrical energy without a conventional electric generator*. MHD converter system is a heat engine whose efficiency, like all heat engine, is increased by supplying the heat at the highest practical temperature and rejecting it at the lowest practical temperature. MHD generation looks the most promising of the direct conversion techniques for the large scale production of electric power.

Principle of MHD Power Generation :

Faraday's law of electromagnetic induction states that when a conductor and a magnetic field move in respect to each other, an electric voltage is induced in the conductor. The conductor need not be a solid—it may be a *gas or liquid*. The magnetohydrodynamic (MHD) generator uses this principle by forcing a *high-pressure high temperature combustion gas* through a strong magnetic field.

Fig. 10.33 shows the comparison between a *turbogenerator* and the *MHD generator*.

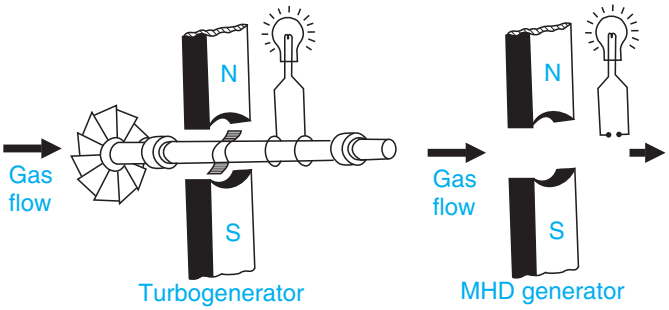


Fig. 10.33. Comparison between the conventional turbogenerator and the MHD generator.

MHD systems

The broad classification of the MHD systems is as follows :

1. Open cycle systems
2. Closed cycle systems

(*i*) Seeded inert gas systems

(*ii*) Liquid metal systems.

Open Cycle MHD systems

Fig. 10.34 shows an open cycle MHD system. Here the fuel (such an oil, coal, natural gas) is burnt in the combustion chamber, air required for combustion is supplied from *air preheater*. The hot gases produced by the combustion chamber are then seeded with a small amount of an ionized alkali metal (cesium or potassium) to increase

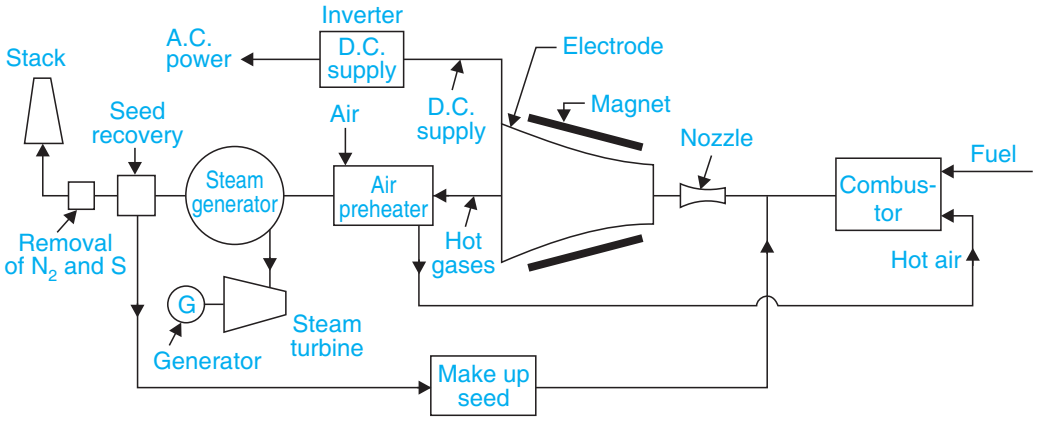


Fig. 10.34. Open cycle MHD system.

the electrical conductivity of the gas. The ionization of potassium (generally potassium carbonate is used as seed material) takes place due to gases produced at temperature of about 2300–2700°C by combustion. The hot pressurised working fluid so produced leaves the combustion chamber and passes through a convergent divergent nozzle. The gases coming out the nozzle at high velocity then enter the MHD generator. The expansion of the hot gases take place in the generator surrounded by powerful magnents. The MHD generator produces direct current. By using an *inverter* this direct current can be converted into alternating current.

Closed cycle MHD systems

A liquid metal closed cycle system is shown in Fig. 10.35. A liquid metal (potassium) is used as working fluid in this system. The liquid potassium after being heated in the breeder reactor is passed through the nozzle where its velocity is increased. The vapour formed due to nozzle action are separated in the separator and condensed and then pumped back to the reactor as shown in Fig. 10.35. Then the liquid metal with high velocity is passed through MHD generator to produce D.C. power. The liquid potassium coming out of MHD generator is passed through the heat exchanger (boiler) to use its remaining heat to run a turbine and then pumped back to the reactor.

This system entails many constructional and operational difficulties.

Advantages of MHD systems

1. More reliable since there are no moving parts.
2. In MHD system the efficiency can be about 50% (still higher expected) as compared to less than 40% for most efficient steam plants.

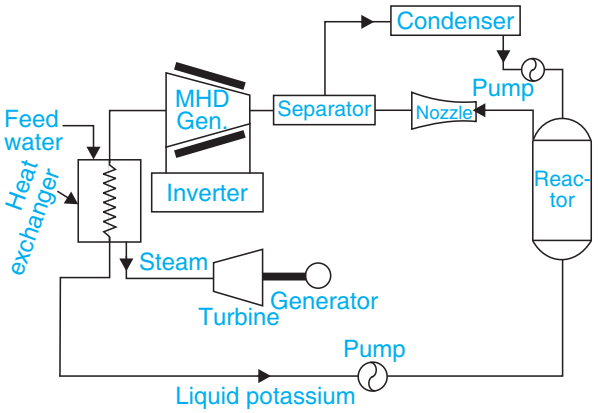


Fig. 10.35. Closed cycle (liquid metal) system.

3. Power produced is free of pollution.
4. As soon as it is started it can reach the full power level.
5. The size of plant is considerably smaller than conventional fossil fuel plants.
6. Less overall operational cost.
7. The capital cost of MHD plants is comparable to those of conventional steam plants.
8. Better utilization of fuel.
9. Suitable for peak power generation and emergency service.

Drawbacks of MHD system

1. MHD systems suffer from the reverse flow (short circuits) of electrons through the conducting fluids around the ends of the magnetic field. This loss can be reduced by (*i*) increasing aspect ratio (*L*/*d*) of the generator, (*ii*) by permitting the magnetic field poles to extend beyond the end of electrodes, and (*iii*) by using insulated vans in the fluid ducts and at the inlet and outlet of the generator.

2. There will be high friction losses and heat transfer losses. The friction loss may be as high as 12% of the input.

3. The MHD system operates at very high temperatures to obtain high electrical conductivity. But the electrodes must be relatively at low temperatures and hence the gas in the vicinity of the electrodes is cooler. This increases the resistivity of the gas near the electrodes and hence there will be a very large voltage drop across the gas film. By adding the seed material, the resistivity can be reduced.

4. The MHD system needs very large magnets and this is a major expense.

5. Coal, when used as a fuel, poses the problem of molten ash which may short circuit the electrodes. Hence oil or natural gas are considered to be much better fuels for this system. This restriction on the use of fuel makes the operation more expensive.

10.7.5. Electrostatic Mechanical Generators

Electrostatic mechanical generators convert mechanical energy, usually mechanical potential energy of a fluid directly into electrical energy.

Fig. 10.36 shows the principle of working of liquid drop electrostatic mechanical generator. In this, *the gravitational potential energy of water droplets is directly converted into electrical energy.* The electric charge is transferred from one electrode to another by an insulated belt. All these electrostatic devices are having the characteristic of fairly low currents and very high voltages. This is yet only a laboratory model and commercial power generation has yet to be done.

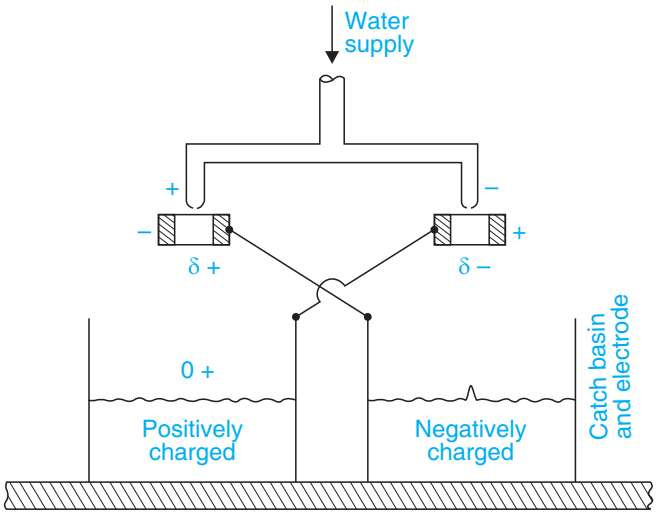


Fig. 10.36. Liquid drop electrostatic mechanical generator.

10.7.6. Electro Gas-Dynamic Generators (EGD)

The EGD generator uses the potential energy of a high pressure gas to carry electrons from a low potential electrode to a high potential electrode, thereby doing work against an electric field. A schematic diagram of EGD is shown in Fig. 10.37.

Carona electrode at the entrance of the duct generates electrons. This ionised gas particles are carried down the duct with the neutral atoms and the ionized particles are neutralised by the collector electrode, at the end of the insulated duct. The working fluid in these systems are commonly, either combustion gases produced by burning of fuel at high pressures or it is a pressurised reactor gas coolant. The maximum power output from EGD is about 10 to 30 W per channel. Hence, several thousand channels are connected in series and parallel. The voltage produced is very high, of the order of 1,00,000 to 2,00,000 V. Thus, it needs very good high voltage insulators. (Beryllium oxide, Beo, is generally used).

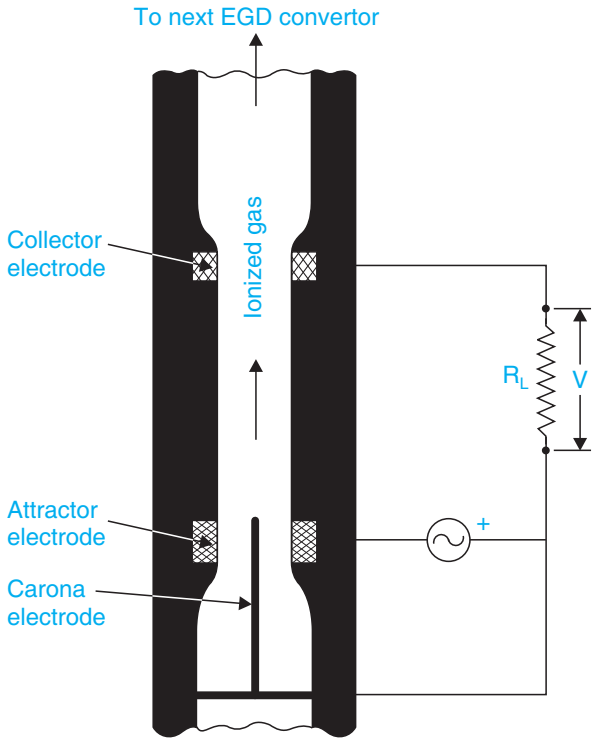


Fig. 10.37. Gas duct in an EGD convertor.

EGD can produce a high efficiency equal to MHD-steam combination.

Advantages of EGD over MHD systems :

1. EGD systems operate at relatively low temperatures.
2. No need for injection and recovery of seed material.
3. It is self contained since it does not need a steam generator.
4. Energy can be extracted till the gases reach almost the stack temperature.
5. Does not need large quantities of condenser cooling water.

EGD and MHD hold the prospects of offering the best solutions for high efficiency, large capacity systems for the production of electricity.

10.7.7. Fuel Cells

A fuel cell is an electrochemical device in which the chemical energy of a conventional fuel is converted directly and efficiently into low voltage, direct-current electrical energy. One of the chief advantages of such a device is that because the conversion, at least in theory, can be carried out isothermally, the Carnot limitation on efficiency does not apply. A fuel cell is often described as a primary battery in which the fuel and oxidizer are stored external to the battery and fed to it as needed.

Fig. 10.38 shows a schematic diagram of a fuel cell. *The fuel gas diffuses through the anode and is oxidized, thus releasing electrons to the external circuit ; the oxidizer diffuses through the cathode and is reduced by the electrons that have come from the anode by way of the external circuit*.

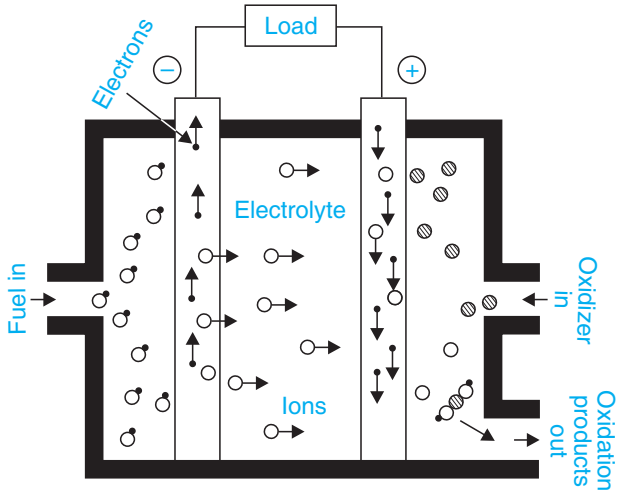


Fig. 10.38. Schematic of a fuel cell.

The fuel cell is a device that keeps the fuel molecules from mixing with the oxidizer molecules, permitting, however, the transfer of electrons by a metallic path that may contain a load.

Of the available fuels, *hydrogen* has so far given the most promising results, although cells consuming coal, oil or natural gas would be economically much more useful for large scale applications.

Some of the possible reactions are :

Hydrogen/oxygen 1.23 V

$$2H_2 + O_2 \longrightarrow 2H_2O$$

Hydrazine 1.56 V

$$N_2H_4 + O_2 \longrightarrow 2H_2O + N_2$$

Carbon (coal) 1.02 V

$$C + O_2 \longrightarrow CO_2$$

Methane 1.05 V

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

Hydrogen-oxygen cell :

The hydrogen-oxygen device shown in Fig. 10.39 is typical of fuel cells. It has three chambers separated by two porous electrodes, the *anode* and the *cathode*. The middle chamber between the electrodes is filled with a strong solution of potassium hydroxide. The surfaces of the electrodes are chemically treated to repel the electrolyte, so that there is minimum leakage of potassium hydroxide into the outer chambers. The gases diffuse through the electrodes, undergoing reactions as shown below :

$$4KOH \longrightarrow 4K^+ + 4(OH)^-$$

Anode : $2H_2 + 4(OH)^- \longrightarrow 4H_2O + 4e^-$

Cathode : $O_2 + 2H_2O + 4e^- \longrightarrow 4(OH)^-$

Cell reaction $2H_2 + O_2 \longrightarrow 2H_2O$

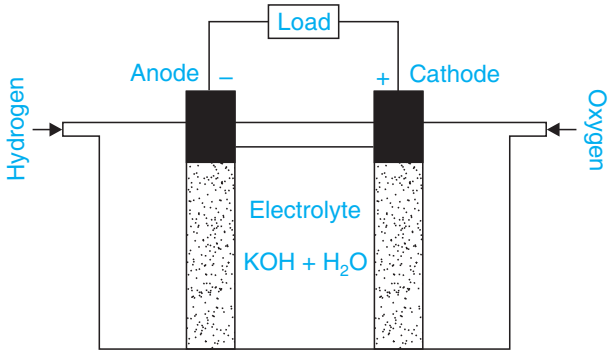


Fig. 10.39. Hydrogen-oxygen fuel cell.

The water formed is drawn off from the side. The electrolyte provides the $(OH)^-$ ions needed for the reaction, and remains unchanged at the end, since these ions are regenerated. The electrons liberated at the anode find their way to the cathode through the external circuit. *This transfer is equivalent to the flow of a current from the cathode to the anode.*

Such cells when properly designed and operated, have an open circuit voltage of about 1.1 volt. Unfortunately, their life is limited since the water formed continuously dilutes the electrolyte. Fuel efficiencies as high as 60 to 70% may be obtained.

Advantages and disadvantages of Fuel cells

Advantages :

1. Conversion efficiencies are very high.
2. Require little attention and less maintenance.
3. Can be installed near the use point, thus reducing electrical transmission requirements and accompanying losses.
4. Fuel cell does not make any noise.
5. A little time is needed to go into operation.
6. Space requirement considerably less in comparison to conventional power plants.

Disadvantages :

1. High initial cost.
2. Low service life.

Applications of Fuel cells :

The applications of fuel cell relate to :

1. Domestic use
2. Automotive vehicles
3. Central power stations
4. Special applications.

Note. The human body functions essentially like a fuel cell. Living things take in food (fuel) and oxygen to produce both thermal energy and work output. They are not heat engines.

10.7.8. Nuclear Batteries

A nuclear battery works on the principle that *beta emitter can produce the electrical energy*.

Nuclear batteries *are of the following two kinds* : (*i*) *High voltage* atomic battery and (*ii*) *Low voltage* atomic battery.

10.7.8.1. High voltage atomic battery

Fig. 10.40 shows the schematic diagram of a high voltage atomic battery.

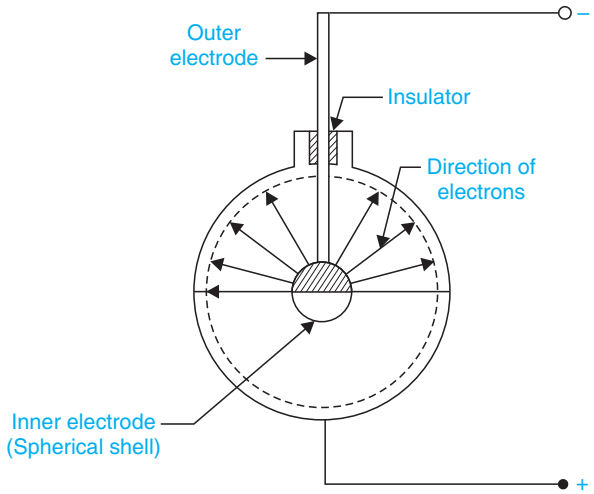


Fig. 10.40. High voltage atomic battery.

It consists of an inner spherical electrode on the surface of which is deposited a powerful beta emitting (*i.e.,* fast electrons) substance. This is surrounded by another spherical condenser and the inner surface of this condenser becomes negatively charged. This acts as the outside electrode and is properly insulated at the opening. The inner and outer electrodes become the –ve and +ve terminals of the battery.

Sr^{90} isotope can be used since its half life is 28 years. These batteries perform independent of the temperature unlike the accumulators whose electrolyte freezes at low temperatures. These also supply a *very steady constant potential.*

This has yet to be developed on a commercial scale.

10.7.8.2. Low voltage atomic battery

Fig. 10.41 shows a low voltage battery.

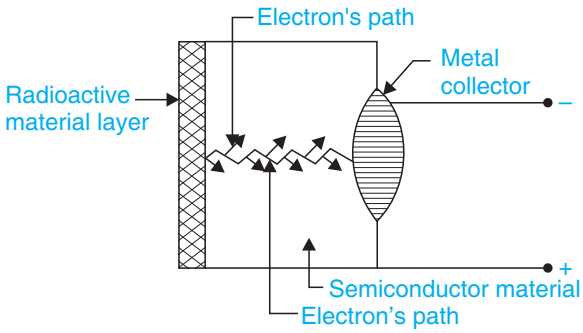


Fig. 10.41. Low voltage atomic battery.

In this Sr^{90} (beta emitter) is deposited on the surface of a semiconductor (germanium or silicon) at one end and the other end is having a metallic collector. The semiconductor has the characteristic of undirectional current flow. The fast electrons pass through the semiconductor and strike the metallic disc at the other end and the two ends of the semiconductor become the –ve and +ve terminals of the battery. The power produced by this battery is a few microwatts at a potential difference of 1/10 volt. This power is sufficient to *feed a small radio*.

HIGHLIGHTS

1. The periodic rise and fall of the water level of sea which are carried by the action of sun and moon on water of the earth is called the *tide*.
2. In a single basin arrangement power can be generated only intermittently.
3. The solar farm consists of a whole field covered with parabolic trough concentrators and a 'solar tower' consists of a central receiver on a tower and a whole field of tracking.
4. "If two dissimilar materials are joined to form a loop and the two junctions maintained at different temperatures, an e.m.f. will be set up around the loop". This is called *Seebeck effect*.
5. A thermionic converter works because of the phenomenon of 'thermionic emission'.
6. 'Photovoltaic effect' is defined as the generation of an electromotive force as a result of absorption of ionizing radiation.
7. 'MHD generator' is device which converts heat energy of a fuel directly into electrical energy without a conventional electric generator.
8. A 'fuel cell' is an electrochemical device in which the chemical energy of a conventional fuel is converted directly and efficiently into low voltage, direct current electrical energy.

THEORETICAL QUESTIONS

1. List the various non-conventional energy sources.
2. Explain with a real diagram a wind electric generating power plant.
3. Write a short note on 'Wind Electricity Economics'.
4. Name the components of a tidal power plant.
5. Give the classification of tidal power plants.
6. Give the working of a single basin tidal power plant.
7. What are the advantages and limitations of tidal power generation ?
8. Explain with the help of a neat diagram a solar pond electric power plant.
9. Describe the working of a 'solar tower plant'.
10. Give the working a geothermal plant.
11. What is 'Thermoelectric effect' ?
12. Write a short note on 'Thermoelectric generator'.
13. Define work function.
14. Explain with a neat diagram the working of a 'Thermoelectric generator'.
15. What is a photovoltaic cell ?
16. How are silicon cells fabricated ?
17. Write down the advantages and disadvantage of 'Photovoltaic solar energy conversion'.
18. Describe open cycle MHD system.
19. What is a fuel cell ?
20. Describe a hydrogen-oxygen cell.
21. State the advantages and disadvantages of fuel cells.
22. Write short notes on the following :
    (*a*) Working of MHD generator.
    (*b*) Fuel cells and its applications.
23. Describe with the help a neat sketch, the working of a solar power plant. What are its salient features ?

COMPETITIVE EXAMINATIONS QUESTIONS

1. (*a*) Write a short note on the possibility of the utilization of solar energy for power generation in India.

(*b*) Discuss briefly the advantages of combined working of different types of power plants.

(*c*) Write short notes on base load stations and peak load stations.

2. (*a*) Narrate the elements of cost of power.

(*b*) Define diversity factor and state the advantages of diversity of load in a power system.

(*c*) Describe how power is generated by MHD.

3. Write short notes on the following :

(*a*) Working of MHD generator ;

(*b*) Fuel cells and its application ;

(*c*) Free piston engine plants.

4. (*a*) Describe, with the help of a neat sketch, the working of a solar power plant. What are its salient features ?

(*b*) What is the function of circuit breaker in a power plant ? Explain its principle of working. What are the different types of circuit breakers commonly used ?

5. Write short notes on the following :

(*a*) Hydrology and its importance in selecting the site for a hydel power station ;

(*b*) Moderator and Coolant of a nuclear reactor ;

(*c*) Solar power and its uses.

6. Write short notes on the following :

(*i*) MHD generator ; (*ii*) Solar collectors ;

(*iii*) Electrical protection devices in power plant ;

(*iv*) Pneumatic ash handling system.

11 Plant Instrumentation

11.1. General aspects. 11.2. Classification of instruments. 11.3. Pressure gauges—Pressure—Types of pressure measurement devices—Mechanical-type instruments—Electrical transducers. **11.4. Thermometers**—Temperature—Temperature measuring instruments. **11.5. Liquid level gauges**—Gauge glass—Electrical level gauges. **11.6. Flow meters. 11.7. pH measuring instruments. 11.8. Gas analysers. 11.9. Humidity measuring instruments. 11.10. Impurity measuring instruments. 11.11. Speed measuring instruments. 11.12. Steam calorimeters and fuel calorimeters**—Steam calorimeters—Fuel calorimeters—*Highlights*—*Theoretical Questions*.

11.1. GENERAL ASPECTS

In power plants the instruments are used for a number of reasons as to operate the power plant as efficiently as possible. Instruments provide accurate information for guidance to safe, continuous and proper plant operation.

The functions which the various instruments are required to perform are listed below :

1. **Operating guidance.** The instruments provide guidance to operate the power plant efficiently and economically.

2. **Performance calculations.** They render help in making performance calculations in respect of plant working.

3. **Maintenance and repair guidance.** As the instruments enable us to check the internal conditions of the equipment, thus they provide us maintenance and repair guidance.

4. **Economical supervision.** They enable us to supervise the plant economically.

5. **Cost allocation.** The instruments extend a helping hand in dealing with the problems concerning costs accounting and cost allocations.

11.2. CLASSIFICATION OF INSTRUMENTS

The two general classification of instruments are :

1. Those employing *purely mechanical methods*.

2. Those employing *electro-mechanical methods*.

With the increase in automation electronics is being used more widely in the field of instruments. Remote control has become an established practice in power plant engineering and specially in nuclear power station where the complete equipment is watched and controlled from a distance. Hence the importance of instrumentation in the power plant engineering has increased.

The instruments can also be classified as follows :

1. Indicating instruments
2. Recording instruments
3. Indicating and recording instruments
4. Indicating and integrating instruments
5. Indicating, recording and integrating instruments.

Commonly used instruments in a power plant

1. Pressure gauges
2. Thermometers
3. Liquid level gauges
4. Flow meters (Steam and gas)
5. pH measuring instruments
6. Gas analysers
7. Humidity measuring instruments
8. Impurity measuring instruments
9. Speed measuring instruments
10. Steam calorimeters and fuel calorimeters
11. Gong alarms
12. Electrical instruments.

(*i*) Ammeters (*ii*) Voltmeters
(*iii*) Wattmeters (*iv*) Power factor meters
(*v*) Reactive volt ampere meters
(*vi*) Ground detectors.

11.3. PRESSURE GAUGES

11.3.1. Pressure

Pressure is defined as a force per unit area. Pressures are exerted by gases, vapours and liquids. The instruments that we generally use, however, record pressure as the difference between two pressures. Thus, it is the *difference between the pressure exerted by a fluid of interest and the ambient atmospheric pressure*. Such devices indicate the pressure either above or below that of the atmosphere. When it is *above the atmospheric pressure*, it is termed *gauge pressure* and is *positive*. When it is *below* atmospheric, it is *negative* and is known as *vacuum*. Vacuum readings are given in millimetres of mercury or millimetres of water below the atmosphere.

It is necessary to establish an absolute pressure scale which is independent of the changes in atmospheric pressure. A pressure of absolute zero can exist only in complete vacuum. *Any pressure measured above the absolute zero of pressure* is termed an '*absolute pressure*'.

A schematic diagram showing the *gauge pressure, vacuum pressure* and the *absolute pressure* is given in Fig. 11.1.

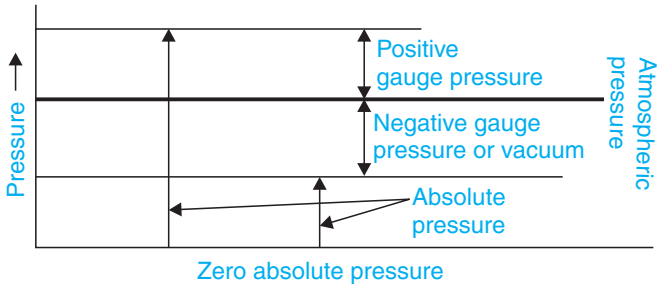


Fig. 11.1. Schematic diagram showing gauge, vacuum and absolute pressures.

Mathematically :

(*i*) Absolute pressure = atmospheric pressure + gauge pressure

$$p_{abs} = p_{atm.} + p_{gauge}$$

(*ii*) Vacuum pressure = atmospheric pressure – absolute pressure

Atmospheric pressure is measured with the help of barometer.

Unit for pressure

The fundamental SI unit of pressure is newton per square metre (N/m^2). This is also known as *Pascal*. In MKS it is usually expressed in kgf/cm^2.

Low pressures are often expressed in terms of mm of water or mm of mercury. This is an abbreviated way of saying that the pressure is such that which will support a liquid column of stated height.

11.3.2. Types of Pressure Measurement Devices

The pressure may be measured by means of indicating gauges or recorders. These instruments may be mechanical, electro-mechanical, electrical or electronic in operation.

1. **Mechanical instruments.** These instruments may be classified into following two groups :
   - — The *first group* includes those instruments in which the *pressure measurement is made by balancing an unknown force with a known force*.
   - — The *second group* includes those employing *quantitative deformation of an elastic member for pressure measurement*.

2. **Electro-mechanical instruments.** These instruments usually employ *mechanical means for detecting the pressure* and *electrical means for indicating or recording the detected pressure*.

3. **Electronic instruments.** Electronic pressure measuring instruments normally depend on some *physical change* that can be detected and indicated or recorded electronically.

11.3.3. Mechanical Type Instruments

Some of the above mentioned instruments are discussed below.

The *mechanical type instruments* could be classified as follows :

(*i*) Manometer gauges
(*ii*) Limp diaphragm
(*iii*) Metal diaphragm and bellows
(*iv*) Bourdon tube type which may be spiral or helical.

11.3.3.1. Liquid manometers

Low pressures are generally determined by *manometers* which employ liquid columns. It is difficult and costly to construct manometers to measure high pressures, as otherwise the liquid column will become unwieldy and temperature corrections will also be difficult. Their use is, therefore, restricted to low pressures only, and for such purposes they are quite accurate.

The liquid commonly employed for manometers are mercury and water. Mercury is used for high and water for low pressures. For this purpose a liquid is suitable if it has a low viscosity, so that it can adjust itself quickly, and also a low co-efficient of thermal expansion, so that density changes with temperature are minimum.

The following manometers will be described :

1. U-tube manometer
2. Cistern manometer
3. Micro-manometer.

U-tube Manometer :

A U-tube manometer is in the form of U-tube and is made of glass. When no pressure is applied, the height of

the liquid in the two legs is the same. The pressure is then applied to one leg, whilst the other is open to the atmosphere. Under this pressure the liquid will *sink* in this leg and will *rise* in the other. As the other leg is open to the air, therefore, the pressure on this side is known, and is barometric. Now the pressure applied to the first leg can be calculated. This is explained with reference to Fig. 11.2. This consists of a water manometer.

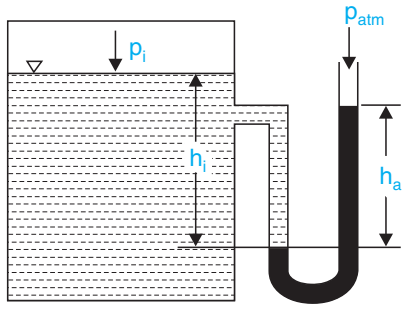


Fig. 11.2. Principle of U-tube manometer.

Considering equilibrium condition, we have :

$$p_{atm} + w_a\, h_a = p_i + w_i\, h_i$$

$$\therefore \quad p_i = p_{atm} - w_a\, h_a - w_i\, h_i$$

where, p_{atm} = Atmospheric pressure,

p_i = Pressure over water surface in the container,

h_a = Height of liquid in U-tube manometer,

h_i = Difference between water surface and lower surface of the liquid in manometer,

w_a = Specific weight of liquid, and

w_i = Specific weight of water.

The U-tube manometer shown in Fig. 11.3 is of the simplest form. However, readings have to be taken at *two different places*. Moreover, the *deflection of the two columns may not be the same*. To avoid this difficulty cistern or well type manometer is used.

Cistern manometer :

Fig. 11.4 shows a cistern manometer. The mercury reservoir A is made large enough so that change of level in the reservoir is negligible. This form of manometer is generally used for measuring pressures above atmospheric. In this case, *only one reading of the level in the column is required*. However, a zero setting is necessary.

Micro-manometer :

The U-tube manometer (discussed above) is not very suitable for measuring very low pressures. Therefore, for such purposes, precision types are required. They are called *multiplying* or *micro-manometers*, because they multiply the movement of the level of the liquid. By far the most widely used type of multiplying manometer is the *inclined manometer*. If the tube is inclined as shown in Fig. 11.5 the sensitiveness of the U-tube manometer is increased. The inclined tube *causes a larger displacement of the liquid along the tube for a given pressure difference*.

The principle of the inclined manometer is explained in Fig. 11.6. If pressure $p_1 = p_2$, then the level of liquid is shown by LM. However, when p_1 is slightly greater than p_2, the level in the reservoir sinks by h_2, whilst level in the tube rises by a greater distance h_1, as shown in the diagram. If h is the vertical distance between the two surfaces due to difference of pressure, then

$$h = h_1 + h_2$$

also $$h_1 = d \sin \theta$$

and $$h_2 \times A = d \times a$$

where, A = Area of cross-section of the reservoir, and

a = Area of cross-section of the inclined tube.

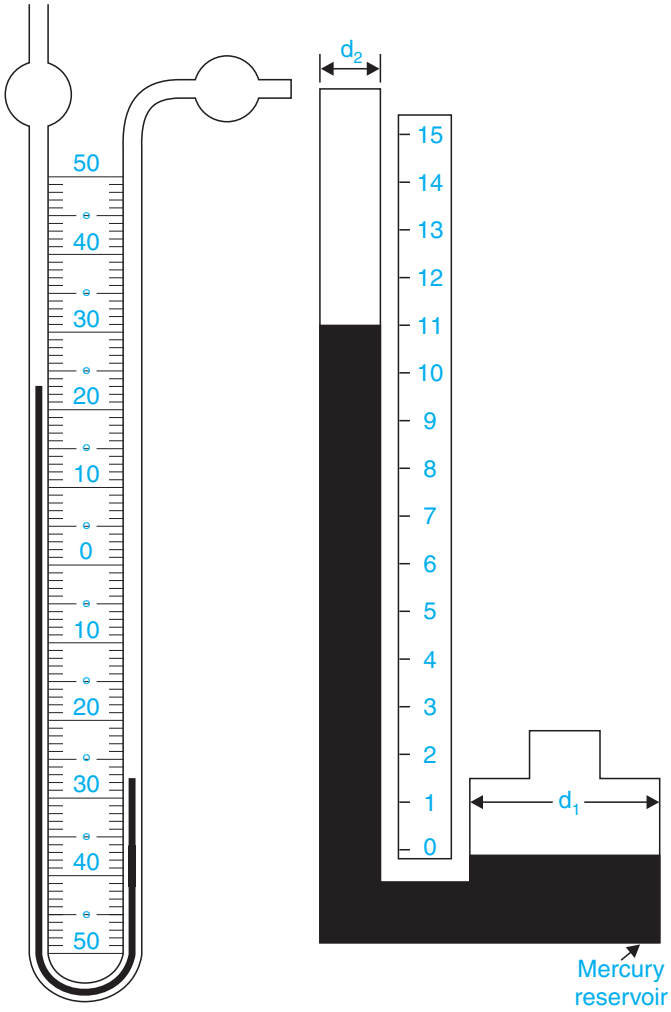


Fig. 11.3. U-tube manometer. **Fig. 11.4.** Cistern manometer.

Also the pressure difference Δp *i.e.*, $(p_1 - p_2)$

$$= hw = \left(d \times \sin\theta + d \times \frac{a}{A}\right) w$$

$$= dw \left(\sin\theta + \frac{a}{A}\right)$$

where w is the specific weight of the liquid.

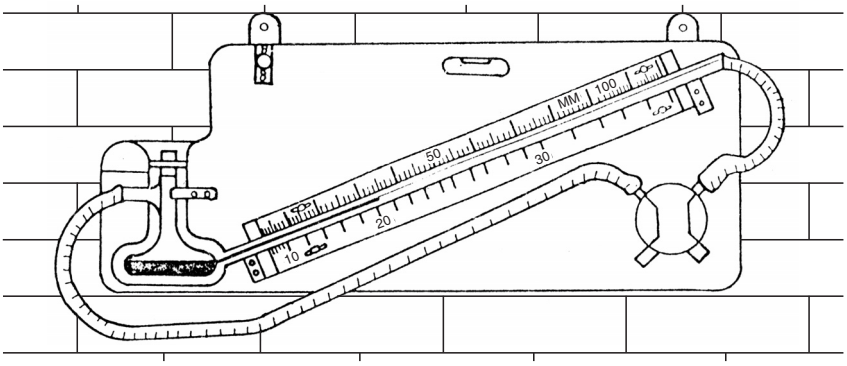


Fig. 11.5. Inclined manometer.

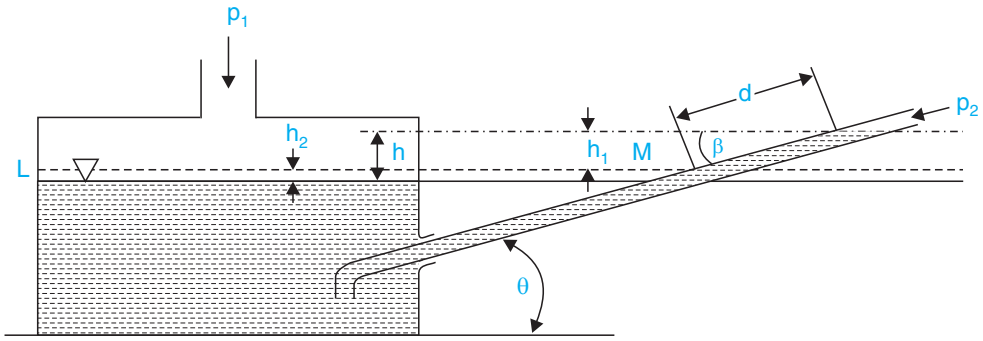


Fig. 11.6. Principle of inclined manometer.

The sensitiveness of the instrument can be varied by *changing the slope of the inclined tube*. The position of the inclined tube is so arranged that $\left(\sin\theta + \frac{a}{A}\right)$ is round figure.

The multiplication factor of the gauge is :

$$\frac{l}{h} = \frac{1}{\sin\theta + \frac{a}{A}} .$$

Thus the multiplication factor depends on θ and $\frac{a}{A}$. The *smaller the valves of* θ *and* $\frac{a}{A}$ *, the greater the multiplication factor*.

11.3.3.2. Important types of pressure gauges

The manometers and U-tubes (discussed earlier) are suitable for comparatively *low pressures*. For high pressures they become unnecessarily larger even when they are filled with heavy liquids. Therefore, for measuring medium and high pressures, we make use of elastic pressure gauges. They employ different forms of elastic systems such as tubes, diaphragms or bellows etc. to measure the pressure. The elastic deformation of these elements is used to show the effect of pressure. Since these elements are deformed within the elastic limit only, therefore these gauges are sometimes called *elastic gauges*. Sometimes they are also called secondary instruments, which implies that they must be calibrated by comparison with primary instruments such as manometers etc.

Some of the important types of these gauges are enumerated and discussed below :

1. Bourdon tube pressure gauge
2. Diaphragm gauge
3. Vacuum gauge.

Bourdon Tube Type Pressure Gauge

A Bourdon type tube pressure gauge is used for measuring *high as well as low pressures*. A simple form of this gauge is shown in Fig. 11.7. In this case the pressure element consists of a metal tube of approximately *elliptical cross-section*. This tube is bent in the form of a segment of a circle and responds to pressure changes. When one end of the tube which is attached to the gauge case, is connected to the source of pressure, the internal pressure causes the tube to expend, whereby circumferential stress *i.e.*, hoop tension is set up. The free end of the tube moves and is in turn connected by suitable levers to a rack, which engages with a small pinion mounted on the same spindle as the pointer. Thus the pressure applied to the tube causes the rack and pinion to move. The pressure is indicated by the pointer over a dial which can be graduated in a suitable scale.

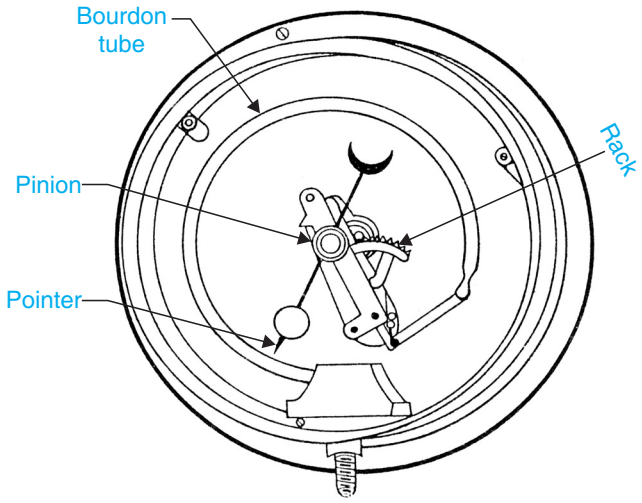


Fig. 11.7. Bourdon tube pressure gauge.

The Bourdon tubes are generally made of *bronze* or *nickel steel*. The former is generally used for low pressures and the latter for high pressures.

Depending upon the purpose for which they are required Bourdon tube gauges are made in different forms, some of them are :

(*i*) *Compound Bourdon tube.* These are used for measuring pressures both above and below atmospheric.

(*ii*) *Double Bourdon tube.* These are used where vibrations are encountered.

Diaphragm Gauge

This type of gauge employs a metallic disc or diaphragm instead of a bent tube. This disc or diaphragm is used for *actuating* the indicating device.

Refer to Fig. 11.8. When pressure is applied on the lower side of the diaphragm, it is deflected upward. This movement of the diaphragm is transmitted to a rack and pinion. The latter is attached to the spindle of needle moving on a graduated dial. The dial can again be graduated in a suitable scale.

Vacuum Gauge

Bourdon gauges discussed earlier can be used to measure vacuum instead of pressure. Slight changes in the design are required for this purpose. Thus, in this case, the tube be *bent inward instead of outward* as in pressure gauges. *Vacuum gauges* are graduated in millimetres of mercury below atmospheric pressure. In such cases, therefore, absolute pressure in millimetres of mercury is the difference between barometer reading and vacuum gauge reading.

Vacuum gauges are used to measure the vacuum in the *condensers* etc. If there is leakage, the vacuum will drop.

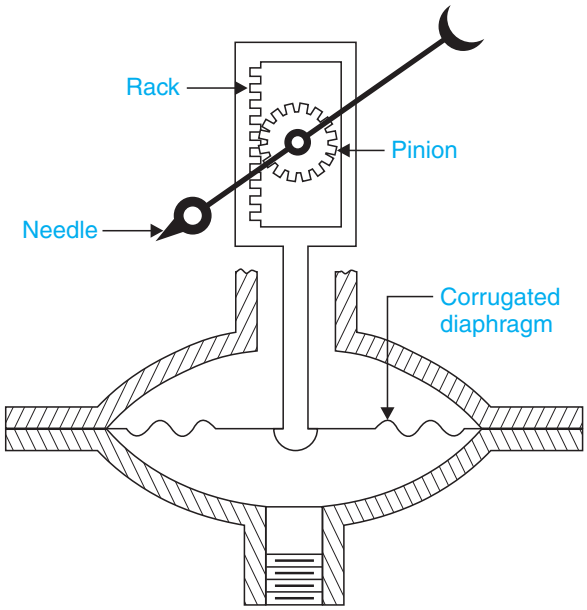


Fig. 11.8. Principle of diaphragm gauge.

The pressure gauge installation require the following considerations :

(*i*) Flexible copper tubing and compression fittings are recommended for most installations.

(*ii*) The installation of a gauge cock and tee in the line close to the gauge is recommended because it permits the gauge to be removed for testing or replacement without having to shut down the system.

(*iii*) Pulsating pressures in the gauge line are not required.

(*iv*) The gauge and its connecting line is filled with an inert liquid and as such liquid seals are provided. Trapped air at any point of gauge lines way cause serious errors in pressure reading.

11.3.4. Electrical Transducers

A *transducer is a device for converting a signal of one sort into the other type*. In other words, a pressure gauge is a transducer for converting the distortion of a Bourdon spring into an indication through use of a calibrated dial and so on. In case of electrical transducers for measuring pressure, various transformations which are needed to convert pressure to some sort of usable electrical signal can be :

1. The change of resistance of an elastic material such as wire.

2. The change in capacitance when the distance between capacitor plates is varied or the dielectric is changed.

3. The conversion of a changing pressure into electrical voltage signals.

4. Creation of a voltage by the movement of a coil within a magnetic field.

5. Generation of a voltage or current through the use of photo-electric effects.

6. Torque-balance system (electromagnetic).

11.3.4.1. Potentiometer devices

One of the simplest of pressure or voltage transducer uses a potentiometer. The potentiometer is used to convert a pressure signal into an electrical voltage as shown in Fig. 11.9.

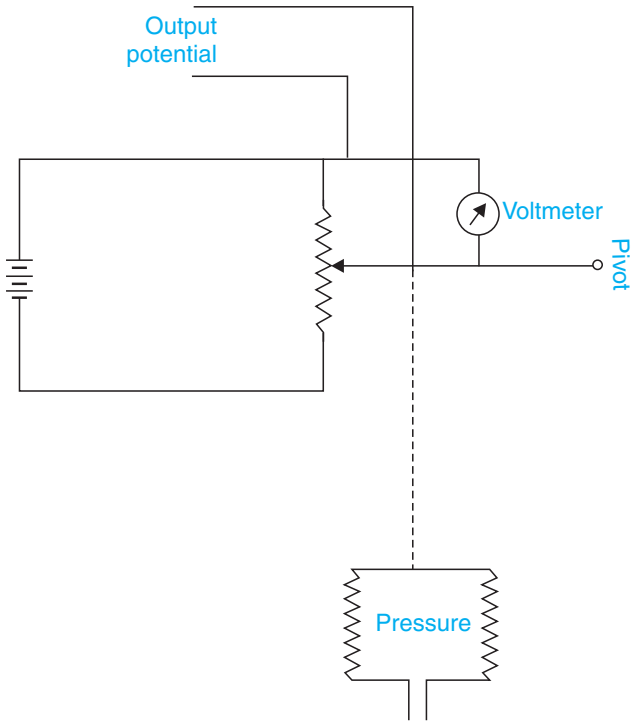


Fig. 11.9. Pressure-voltage transducer.

The potentiometer should have little friction. Levers may be used to match the required movement of the potentiometer with that of the bellows. The signal applied to the potentiometer may be relatively large of the order of several volts. By the use of potentiometric method the signal can be sent relatively long distance. In that case a remote reading systems may employ servomechanic system. In that case the galvanometer of the potentiometer is brought to the zero position.

11.3.4.2. Electromagnetic transducers

For many years a technique has been used which consists of a coil in the plate or grid circuit of an oscillating tube (one that is generating alternating current) to deliver current to some other circuit. The energy may be transferred into some other winding having a transformer action. The coil has to deliver more power to the secondary winding, the additional power must come from the winding in the plate. The increase in plate current causes relays to operate at some predetermined values of current. It can also be used to develop voltages across known resistors. It can cause electromagnets to establish forces used for measuring the force applied which is obtained by pressure bellows.

11.4. THERMOMETERS

11.4.1. Temperature

Temperature can be defined as a thermal state which depends upon the internal or molecular energy of the body. In practice, mean kinetic energy of molecules of a body changes, thus when body possessing high mean molecular kinetic energy is brought in contact with a body having low value, the energy will flow from the higher level to the lower level. This gives us an idea of the hot and cold bodies and the heat which is associated with them.

11.4.2. Temperature Measuring Instruments

Temperature measurements are among the most common and the most important measurement in a power plant. The precise control of temperature is essential in thermal power stations. Temperature measurements may be made in many ways. They can be classified in two broad categories :

1. Non-electrical method

(*i*) By using change in volume of a liquid when its temperature is changed.

(*ii*) By using change in pressure of a gas when its temperature is changed.

(*iii*) By using change in the vapour pressure when the temperature is changed.

2. Electrical method

(*i*) By thermocouples.

(*ii*) By change in resistance of material with change in temperature.

(*iii*) By comparing the colours of filament and the object whose temperature is to be found out.

(*iv*) By ascertaining the energy received by radiation.

The thermometers may also be classified as follows :

1. Expansion thermometers

(*i*) Liquid-in-glass thermometers

(*ii*) Bimetallic thermometers

2. Pressure thermometers

(*i*) Vapour pressure thermometers

(*ii*) Liquid-filled thermometers

(*iii*) Gas-filled thermometers

3. Thermocouple thermometers
4. Resistance thermometers
5. Radiation pyrometers
6. Optical pyrometers.

11.4.2.1. Expansion thermometers

The expansion thermometers make use of the differential expansion of two different substances. Thus in liquid-in-glass thermometers, it is the difference in expansion of liquid and the containing glass. And in bimetallic thermometers, the indication is due to the difference in expansion of the two solids. These thermometers are discussed below :

(*i*) **Liquid-in-glass thermometer.** This is a very familiar type of thermometer. The mercury or other liquid fills the glass bulb and extends into the bore of the glass stem. Mercury is the most suitable liquid and is used from – 38.9°C (melting point) to about 600°C. The thermometers employed in the laboratory have the scale engraved directly on the glass stem. A usual type of mercury-in-glass thermometer is shown in Fig. 11.10. An expansion bulb is usually provided at the top of the stem to allow room for expansion of mercury, in case the thermometer is subjected to temperatures above its range. The upper limit for Mercury-in-glass thermometers is about 600°C. As the upper limit is far above the boiling point of mercury, some inert gas *i.e.*, nitrogen is introduced above the mercury to prevent boiling.

Pentane, Ethyl alcohol and Toluene are the other liquids which can be used for liquid-in-glass thermometers. Since these liquids are normally colourless a dye is added to facilitate reading. These liquids have a low freezing point as shown below and are suitable for low temperature thermometers.

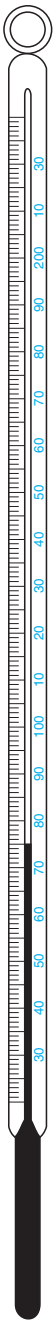


Fig. 11.10. Mercury-in-glass thermometer.

Liquid	*Boiling point*	*Freezing point*
Pentane	36°C	– 130°C
Ethyl alcohol	78°C	– 100°C
Toluene	110°C	– 92°C

(*ii*) **Bimetallic thermometers.** In a bimetallic thermometer differential expansion of bimetallic strips is used to indicate the temperature. It has the advantage over the liquid-in-glass thermometer, that it *is less fragile* and is *easier to read*. In this type of thermometer two flat strips of different metals are placed side by side and are welded together. Many different metals can be used for this purpose. Generally one is a *low expanding metal* and the other is *high expanding metal*. The bimetal strip is coiled in the form of spiral or helix. *Due to rise in temperature, the curvature of the strip changes. The differential expansion of a strip causes the pointer to move on the dial of the thermometer.*

11.4.2.2. Pressure thermometers

In pressure thermometers liquids, gases and vapours can all be used. The principle on which they work is quite simple. The fluid is confined in a closed system. In this case the *pressure is a function of the temperature*, so that when the fluid is heated, the pressure will rise. And the temperature can be indicated by Bourdon type pressure gauge. In general, the thermometer consists of a bulb which contains bulk of the fluid. The bulb is placed in the region whose temperature is required. A capillary tube connects the bulb to a Bourdon tube, which is graduated with a temperature scale.

Pressure thermometers are discussed below :

(*i*) **Vapour pressure thermometer.** A schematic diagram of a vapour pressure thermometer is shown in Fig. 11.11. When the bulb containing the fluid is installed in the region whose temperature is required, some of the fluid vapourizes, and increases the vapour pressure. This

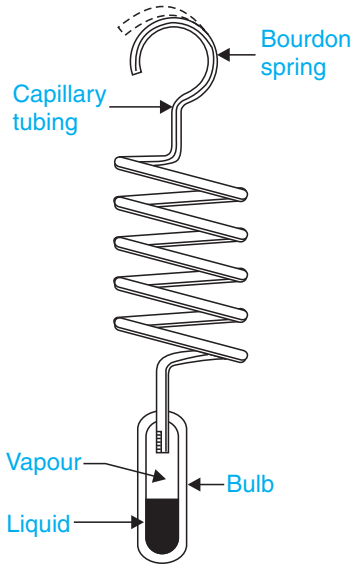


Fig. 11.11. Vapour pressure thermometer.

change of pressure is indicated on the Bourdon tube. The relation between temperature and vapour pressure of a volatile liquid is of the *exponential form*. Therefore, the scale of a vapour pressure thermometer will not be linear.

(*ii*) **Liquid-filled thermometer.** A liquid-filled thermometer is shown in Fig. 11.12. In this case, the *expansion of the liquid causes the pointer to move on the dial.* Therefore liquids having high co-efficient of expansion should be used. In practice, many liquids *e.g.* mercury, alcohol, toluene, and glycerine have been successfully used. The operating pressure varies from about 3 to 100 kgf/cm^2. These type of thermometers could be used for a temperature upto 650°C in which mercury could be used as the liquid.

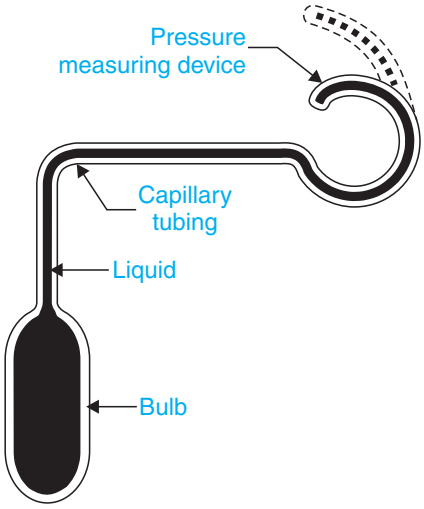


Fig. 11.12. Liquid-filled thermometer.

In actual design, the internal diameter of the capillary tube and Bourdon tube is made much smaller than that of the bulb. This is because the capillary tube is subjected to a temperature which is quite different from that of the bulb. Therefore, to minimise the effect of variation in temperature to which the capillary tube is subjected, the *volume of the bulb is made as large as possible as compared with the volume of the capillary.* However, large volume of bulb tends to increase time lag, therefore, a *compensating device is usually built into the recording or indicating mechanism, which compensates the variations in temperature of the capillary and Bourdon tubes.*

(*iii*) **Gas-filled thermometers.** The temperature range for gas thermometer is practically the same as that of liquid filled thermometer. The gases used in the gas thermometers are *nitrogen* and *helium*. Both these gases are chemically inert, have good values for their co-efficient of expansion and have low specific heats. The construction of this type of thermometer is more or less the same as mercury-thermometer in which Bourdon spring is used. The errors are also compensated likewise. The only difference in this case is that bulb is made much larger than used in liquid-filled thermometers. For good performance the volume of the bulb should be made at least 8 times than that of the rest of the system.

These thermometers are generally used for pressures below 35 kgf/cm^2.

11.4.2.3. Thermocouple thermometers

For higher range of temperature *i.e.*, above 650°C, filled thermometers are unsuitable. For higher range of temperature, thermocouples and pyrometers are used.

In its simplest form a thermocouple consists of *two dissimilar metals or alloys which develop e.m.f. when the reference and measuring junctions are at different temperatures.* The reference junction or cold junction is usually maintained at some constant temperature, such as 0°C and the device used for measuring the temperatures. Fig. 11.13 shows a simple circuit of a thermocouple and the temperature measuring device. In many industrial installations the instruments are equipped with automatic compensating devices for tempearture changes of the reference junction, thus eliminating the necessity of maintaining this junction at constant temperature.

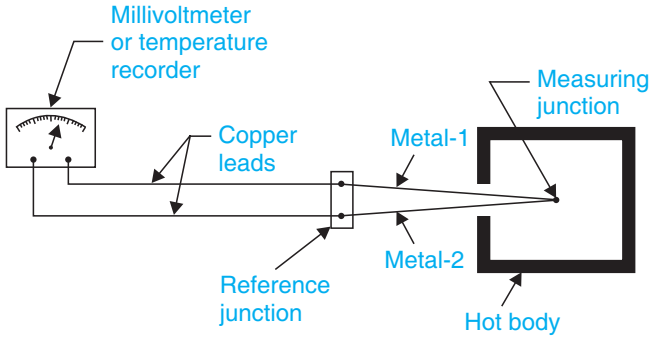


Fig. 11.13. Thermocouple.

Table 11.1 gives the composition, useful temperatures range and temperature versus e.m.f. relationship for some commercial thermocouples.

Table 11.1. Composition, Useful Temperature Range and e.m.f. Produced for Some Thermocouples

S. No.	*Thermocouple*	*Composition*	*Temperature (°C)*		*Thermo-electric power*		*Remarks*
			Useful-range	*Max.*	*°C*	*Milli-volt*	
1.	*Platinum vs Platinum-rhodium*	Pure platinum vs Pt + 10 or 13% Rh	400 to 1450	1700	0 500 1000 1500	0.0 4.219 9.569 15.498	Used for high temperature measurements
2.	*Chromel vs Alumel*	90% Ni + 10% Cr vs 95 Ni + 5% (Al + Sn) Mn	– 200 to 1200	1450	– 200 0 300 600 900 1200	– 5.75 0.0 12.21 24.90 37.36 48.85	High resistance to oxidation
3.	*Iron vs Constantan*	Pure iron vs 45–60% Cu + 55–40% Ni	– 200 to 750	1000	– 200 0 300 600 900	– 8.27 0.0 16.59 33.27 52.29	—
4.	*Copper vs Constantan*	Pure copper vs Cu-Ni constantan	– 200 to 350	600	– 200 0 200 400	– 5.539 0.0 9.285 20.865	Not suitable in air due to excessive oxidation.

11.4.2.4. Resistance thermometers

The fact that the electrical resistance of the metals increases with temperature is made use of in resistance thermometers which are purely electrical in nature. A *resistance thermometer is used for precision measurements below 150°C.*

A simple resistance thermometer consists of a *resistance element or bulb, electrical loads, and a resistance measuring or recording instrument.* The resistance element (temperature sensitive element) is usually supplied by the manufacturers with its protecting tube and is ready for electrical connections. The resistance of the metal used as resistance element should be reproducible at any given temperature. *The resistance is reproducible if the composition or physical properties of the metal do not change with temperature. For this purpose platinum is preferred.* A *platinum resistance thermometer* can measure temperatures to within ± 0.01°C. However, because of high cost of platinum, nickel and copper are used as resistance elements for industrial purposes for low temperatures. The fine resistance wire is wound in a spiral form on a mica frame. The delicate coil is then enclosed in a porcelain or quartz tube. The change of resistance of this unit can be measured by instruments such as wheatstone bridge, potentiometer or galvanometer.

Advantages

The resistance thermometers possess the following *advantages* over other devices :

1. A resistance thermometer is very accurate for low ranges below 150°C.
2. It requires no reference junction like thermocouples and as such is more effective at room temperature.
3. The distance between the resistance element and the recording element can be made much larger than is possible with pressure thermometers.
4. It resists corrosion and is physically stable.

Disadvantages

1. The resistance thermometers cost more.
2. They suffer from time lag.

11.4.2.5. Radiation pyrometer

A device which measures the total intensity of radiation emitted from a body is called *radiation pyrometer.*

The elements of a total radiation pyrometer are illustrated in Fig. 11.14. It collects the radiation from an object (hot body) whose temperature is required. A mirror is used to focus this radiation on a thermocouple. This energy which is concentrated on the thermocouple raises its temperature, and in turn generates an e.m.f. This e.m.f. is then measured either by the galvanometer or potentiometer method. Thus rise of temperature is a function of the amount of radiation emitted from the object.

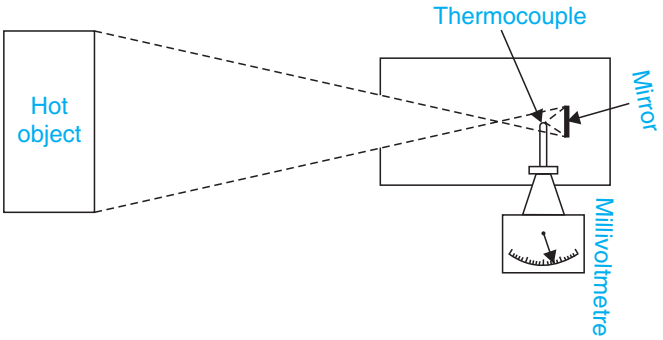


Fig. 11.14. A schematic diagram of radiation pyrometer.

Advantages of the pyrometers

1. The temperature of moving objects can be measured.

2. A higher temperature measurement is possible than that possible by thermocouples etc.

3. The average temperatures of the extended surface can be measured.

4. The temperatures of the objects which are not easily accessible can be measured.

11.4.2.6. Optical pyrometer

An optical pyrometer works on the *principle that matters glow above 480°C and the colour of visible radiation is proportional to the temperature of the glowing matter.* The amount of light radiated from the glowing matter (solid or liquid) is measured and employed to determine the temperature.

Fig. 11.15 shows a *disappearing filament pyrometer.*

Operation

— The optical pyrometer is sighted at the hot body and focused.

— In the beginning filament will appear dark as compared to the background which is bright (being hot).

— By varying the resistance in the filament circuit, more and more current is fed into it, till filament becomes equally bright as the background and hence disappears.

— The current flowing in the filament at this stage is measured with the help of an ammeter which is calibrated directly in terms of temperature.

— If the filament current is further increased, the filament appears brighter as compared to the background which then looks dark.

An optical pyrometer can measure temperatures ranging from 700 to 4000°C.

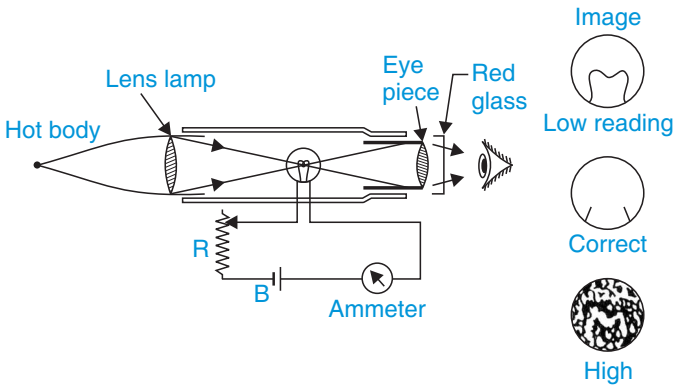


Fig. 11.15. Optical pyrometer.

Table 11.2 gives the summary of temperature range of different instruments.

11.5. LIQUID LEVEL GAUGES

In a boiler house one of the important readings is the *level of water.* The water level should be measured in all boilers all the times. Out of several methods available for determining the levels, some of them are as follows :

1. By sight glass
2. Cable and float
3. By hydrostatic pressure
4. By float and hydraulic pressure
5. By strain gauges
6. By radiation absorption gauges.

11.5.1. Gauge Glass

In case of high pressure boilers (350 kgf/cm^2, 650°C) special attention is given to the sufficient strength of the glass. One of the drawbacks of the gauge glass is when liquid stains or discolours the tube to such a degree that the level cannot be read and the tube cleaning is required. A special device uses a special guide float carrying a permanent magnet within a stainless-steel chamber and a scale consisting of a series of magnetised elements mounted on

Table 11.2. Summary of Temperature Range of Different Instruments

Type of Instruments	*Liquid-in-Glass Thermometer*	*Bimetallic Thermometer*	*Pressure thermometers*			*Thermocouples*			*Resistance thermometers*				*Radiation Pyrometers*	*Optical Pyrometers*
			Vapour Pressure	*Liquid-filled*	*Gas-filled*	*Iron-Constantan*	*Copper-Constantan*	*Chromel Alumel*	*Platinum Platinum-Rhodium*	*Copper*	*Nickel*	*Platinum*		
	Mercury												–	–
Low temperature limit	– 39°C	– 75°C	– 250°C	– 87°C	– 269°C	– 196°C	– 250°C	– 184°C	0°C	– 140°C	– 184°C	– 184°C	About room temp.	760°C
High temperature limit	600°C	540°C	316°C	650°C	540°C	760°C	350°C	1260°C	1540°C	120°C	316°C	760°C	As high as desired	As high as desired
Remarks	Low price; Fairly accurate; Easily broken.	Easier to read than Liquid-in-glass thermometers.	Normally scale non-linear.	To be compensated for variation in ambient temperatures.	Requires large bulb; Linear scale.	Widely used in Industry.	Constantan is 60% Cu, 40% Ni.	Chromel is 20% Cr, 80% Ni. Alumel is 2% Al, 98% Ni.	Expensive.	Very sensitive. Suitable for narrow range instruments.			–	–

the outside of the chamber. They are attracted to each other thus forming a continuous scale, one face being painted and the other silver. The liquid level in modern thermal power station is indicated on a liquid level recorder which is generally located at a distance from the actual boiler tank.

11.5.2. Electrical Level Gauges

A simpler way of measuring the level using electrical circuit is the use of triode tube. Fig. 11.16 shows the principle of electrical transducers. If the level in the tank is below the required level G, there is no

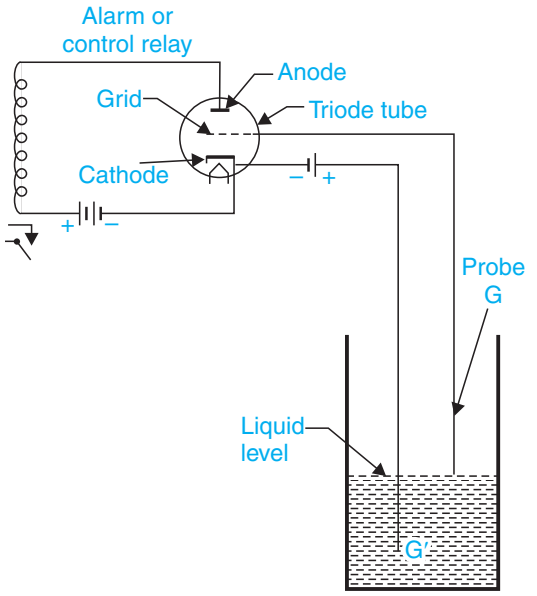


Fig. 11.16. Electrical level gauge principle.

complete circuit to the grid of the tube, which then accumulates a charge of electrons. This makes it very negative in effect and reduces the tube plate current to a very small amount. Under these circumstances, very little current in the relay coil completes the alarm circuit. The alarm thus indicates the dangerously low level in the boiler tank. A red light signal also serves the same purpose. On the other hand if the level of water rises, it completes the circuit between G and other terminals G'. The electrons can then be removed from the grid circuit. As the grid is made less negative, the plate current will continue to rise until sufficient current flows in the relay coil to operate it. The triode tube can well be replaced by transistors.

11.6. FLOW METERS

The various flow meters employed for measuring flow rates are as follows :

1. *Steam flow meters*—measure steam output of boilers and turbine supply etc.

2. *Air flow meters*—measure air flow rate in gas turbines etc.

3. *Water flow meters*—measure feed water condensate and pump discharge.

Rate of flow of water is generally measured by a venturimeter Fig. 11.17. It consists of three parts :

(*i*) A short converging part

(*ii*) Throat

(*iii*) Diverging part.

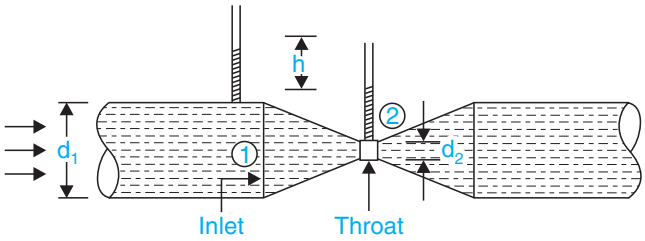


Fig. 11.17. Venturimeter.

A venturimeter works on Bernoulli's principle. As the water flows from end 1 to end 2 a difference between water levels (h) in the piezometers is obtained.

The rate of water discharge (Q) is given by

$$Q = C_d \times \frac{a_1 a_2}{\sqrt{a_1^2 - a_2^2}} \times \sqrt{2gh}$$

where a_1 = Area at section 1 = $\frac{\pi}{4} d_1^2$,

a_2 = Area at section 2 = $\frac{\pi}{4} d_2^2$,

h = Difference in water levels in the piezometers, and

C_d = Co-efficient of discharge.

11.7. pH MEASURING INSTRUMENTS

The pH is a number denoting the degree of acidity or alkalinity of a substance. It does not indicate the quantity of acid or alkaline in a solution as found by titration method. It is derived by measuring the amount of hydrogen ion (H^+) in grams per litre of solution. For example, pure water ionizes to produce 10^{-7} grams of H_2 ions per litre. Therefore, any substance producing 10^{-7} grams of hydrogen ions per litre is considered to be a neutral solution. The greater the amount of hydrogen ions present in solution its acid reaction becomes stronger. Therefore, pure water being neutral solution, any solution producing more hydrogen ion than pure water will be acidic and degree is governed by the difference. Other solution producing less hydrogen ions than pure water will be alkaline and the degree is also governed by the difference.

The pH value of all solutions is accommodated between 0 and 14. The selection of the numbers 0 to 14 is not arbitrary but is actually the number of decimal places required to record the measure of weight of H_2 ions per litre of solution having ascending or descending values of acid and alkaline. Thus a solution having no decimal place is represented by 1 or 1 gram of H_2 ions per litre. This solution would be highly acidic as compared with water. Such value on pH scale is represented as zero. Acid or alkaline nature of a solution depends on whether hydrogen or hydroxyl (OH) ions predominate. The pure water contains H^+ and OH^- ions. The extent to which this dissociation is present in a given sample depends upon temperature. At 20°C, the concentration of these ions is of the order of 10^{-14}. Due to this, pH scale has been spread to 14.

Earlier pH number was measured by observing the *change in colour or turbidity by comparing it with a standard sample*. The mostly used *now a days is to find pH numbers by measuring the potential created by a special battery*. The hydrogen ion reacts with a special glass electrode and produces a potential whose value can be measured. It has been seen that the current flow in the ionisation cell is extremely small, being of the order of a billionth of an ampere. This can be detected by passing it through a resistor of extremely high value. The potential developed under these conditions is then read by noting the response of a meter in the plate circuit of a special vacuum tube. The circuit has two cells, one the *active cell which produces an e.m.f. proportional to the hydrogen ion concentration. The second cell is used for reference purposes*. This reference cell is made with calomel, which is a compound of mercury or with silver-silver chloride. One of the methods of measuring hydrogen ion concentrations is based on the fact that when a piece of metal is placed in an ionic solution of the same metal, there will be a potential developed between the metal and the solution. *The value of this e.m.f. is proportional to the concentration of ions.*

11.8. GAS ANALYSERS

The gas analysis is carried out to determine the concentration of one or more components of a gas mixture. In *steam power plants*, the object of gas analysis is to keep the concentration of carbon dioxide (CO_2) and oxygen (O_2) as *minimum as possible* therefore, constant recording of these components in exhaust gases is necessary. The recording of these components helps to improve the efficiency of steam generation. The common types of analysers used for the measurement of CO_2 and O_2 are described next page.

Measurement of Carbon dioxide (CO_2) :

Since the gases differ in their ability to conduct the heat, therefore, the *proportion of various constituents of flue gases* can be determined by *measuring their thermal conductivity*. If the thermal conductivity of air is considered as *unity* at 0°C, the thermal conductivity of CO_2 = 0.585 ; H_2 = 7.35, N_2 = 1.015 ; O_2 = 1.007 respectively.

Fig. 11.18 shows the commonly used method for measuring CO_2 content is flue gases.

— It consists of hot wire thermal conductivity gas analysis cell which comprises of *two chambers*, each containing a *wire filament* as shown in Fig. 11.18.

— The gas is passed through one chamber whose conductivity is to be measured and other chamber is filled with a reference gas like air and scaled.

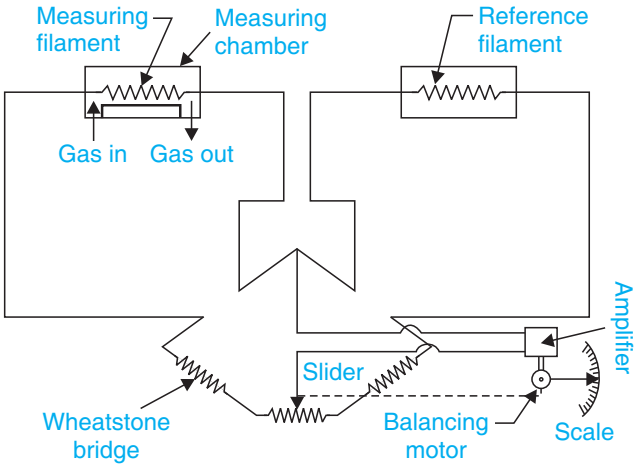


Fig. 11.18. Electrical circuit for the measurement of CO_2 content in the gases.

— The platinum wire elements are passed through the cells (as shown in Fig. 11.18) and form a Wheatstone bridge circuit. Under normal working conditions, these elements are heated by the bridge current.

— The temperature of the filament in the measuring chamber rises as the conductivity of the gases passing around it decreases, as the heat of the filament cannot be carried by the gases. Thus the temperature, and hence the resistance of the two platinum wire elements changes, and unbalances the bridge and provides an *unbalanced voltage which is proportional to the percentage of* CO_2. This unbalanced voltage can be used for measuring the percentage of CO_2 in flue gases.

— To compensate the error which would arise from variation in temperature of the gas, another resistance is inserted in the circuit (not shown).

This type of instrument gives accurate values if *the proportion of H_2 present is small and constant*.

Measurement of Oxygen (O_2)

Although there are other methods to measure O_2, we shall discuss have only "*paramagnetic oxygen analyser*". This analyser works on the principle of *paramagnetic properties of O_2*. Oxygen is the only paramagnetic component in the flue gases. It has very high magnetic permanence compared with other gases. The magnetic permanence of paramagnetic gases *decreases with an increase in temperature*. The gas molecules near the heated body in the magnetic field lose part of their magnetic properties and are pushed out of the magnetic field by cooler molecules. The temperature of the cooler molecules entered in the magnetic field where heated body is situated is increased and in turn they are also pushed out of magnetic field by other molecules. In this way, a convection flow known as '*Magnetic Wind*' is created which cools the heated body. The magnetic wind increases with an increase in O_2 content in the flue gases and cooling of the heated body is intensified. *The temperature change of heated body alters its electric resistance which indicates the concentration of O_2 in the gas mixture*. Therefore, the O_2 content can be measured by measuring an electric resistance of the heated body which can be one of the arms of Wheatstone bridge.

Fig. 11.19 shows the electric circuit used for O_2 measurement using the magnetic wind type principle.

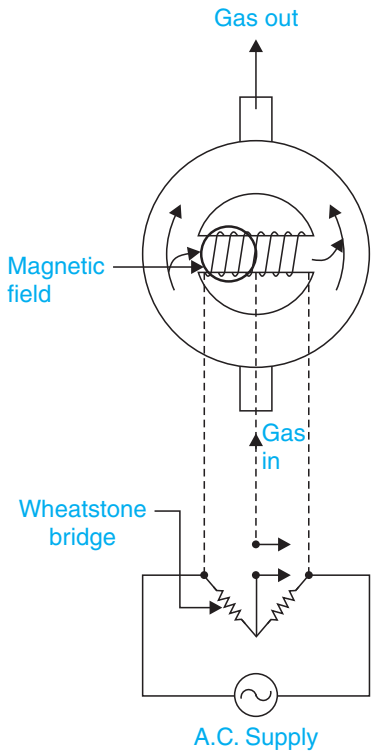


Fig. 11.19. Paramagnetic oxygen analyser.

— The gas is aspirated into the measuring cell through an annulus with an horizontal by-pass tube (as shown in Fig. 11.19). This by-pass tube has two identical adjacent platinum windings on the outside which are connected into a Wheatstone bridge circuit and become heated by the application of voltage across the bridge. One of these windings is cut by an intense magnetic field produced by a large permanent magnet.

— When the sample of flue gas enters into the cell, O_2 is drawn into the bypass by virtue of its paramagnetic properties. It is heated by the winding which reduces the magnetic susceptibility of the gas. Cool O_2 from the gas of higher susceptibility is drawn in the tube displacing the hot gas which passes along the tube back into the annulus. This '*magnetic wind*' *causes differential cooling of the two windings and by the change of resistance with temperature unbalances the bridge. The resulting unbalanced e.m.f. is measured by a standard potentiometer recorder and is proportional to the oxygen content of the sample*.

Measurement of Carbon monoxide (CO) :

A carbon monoxide analyser words on the principle of non-dispersive infra-red absorption and is suitable for all biatomic molecules. The principle of the apparatus is based on *molecular specific absorption of bands of infra-red radiation. The different radiation intensities, depending on the gas concentration, are first converted in the receiver chamber into flow pulses and then into electrical signals*. The system first shoots beams of infra-red and visible light through the gases in the smoke stack. A molecule of a particular gas hungrily absorbs light energy at particular wavelength. By comparing the original intensities of the beam (I_0) with the amount of light that reaches the detector (I), the analyser determines the relative amounts of CO in the gases. The resulting signal is *amplified* and transmitted to the control room. The concentration of the gas is measured in terms of the ratio as log (I/I_0). Therefore, any light level change, darking of the window, scattering of particulates or water droplets in the gas steam, effects both I and I_0 equally, and maintains the ratio unchanged.

Orsat Apparatus

The flue gas analysis can be carried out by **Orsat's apparatus.** Fig. 11.20 shows a typical Orsat's apparatus.

Construction. It consists of a burette, gas cleaner and four absorption pipettes 1, 2, 3, 4. The pipettes are interconnected by means of a manifold fitted with cocks S_1, S_2, S_3, and S_4 and contain different chemicals to absorb *carbon dioxide (CO_2), carbon monoxide (CO)* and *oxygen (O_2)*. Each pipette is also fitted with a number of small glass tubes which provide a greater amount of surface. These tubes are wetted by the absorbing agents and are exposed to the gas under analysis. The measuring burette is surrounded by a water jacket to prevent changes in temperature and density of the gas. Pipette 1 contains *caustic soda (KOH)* which *absorbs carbon dioxide*, pipette 2 is filled with an *alkaline solution of pyrogallic acid* which *absorbs oxygen content of the gas* while pipettes 3 and 4 are provided with an acid solution of *cuprous chloride to absorb carbon monoxide*. Further-more the apparatus has a levelling bottle and a three way cocks to connect the apparatus either to gases or to atmosphere.

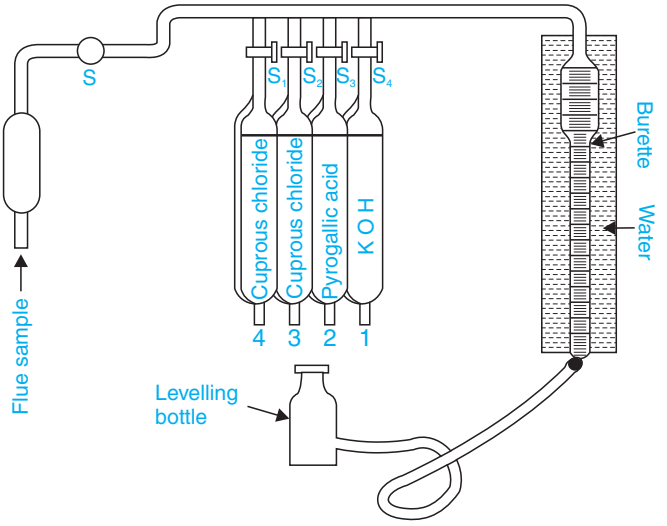


Fig. 11.20. Orsat's apparatus.

Procedure. A 100 cm^3 of gas whose analysis is to be made is drawn into the bottle by lowering the levelling bottle. The stop cock S_1 is then opened and the whole flue gas is forced to pipette 1. The gas remains in this pipette for sometime and most of the carbon dioxide is absorbed. The levelling bottle is then lowered to allow the chemical to come to its original level. The volume of gas thus absorbed is read on the scale of the measuring burette. The flue gas is forced through the pipette 1 for number of times to ensure the whole of the carbondioxide is absorbed. Further, the remaining flue gas is then forced to the pipette 2 which contains pyrogallic acid to absorb whole of oxygen. The reading on the measuring burette will be the sum of volume of CO_2 and O_2. The oxygen content can then be found out by subtraction. Finally, as before, the sample of gas is forced through the pipettes 3 and 4 to absorb carbon monoxide completely.

The amount of nitrogen in the sample can be determined by subtracting from total volume of gas the sum of carbon dioxide, carbon monoxide and oxygen contents.

Note. *Orsat apparatus provides the percentage of dry flue gases because steam if present will be condensed and sulphur dioxide absorbed.*

11.9. HUMIDITY MEASURING INSTRUMENTS

Definitions

Humidity. It is the measure of water vapour present in a gas. It is usually measured as absolute humidity, relative humidity or dew point temperature.

Absolute humidity. It is the mass of water vapour present per unit volume.

Specific humidity. It is the ratio of mass of water vapour present in a sample of a moist gas to the mass of the entire sample.

Relative humidity. It is the ratio of water vapour pressure actually present to water vapour pressure required for saturation at a given temperature. The ratio is expressed in per cent. Relative humidity (RH) is always dependent upon temperature.

Moisture. It refers to the amount of liquid absorbed by a solid. It has also been used to refer to the water chemically bound, adsorbed, or absorbed in a liquid.

Dew point. It is the temperature at which saturation of water vapour pressure is equal to the partial pressure of water vapour in the atmosphere. The relative humidity at dew point is 100%. The dew point has also been defined as the temperature at which the actual quantity of water vapour in the atmosphere is sufficient to saturate this atmosphere with water vapour.

Measuring Instruments

Hygrometers

The hygrometer is an instrument which measures humidity directly. It can be calibrated in terms of absolute humidity. More frequently its output is used to indicate relative humidity.

The various types of hygrometers used are :

1. Resistive hygrometer
2. Capacitive hygrometer
3. Microwave hygrometer
4. Aluminium oxide hygrometer
5. Crystal hygrometer.

The *resistive hygrometer* is described below.

Resistive hygrometer. Some hygroscopic salts exhibit a change in resistivity with humidity. The most common is *lithium chloride*. This, with a binder, may be coated on a wire or on electrodes. Resulting resistance changes cover a wide range, *e.g.* 10^4 to 10^9 Ω as the humidity changes from 100 to 0 per cent. This makes it impractical to design a single element to operate from 1 to 100 per cent relative humidity. Instead *several elements* are used, each in a narrow range, with provision for switching elements. Resistance is measured either with a Wheatstone bridge or by a combination of current and voltage measurements.

Most of these must not be exposed to conditions of 100 per cent humidity as the resulting condensation may damage the device. Either they must be operated in a constant temperature environment or temperature corrections must be made. These are accurate to within ± 2.5 per cent or ± 1.5 per cent in some cases. Response times are typically of the order of a few seconds. These are currently the most common electronic hygrometers.

A typical resistance hygrometer is shown in Fig. 11.21. Two metal grids are bonded to a sheet of plastic.

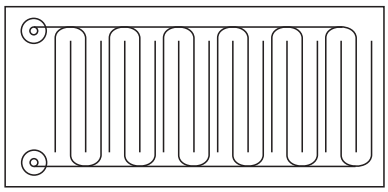


Fig. 11.21. Resistive hygrometer.

The whole is coated with a layer of moisture sensitive chemical such as lithium chloride. The resistance changes when this chemical is exposed to variations in humidity. The higher the relative humidity, the more moisture the lithium chloride will absorb, and the lower will be its resistance.

The resistance of the sensing unit is a measure of the relative humidity. Resistance should be measured by applying A.C. to the Wheatstone bridge. D.C. voltage is not applied because it tends to breakdown the lithium chloride to its lithium and chlorine atoms. The current flow is a measure of the resistance and hence of the relative humidity.

Psychrometers

The psychrometer is a humidity measuring instrument which utilizes one wet bulb thermometer and one dry bulb thermometer. The dry bulb thermometer measures the ambient temperature and the wet bulb thermometer measures temperature reduction due to evaporative cooling. A wick, a porous ceramic sleeve, or a similar device saturated with water is in close physical contact with the "bulb" (sensing portion) of the wet bulb thermometer to keep it moist. Relative humidity is determined from the two temperature readings and a reading of the barometric pressure usually with the help of a **Psychrometric Chart.** At any given ambient temperature, the relative humidity decreases as the difference between dry bulb and wet bulb readings increases.

Some of the psychrometers are described below :

1. Sling psychrometer :

This device consists of two similar thermometers mounted side by side as shown in Fig. 11.22. The bulb of one of the thermometers is covered by a wet cloth.

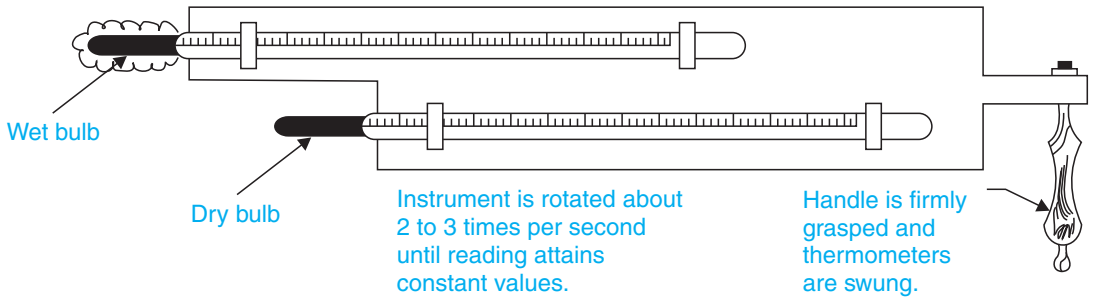


Fig. 11.22. Sling psychrometer.

When a thin film of water is brought into close contact with air, a portion of it evaporates, and the temperature of the remaining water is lowered due to heat required by the evaporation process. The amount of evaporation and consequent lowering of the temperature depends upon the capability of the air to absorb the moisture. Thus if the relative humidity is lower, air has small moisture and can therefore absorb more. Hence the evaporation is faster and the temperature of the remaining water will be lower.

In the sling psychrometer, a handle is provided whereby the thermometer may be whirled, so that the bulbs continuously come in contact with fresh air. If this is not done the stagnant mositure-laden air will engulf the thermometer thereby causing errors.

The dry bulb thermometer is unaffected by the moving air and registers the ambient temperature. The wet bulb thermometer shows a lower temperature due to evaporation. Since the cooling effect is a function of the relative humidity of air, the relative humidity may be determined by comparing the readings of the two thermometers. Relative humidity can directly be read off from psychrometric charts.

Psychrometric charts graphically describe the relationship between the properties of moist air *i.e.*, the dry bulb, the wet bulb and dew point temperatures of the mixture and humidity.

2. Commercial type psychrometer :

A commercial type psychrometer is shown in Fig. 11.23. The filled system thermometer bulbs are placed adjacent to each other and air is blown across the assembly or they may be placed where there is strong current of air (nearly 5 m/s). One of the bulbs is coated with a knitted or woven cotton which is suspended into a water reservoir whose level is controlled so that the required conditions are satisfied. The temperatures are recorded by suitable recorders.

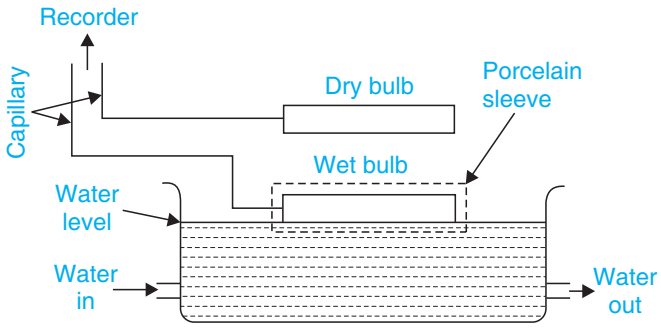


Fig. 11.23. Commercial type psychrometer.

The two thermometers are connected to a recorder through capillary tubes. In order to avoid errors arising on account of contamination of the wick the bulb may be enclosed in a porcelain sleeve and water is pumped into the annular space at a constant rate. These instruments are not suited for instantaneous monitoring and control of humidity.

A variation in the indication and recording arrangement is also possible if the filled in thermometers are replaced by resistance thermometers or thermocouples.

Dew Point Measurements

The dew point is a discrete temperature. Specially, it is that temperature at which liquid water and water vapour, or ice and water vapour are in equilibrium. At this temperature only one value of saturation vapour pressure (of water vapour) exists. Hence, the absolute humidity can be determined from this temperature if the pressure is known.

Two methods used for measuring dew point temperatures are given below :

First Method

Refer to Fig. 11.24. This method uses the resistive hygrometer described previously. The arrangement consists of a thin metal tube covered with a glass cloth saturated with lithium chloride. A double winding of silver is made over the glass cloth.

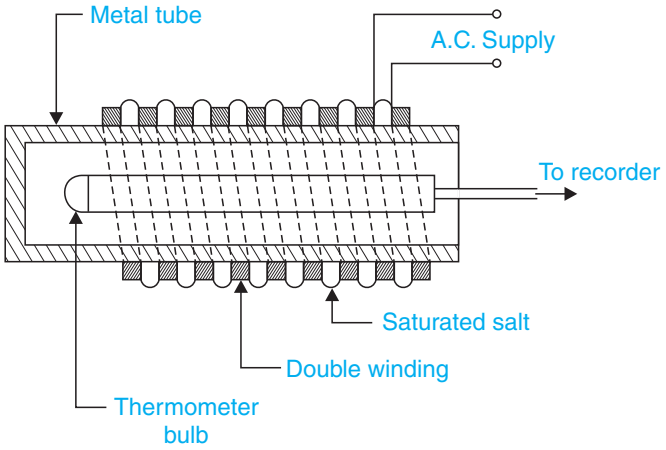


Fig. 11.24. Dew point recorder.

A low voltage A.C. supply is connected to the winding. The electric conductivity between the wires is proportional to the moisture in the salt absorbed from surrounding gas. When the humidity is low, there is small current flow, and the temperature rise of the winding is small. When the humidity is high, a high current flows through the winding causing large heat to be generated and the temperature of the cell is high. The thermometer placed inside the metal tube measures the cell temperature, and therefore absolute humidity or dew point.

This instrument can be used for measuring dew point with an accuracy of ± 2%. The main advantage of this dew point instrument are its *simplicity* and *fast response*.

Second Method

This method determines the temperature at which moisture condenses by impinging a jet of the gas (whose dew point is to be measured) on a mirror and finding the exact temperature at which the surface becomes cloudy. This method is shown in Fig. 11.25. Automatic control can be used by having feedback.

The gas is supplied continuously. This dew point recorder is provided with arrangements for both cooling and heating of the mirror. Light falling on the mirror from a standard light source is reflected on a photo-tube. Another photo-tube receives light straight from the source. The outputs of tubes are then compared by a comparator. If the mirror is foggy due to condensation an error signal is sent and the heater starts functioning and the refrigerator is turned off. If the condensation has not started, the heater is shut off and the refrigerator turned is on. The cycle continues. Thus, the temperature of the mirror tells about the temperature necessary to condense the gas. The temperature is sensed by a thermocouple. The temperature is measured and recorded by a suitable device.

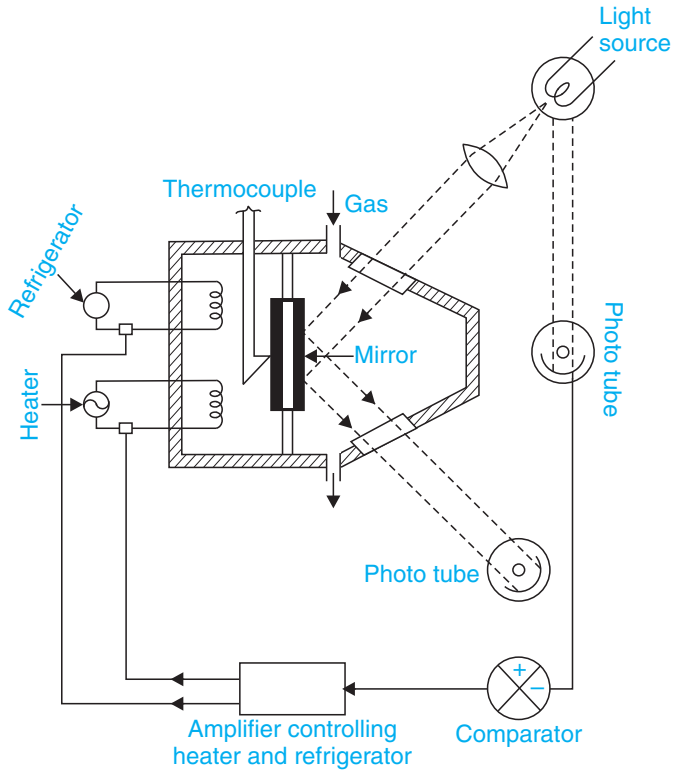


Fig. 11.25. Schematic diagram of dew point recorder.

11.10. IMPURITY MEASURING INSTRUMENTS

The following impurities may be present in the *feed water* used in a boiler to generate steam :

1. Sodium chlorides and other chlorides
2. Calcium sulphate and other sulphates
3. CO_2 from evaporators
4. Silica from dust etc.
5. Oxygen from air in condenser etc.
6. Metallic pieces picked up by steam while passing through pipes.

The above mentioned impurities should be kept to the *minimum*.

Fig. 11.26 shows *dionic water purity meter*.

— *It works on the principle that the electrical conductivity of an electrolyte dissolved in water depends on the amount of salt in solution i.e., the extent of impurity*.

The resistance between the opposite faces of a cube of standard water in the instrument is *compared* with the resistance when the water contains more impurities.

— A sample of water, in this water, is allowed to flow through it. The automatic correction for temperature variation is effected by the plunger. The insulating plunger varies water

cross-section automatically by temperature compensator to give correction to 20°C.

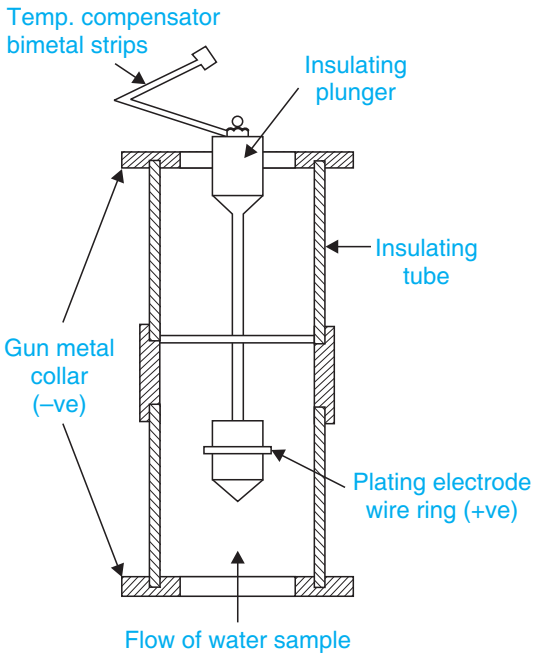


Fig. 11.26. Dionic water purity meter.

— Conductivity is measured of two water columns in between rings and gunmetal collars. *The conductivity per cm^3 indicated is the reciprocal of the resistance measured*. The standard of reference is the resistance of one megaohm between opposite faces of a cm^3 of solution.

— Dionic readings of condensate and feed water at various points of flow are brought to one control point, connections to the meter being provided by special piping. By this arrangement the source of contamination can be speedily located.

11.11. SPEED MEASURING INSTRUMENTS

The following instruments are used for measuring speed :

1. Vibrating reed tachometer.
2. Clock type tachometer.
3. Stroboscope.
4. Revolutions counter.

11.12. STEAM CALORIMETERS AND FUEL CALORIMETERS

11.12.1. Steam Calorimeters

The *dryness fraction of steam* can be measured by using following calorimeters :

1. Tank or bucket calorimeter.
2. Throttling calorimeter.
3. Separating and throttling calorimeter.

11.12.1.1. Tank or bucket calorimeter

The dryness fraction of steam can be found with the help of tank calorimeter as follows :

A known mass of steam is passed through a known mass of water and steam is completely condensed. The heat lost by steam is equated to heat gained by the water.

Fig. 11.27 shows the arrangement of this calorimeter.

The steam is passed through the sampling tube into the bucket calorimeter containing *a known* mass of water.

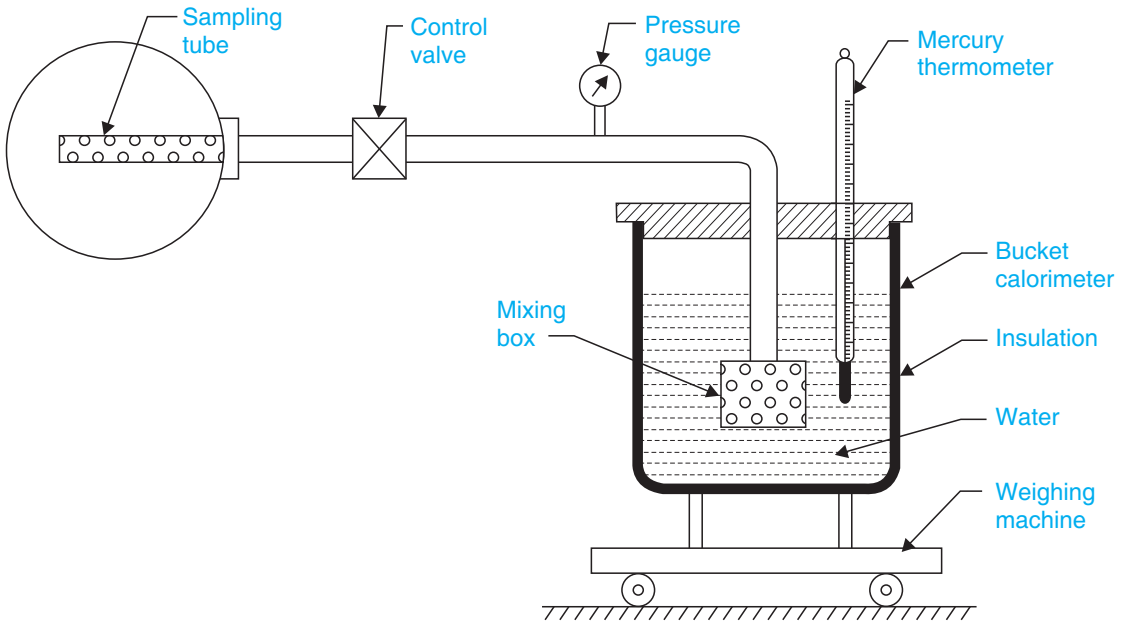


Fig. 11.27. Tank or bucket calorimeter.

The weight of calorimeter with water before mixing with steam and after mixing the steam are obtained by weighing.

The temperature of water before and after mixing the steam are measured by *mercury thermometer*.

The pressure of steam passed through the sampling tube is measured with the help of *pressure gauge*.

Let p_s = Gauge pressure of steam (bar),
p_a = Atmospheric pressure (bar),
t_s = Saturation temperature of steam known from steam table at pressure $(p_s + p_a)$,
h_{fg} = Latent heat of steam,
x = Dryness fraction of steam,
c_{pw} = Specific heat of water,
c_{pc} = Specific heat of calorimeter,
m_c = Mass of calorimeter, kg,
m_{cw} = Mass of calorimeter and water, kg,
$m_w = (m_{cw} - m_c)$
= Mass of water in calorimeter, kg,
m_{cws} = Mass of calorimeter, water and condensed steam, kg,
$m_s = (m_{cws} - m_{cw})$ = Mass of steam condensed in calorimeter, kg,
t_{cw} = Temperature of water and calorimeter before mixing the steam, °C, and
t_{cws} = Temperature of water and calorimeter after mixing the steam, °C.

Neglecting the losses and *assuming* that the *heat lost by steam is gained by water and calorimeter*, we have

$$(m_{cws} - m_{cw})\,[xh_{fg} + c_{pw}\,(t_s - t_{cws})]$$
$$= (m_{cw} - m_c)\,c_{pw}\,(t_{cws} - t_{cw}) + m_c\,c_{pc}\,(t_{cws} - t_{cw})$$
$$\therefore \quad m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})]$$
$$= (t_{cws} - t_{cw})\,[m_{cw} - m_c)(c_{pw} + m_c\,c_{pc}] \quad ...(11.1)$$

or,
$$m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})]$$
$$= (t_{cws} - t_{cw})(m_w c_{pw} + m_c c_{pc})$$

The $m_c c_{pc}$ is known as *water equivalent of calorimeter*.

The value of dryness fraction 'x' can be found by solving the above equation.

The value of dryness fraction found by this method involves some *inaccuracy* since losses due to convection and radiation are not taken into account.

The calculated value of dryness fraction neglecting losses is always less than the actual value of the dryness.

11.12.1.2. Throttling calorimeter

The dryness fraction of wet steam can be determined by using a throttling calorimeter which is illustrated diagrammatically in Fig. 11.28.

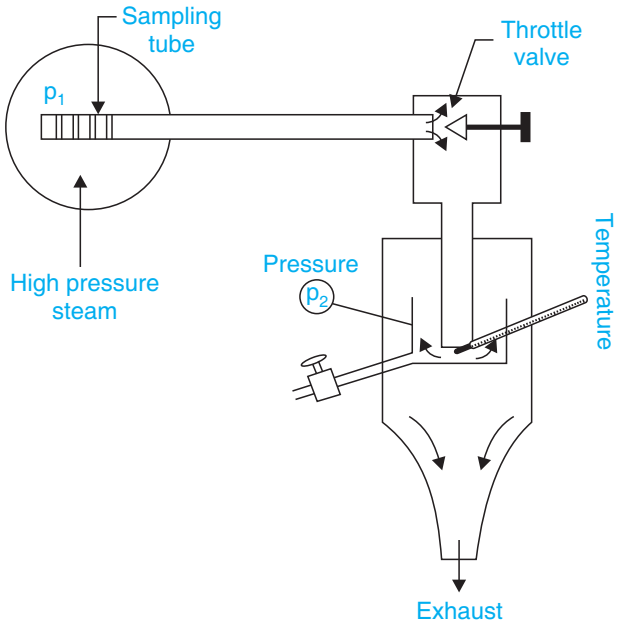


Fig. 11.28. Throttling calorimeter.

The steam to be sampled is taken from the pipe by means of suitably positioned and dimensioned sampling tube. It passes into an insulated container and is throttled through an orifice to atmospheric pressure. Here the temperature is taken and the steam ideally should have about 5.5 K of superheat.

The throttling process is shown on h-s diagram in Fig. 11.29 by the line 1-2. If steam initially wet is throttled through a sufficiently large pressure drop, then the steam at state 2 will become superheated. State 2 can then be defined by the *measured pressure and temperature*. The enthalpy, h_2 can then be found and hence

$$h_2 = h_1 = (h_{f_1} + x_1 h_{fg_1}) \text{ at } p_1$$

[where, $h_2 = h_{f_2} + h_{fg_2} + c_p(T_2 - T_{s_2})$]

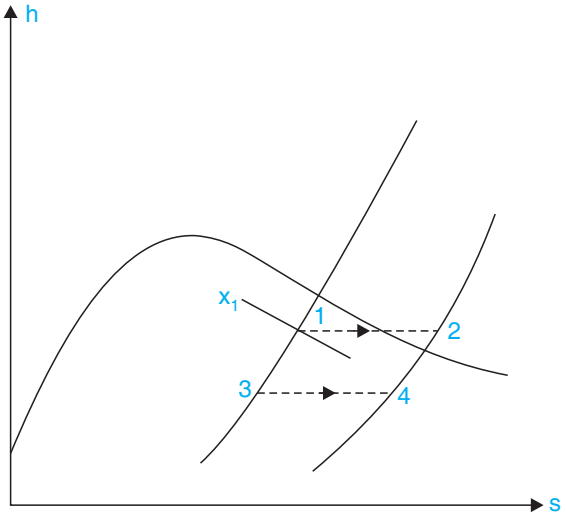


Fig. 11.29. Throttling process.

$$\therefore \quad x_1 = \frac{h_2 - h_{f_1}}{h_{fg_1}} \qquad ...(11.2)$$

Hence the dryness fraction is determined and state 1 is defined.

11.12.1.3. Separating and throttling calorimeter

If the steam whose dryness fraction is to be determined is *very wet* then throttling to atmospheric pressure *may not be sufficient to ensure superheated steam at exit*. In this case it is *necessary to dry the steam partially, before throttling*. This is done by *passing the steam sample from the main through a separating calorimeter* as shown in Fig. 11.30. The steam is made to change direction suddenly, and the water, being denser than the dry steam is separated out. The quantity of water which is separated out (m_w) is measured at the separator, the steam remaining, which *now has a higher dryness fraction*, is passed through the *throttling calorimeter*. With the combined separating and throttling calorimeter it is *necessary* to condense the steam after throttling and measure the amount of condensate (m_s). If a throttling calorimeter only is sufficient, there is no need to measure condensate, the pressure and temperature measurements at exit being sufficient.

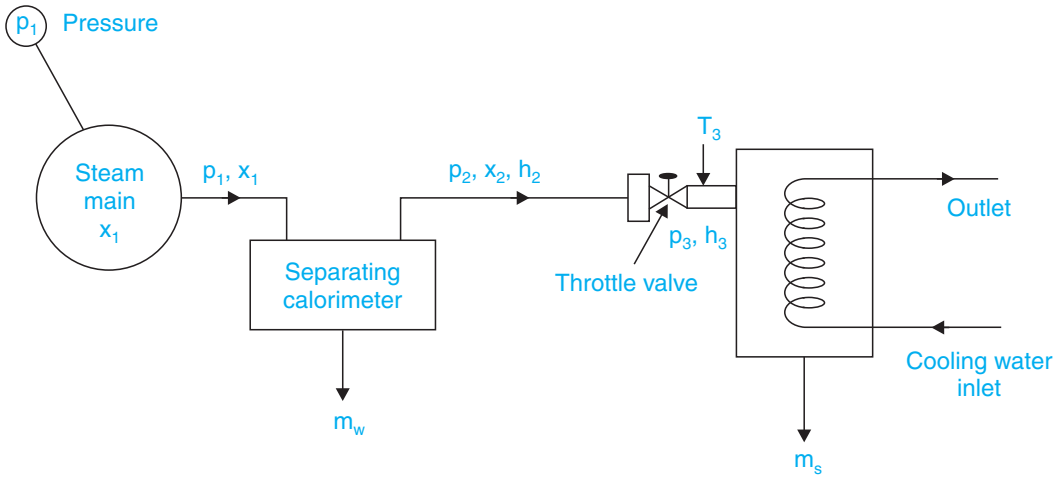


Fig. 11.30. Separating and throttling calorimeter.

Dryness fraction at 2 is x_2, therefore, the mass of dry steam leaving the separating calorimeter is equal to $x_2 m_s$ and this must be the mass of dry vapour in the sample drawn from the main at state 1.

Hence fraction in main,

$$x_1 = \frac{\text{Mass of dry vapour}}{\text{Total mass}} = \frac{x_2 m_s}{m_w + m_s} .$$

The dryness fraction, x_2, can be determined as follows :

$$*h_3 = h_2 = h_{f_2} + x_2 h_{fg_2} \text{ at } p_2$$

$$[*h_3 = h_{f_3} + h_{fg_3} + c_p(T_{sup} - T_{s_3}) \text{ a pressure } p_3]$$

or, $$x_2 = \frac{h_3 - h_{f_2}}{h_{fg_2}}$$

The values h_{f_2} and h_{fg_2} are read from tables at pressure p_2. The pressure in the separator is small so that p_1 is approximately equal p_2.

11.12.2. Fuel Calorimeters

11.12.2.1. Bomb calorimeter

The calorific value of solid and liquid fuels is determined in the laboratory by *'Bomb Calorimeter'*. It is so named because its shape resembles that of a bomb. Fig. 11.31 shows the schematic sketch of a bomb calorimeter.

The calorimeter is made of austenitic steel which provides considerable resistance to corrosion and enables it to withstand high pressure. In the calorimeter is a strong cylindrical bomb in which combustion occurs. The bomb has two valves at the top. One supplies oxygen to the bomb and other releases the exhaust gases. A crucible in which a weighed quantity of fuel sample is burnt is arranged between the two electrodes as shown in the Fig. 11.31. The calorimeter is fitted with water jacket which surrounds the bomb. To reduce the losses due to radiation, calorimeter is further provided with a jacket of water and air. A stirrer for keeping the temperature of water uniform and a thermometer to measure the temperature up to an accuracy of 0.001°C are fitted through the lid of the calorimeter.

Procedure. To start with, about 1 gm of fuel sample is accurately weighed into the crucible and a fuse wire (whose weight is known) is stretched between the electrodes. It should be ensured that wire is in close contact with the fuel. To absorb the combustion products of sulphur and nitrogen 2 ml of water is poured in the bomb. Bomb is then supplied with pure oxygen through the valve to an

amount of 25 atmosphere. The bomb is then placed in the weighed quantity of water, in the calorimeter. The stirring is started after making necessary electrical connections, and when the thermometer indicates a steady temperature fuel is fired and temperature readings are recorded after 1/2 minute intervals until maximum temperature is attained. The bomb is then removed ; the pressure slowly released through the exhaust valve and the contents of the bomb are carefully weighed for further analysis.

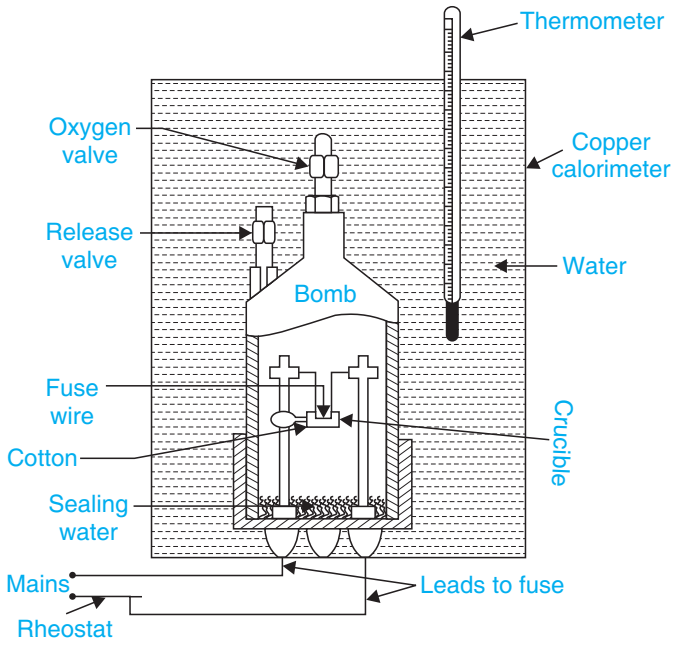


Fig. 11.31. Bomb calorimeter.

The heat released by the fuel on combustion is absorbed by the surrounding water and the calorimeter.

From the above data the calorific value of the fuel can be found in the following way :

Let w_f = weight of fuel sample (kg)

w = weight of water (kg)

C = calorific value (higher) of the fuel (kJ/kg)

w_e = water equivalent of calorimeter (kg)

t_1 = internal temperature of water and calorimeter

t_2 = final temperature of water and calorimeter

t_c = radiation corrections.

Heat released by the fuel sample = $w_f \times C$.

Heat received by water and calorimeter

$$= (w + w_e)\,[(t_2 - t_1) + t_c]$$

Heat lost = heat gained

$$w_f \times C = (w + w_e)[(t_2 - t_1) + t_c]$$

$$C = \frac{(w + w_e)(t_2 - t_1) + t_c}{w_f} \text{ kJ/kg} \qquad ...(11.3)$$

Note 1. Corrections pertain to the heat of oxidation of fuse wire, heat liberated as a result of formation of sulphuric and nitric acids in the bomb itself.

2. It should be noted that *bomb calorimeter measures the higher or gross calorific value because the fuel sample is burnt at a constant volume in the bomb*. Further the bomb calorimeter will measure the H.C.V. directly if the bomb contains adequate amount of water before firing to saturate the oxygen. Any water formed from combustion of hydrogen will, therefore, be condensed.

The procedure of determining calorific values of liquid fuels is similar to that described above. However, if the liquid fuel sample is volatile, it is weighed in a glass bulb and broken in a tray just before the bomb is closed. In this way the loss of volatile constituents of fuels during weighing operation is prevented.

11.12.2.2. Junker's gas calorimeter

The calorific value of gaseous fuels can be determined by junker's gas calorimeter.

Fig. 11.32. illustrates Junker's gas calorimeter. Its principle is somewhat similar to Bomb calorimeter ; in respect that heat evolved by burning the gas is taken away by the water. In its simplest construction it consists of a combustion chamber in which the gas is burnt (in a gas burner). A water jacket through which a set of tubes called flues pass surrounds this chamber. Thermometers are incorporated at different places (as shown in Fig. 11.32) to measure the temperatures.

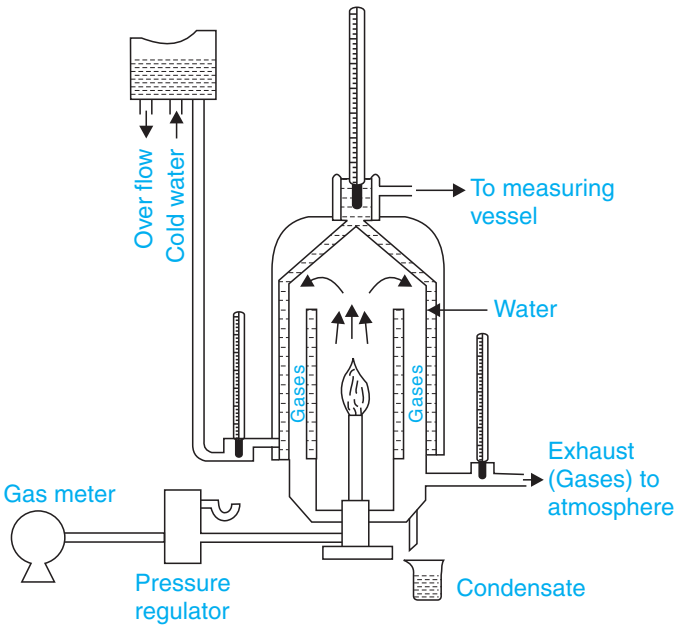


Fig. 11.32. Junker's gas calorimeter.

Procedure. A metered quantity of gas whose calorific value is to be determined is supplied to the gas burner *via* a gas meter which records its volume and a gas

pressure regulator which measures the pressure of the gas by means of a manometer. When the gas burns the hot product of combustion travels upwards in the chamber and then downwards through the flues and finally escape to the atmosphere through the outlet. The temperature of the escaping gas is recorded by the thermometer fitted at the exit and this temperature should be as close to room temperature as possible so that entire heat of combustion is absorbed by water. The cold water enters the calorimeter near the bottom and leaves near the top. Water which is formed by condensation of steam is collected in a pot.

The quantity of gas used during the experiment is accurately measured by the meter and temperature of ingoing and outgoing water are indicated by the thermometers. From the above data the calorific value of the gas can be calculated.

Note **1.** The volume of gas used during the experiment should be converted to volume at S.T.P.

(standard temperature and pressure) *i.e.*, 15°C, 760 mm respectively.

2. The gross calorific value is obtained by dividing the heat given out by corrected volume of gas. The net or lower calorific value of the gas is obtained by subtracting from total heat the heat associated with condensed water (which is obtained by multiplying the weighed condensate by latent heat of vapourisation of water).

HIGHLIGHTS

1. Commonly used instruments in a power plant are :
   (*i*) Pressure gauges, (*ii*) Thermometers, (*iii*) Liquid level gauges, (*iv*) Flow meters, (*v*) pH measuring instruments, (*vi*) Gas analysers, (*vii*) Humidity measuring instruments, (*viii*) Impurity measuring instruments, (*ix*) Speed measuring instruments, (*x*) Steam calorimeters and fuel calorimeters, (*xi*) Gong alarms.
2. Low pressures are generally determined by *manometers* which employ liquid columns.
3. A Bourbon type tube pressure gauge is used for measuring high as well as low pressures.
4. A transducer is device for converting a signal of one sort into the other type.
5. Temperature can be defined as a thermal state which depends upon the internal or molecular energy of the body.
6. A resistance thermometer is used for precision measurements below 150°C.
7. An optical pyrometer works on the principle that matters glow above 480°C and the colour of visible radiation is proportional to the temperature of the glowing matter.
8. The hygrometer is an instrument which measures humidity directly.
9. The psychrometer is a humidity measuring instrument which utilizes one wet bulb thermometer and other dry bulb thermometer.
10. Dionic water purity meter works on the principle that the electrical conductivity of an electrolyte dissolved in water depends on the amount of salt in solution *i.e.*, the extent of impurity.
11. The dryness fraction of steam can be measured by using the following calorimeters :
    (*i*) Tank or bucket calorimeter
    (*ii*) Throttling calorimeter
    (*iii*) Separating and throttling calorimeter.

THEORETICAL QUESTIONS

1. List the functions which the various types of instruments in a power plant have to perform.
2. How are instruments classified ?
3. What is the difference between gauge pressure and absolute pressure ?
4. Enumerate various types of pressure measurement devices.
5. Explain briefly the following :
   (*i*) U-tube manometer (*ii*) Micro-manometer.
6. Describe briefly the following pressure gauges :
   (*i*) Bourdon tube pressure gauge
   (*ii*) Diaphragm gauge.
7. Explain briefly the following :
   (*i*) Electrical transducers
   (*ii*) Electromagnetic transducers.
8. How is temperature defined ?
9. How are temperature measurements made ?
10. How are thermometers classified ?
11. Explain briefly the following :
    (*i*) Bimetallic thermometers
    (*ii*) Liquid filled thermometers
    (*iii*) Gas-filled thermometers.
12. Write a short note on resistance thermometers.
13. Explain with a help of a neat sketch the construction and working of a radiation pyrometer.
14. What are the advantages of pyrometers ?
15. State the principle on which an optical pyrometer works.
16. Describe with the help of a neat sketch an optical pyrometer.
17. Explain briefly the following liquid level gauges :
    (*i*) Gauge glass (*ii*) Electrical level gauges.
18. Write a short note on 'Flow meters'.
19. Explain the procedure for measuring CO_2 content in the gases.
20. What is humidity ? How can it be measured ?
21. Give the description of resistive hygrometer.
22. How can the dryness fraction of steam determined by the following ?
    (*i*) Tank or bucket calorimeter
    (*ii*) Separating and throttling calorimeter.

Major Electrical Equipment in Power Plants

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12.1. INTRODUCTION

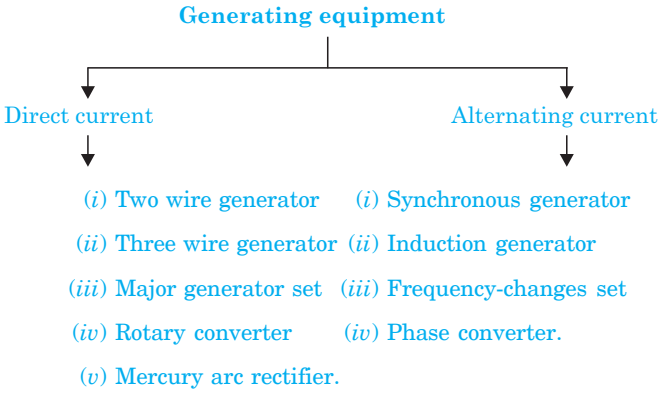
In different types of power plants such as thermal power plant, hydro-power plant, nuclear power plant etc. the electricity is generated. A number of electrical equipments which are available in a power plant are listed below :

1. Generators
2. Excitors
3. Transformers
4. Reactors
5. Circuit breakers
6. Switchgear and protective equipment
7. Control board equipment
8. Busbars
9. Standby generators etc.

12.2. GENERATING EQUIPMENT

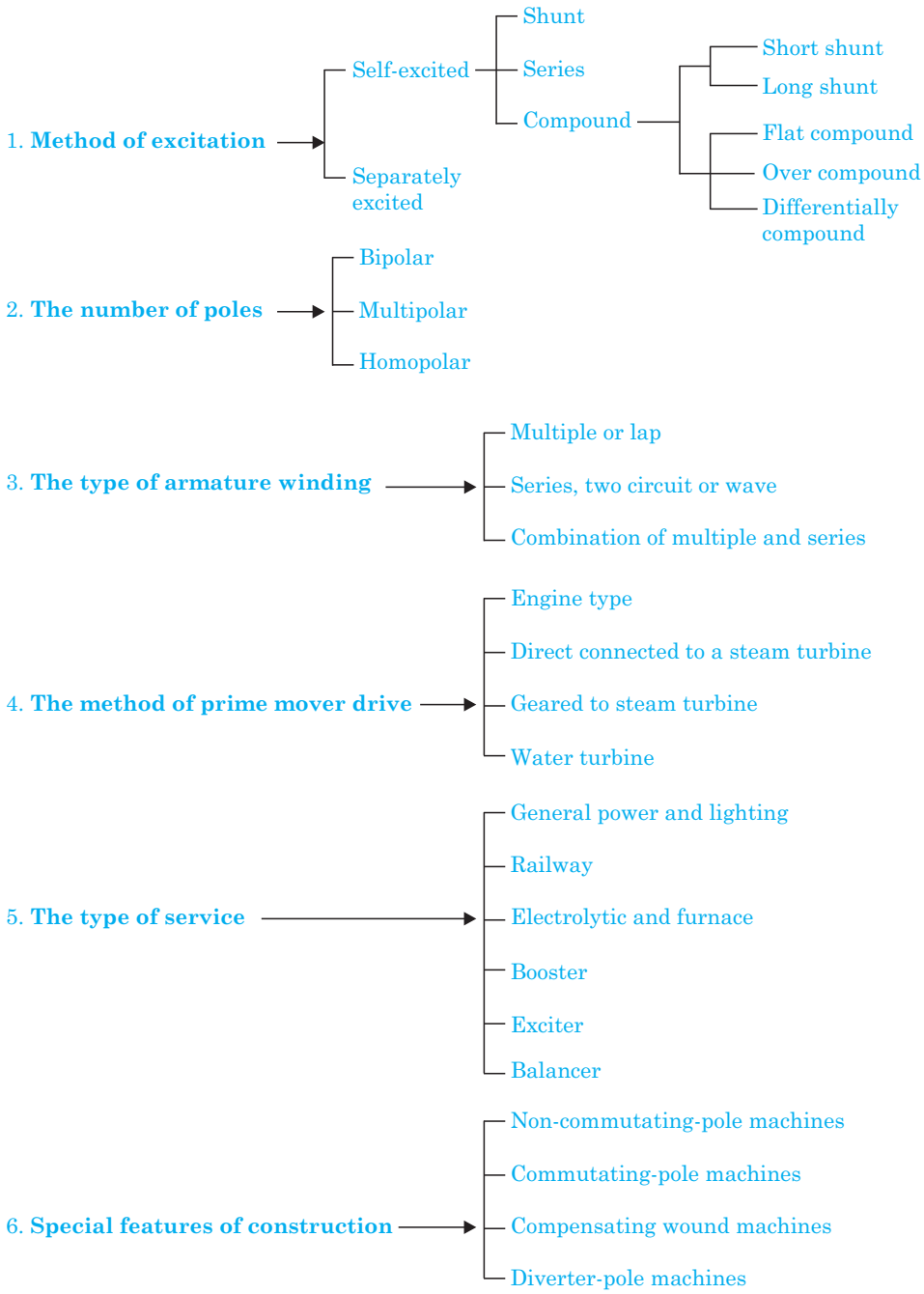
12.2.1. Classification

A broad classification of generating equipment may include the following types of machines :



12.2.2. Two-Wire Direct Current Generators

By two-wire generators are meant such generators as have only two line terminals, one known as the positive terminal and the other as the negative terminal. Direct current generators may be further classified according to :



12.2.2.1. Principle of a generator

An electrical generator is a machine which converts mechanical energy (or power) into electrical energy (or power). This energy conversion is based on the *principle of the production of dynamically induced e.m.f.* As seen from Fig. 12.1, *whenever a conductor cuts magnetic flux, dynamically induced e.m.f. is produced in it according to Faraday's Laws of Electromagnetic induction. This e.m.f. causes current to flow if the conductor circuit is closed.* Therefore, the basic essential parts of an electrical generator are :

(*i*) A magnetic field.

(*ii*) A conductor/conductors which can so move to cut the flux.

12.2.2.2. Elementary generator

If a single-turn coil (see Figs. 12.1 and 12.2) is rotated in a uniform magnetic field at a constant speed, as shown in Figs. 12.1 and 12.2. (*a*), the e.m.f. induced in a given coil side will vary as the coil moves through various positions from 0° to 360° as shown in Fig. 12.2.

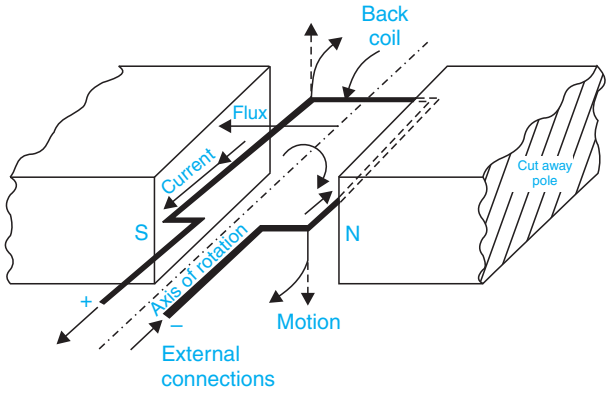
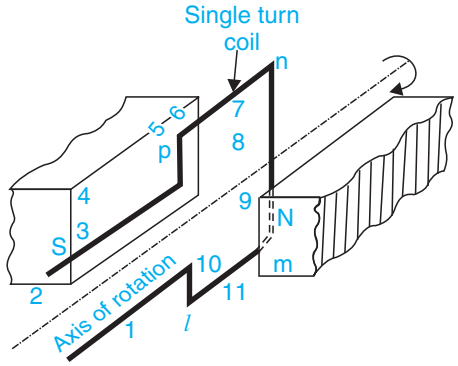
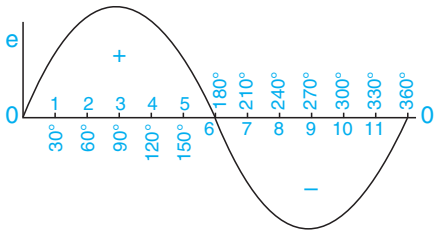


Fig. 12.1. Elementary generator.



(a) Instantaneous positions of rotation at constant speed.



(b) E.m.f. at respective positions.

Fig. 12.2. E.m.f. generated by a coil moving in a uniform field.

— Using coil side *lm* as a reference, it will be noted that when this coil side is in *position 1* shown in Fig. 12.2 (*a*), the e.m.f. induced in the coil is *zero*, since-conductor *lm* (and conductor *np*, as well) is *moving parallel to the magnetic field and experiencing no change in flux linkages.*

— When conductor *lm* moves to position 1, rotating in clockwise direction it cuts the uniform magnetic field at an oblique angle of 30°. The e.m.f. induced in this upward-moving conductor with respect to an external load will be positive and will amount to 50 per cent (e.m.f. $\alpha \sin \theta$) of the maximum induced voltage. The change in voltage is shown graphically in Fig. 12.2 (*b*), where the e.m.f. is positive at position 1 and has the value given.

— When the coil moves to position 2, the e.m.f. induced will be positive and will amount to approximately 86.6 per cent of the maximum induced voltage.

— When the coil reaches 90° (see Fig. 12.1), position 3 [see Figs. 12.1 and 12.2 (*a*)], the conductor *lm* has the *maximum number of flux linkages, since it is moving perpendicularly to the magnetic field, and has the maximum positive value* shown in Fig. 12.2 (*b*).

— Positions 4 and 5 corresponding to 120° and 150° of rotation respectively, yields an e.m.f. in coil side *lm* identical to those produced at positions 1 and 2 [sin 120° = sin 60°, sin 150° = sin 30°] respectively with a positive polarity since the conductor is still moving upward but the change in flux linkage occurs at a slower rate than a position 3 respectively.

— When the conductor *lm* reaches 180°, position 6, the *induced e.m.f. is again zero*, since no *change in flux linkages occurs when a conductor is moving parallel to a magnetic field.*

— In positions 7 and 8 corresponding to 210° and 240° respectively, the e.m.f. in conductor *lm* is reversed since conductor *lm* is now moving downward in the same uniform magnetic field. The e.m.f. induced increases to a negative maximum at 270°, position 9, and finally decreases through positions 10 and 11 corresponding to 300° and 330° back to zero at position 0.

— It is worth noting that the *e.m.f. in a conductor rotating in a magnetic field is both sinusoidal and alternating.* It may be observed that during this process no e.m.f. is induced in coil-sides *mn* or *pl* since these conductors experience no change in flux linkages. Even if an e.m.f. were produced in these coil sides, they would not contribute to the e.m.f. of the coil because they are moving in the same direction through the same field and hence produce equal e.m.f.'s in opposition. Coil sides *lm* and *np*, however, aid

each other, and the total e.m.f. produced by the coil is twice the magnitude represented in Fig. 12.2 (*b*). It should be noted that no e.m.f. is produced in positions 0 and 6 known as the *interpolar* or neutral zones of the dynamo.

— It may be noted that a *sinusoidal wave shape is produced by a conductor rotating in a theoretically uniform field represented in Fig. 12.2, in which the air gap is not constant because of the straight pole sides. If the pole tips are curved so that the pole face produces a more uniform gap and flux density except in the inter-polar regions, the wave shape of the induced e.m.f. will tend to be flat-topped, approaching a square wave more nearly than a sine wave.*

Conversion of Alternating Current into Direct Current by Means of a Commutator. In order to convert the alternating voltage (A.C.) to unidirectional current (D.C.), it is necessary to employ a mechanical switching device which is actuated by the mechanical rotation of the dynamo/generator shaft, called a '*commutator*' (*see* Fig. 12.3).

— The simple split-ring commutator shown consists of two segments (*A* and *B*), secured to and insulated from the armature shaft and from each other as well. Each conducting commutator segment is connected, respectively, to a coil side. Since both coil side and commutator segment are *fastened mechanically* to the same shaft, *the action of the mechanical rotation is to reverse the armature coil and connections to the stationary external circuit at the same instant that the induced e.m.f. reverses in the armature coil side* (*i.e.*, when the coil side moves under an opposite pole). Fixed brushes are arranged to contact the commutator segments, as shown in Fig. 12.3.

— As shown in Figs. 12.2 and 12.3, the e.m.f. induced in coil-side *lm* causes a positive polarity for the first 180° of rotation (positions 0 through 6) and a negative polarity for the remaining 180° (positions 6 through 0). But, in Fig. 12.3, coil side *lm* is connected to commutator segment *A* and the coil side *np* is connected to commutator segment *B*. For the first 180° of rotation, therefore, the positive e.m.f. produced by the coil-side *lm* is connected to the stationary positive brush. For the second 180° of rotation, the negative e.m.f. produced by coil side *lm* is connected to the secondary negative brush. The same effect occurs in reverse order for coil-side *np*.

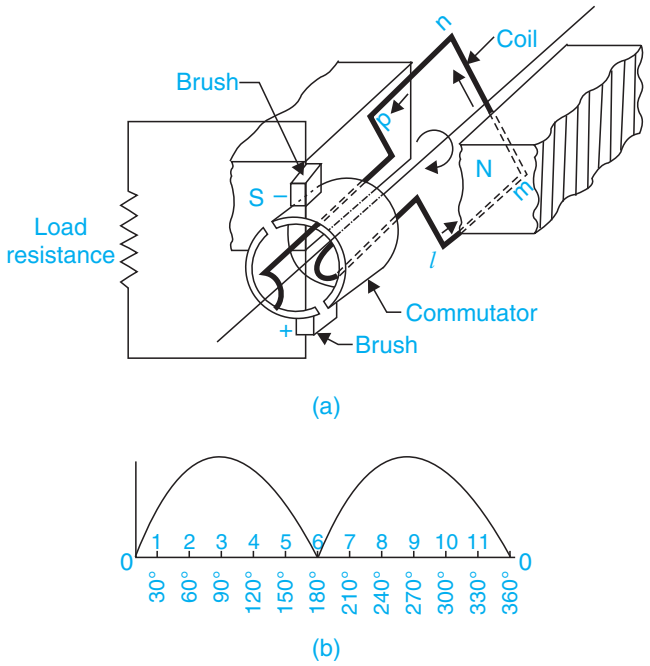


Fig. 12.3. Bipolar generator with two segment commutator.

In effect, therefore, *the action of the commutator is to reverse connections to the external circuit simultaneously and at the same instant the direction of e.m.f. reverses in each of the coil sides. Each brush, positive or negative respectively, is always maintained, therefore, at the same polarity*. Fig. 12.3 (*b*) shows the e.m.f. (and current) wave form produced as a result of the above process for one full cycle (or 360°) of rotation.

— The pulsating unidirectional current which has a zero value twice each cycle as shown in Fig. 12.3 (*b*), is hardly suitable for commercial D.C. use. *The output e.m.f. may be made less pulsating by using a large number of coils and commutator segments* (Fig. 12.4).

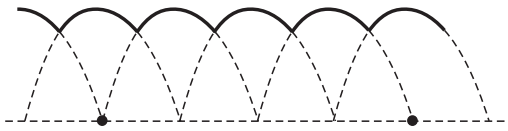


Fig. 12.4. The output e.m.f. with a large number of coils and commutator segments.

— It may be noted that a single turn armature coil generates voltage which is quite small in magnitude. Therefore, the coils employed in commercial generators consist of several turns in series thereby increasing the magnitude of generated e.m.f. in direct proportion to the number of the turns in the coil.

12.2.2.3. Construction of D.C. machines

A D.C. machine consists of *two* main parts :

(*i*) **Stationary Part.** It is designed mainly for *producing a magnetic flux*.

(*ii*) **Rotating Part.** It is called the *armature*, where mechanical energy is converted into electrical (electrical generator), or conversely, electrical energy into mechanical (electric motor).

The stationary and rotating parts are separated from each other by an *air-gap*.

— The *stationary part* of a D.C. machine consists of *main poles*, designed to create the magnetic flux, *commutating poles* interposed between the main poles and designed to ensure sparkless operation of the brushes at the commutator (in very small machines with a lack of space commutating poles are not used) ; and a *frame/* yoke.

— The *armature* is a cylindrical body rotating in the space between the poles and comprising a *slotted armature core*, a *winding* inserted in the armature core slots, a *commutator* and *brush gear*.

Fig. 12.5 shows generator or motor magnetic structure.

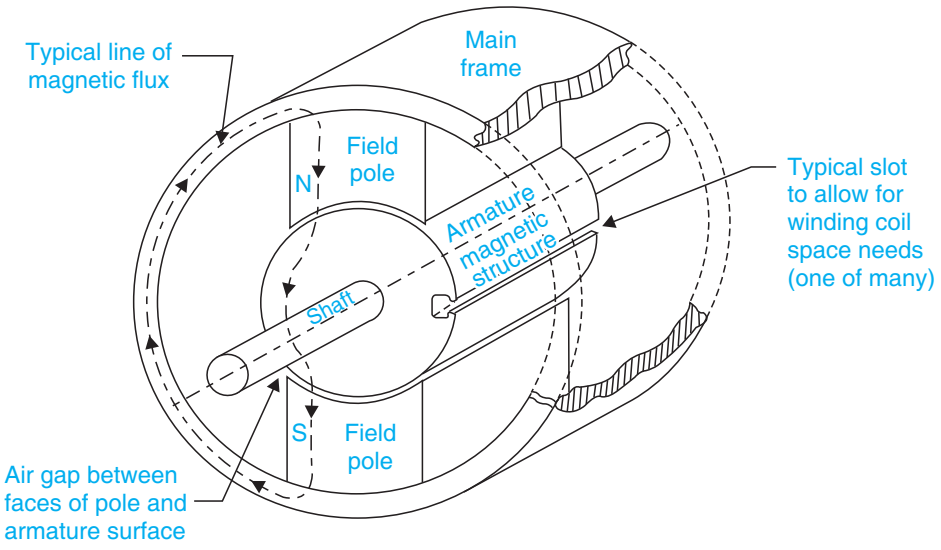


Fig. 12.5. Generator or motor magnetic structure.

Description of Parts of D.C. Machines :

Frame :

Fig. 12.6 shows the sectional view of four pole D.C. machine.

— *The frame is the stationary part of a machine to which are fixed the main and commutating poles and by means of which the machine is bolted to its bed plate.*

— *The ring-shaped portion which serves as the path for the main and commutating pole fluxes is called the 'yoke'.*

— *Cast iron* used to be the material for the frame/ yoke in *early machines* but now it has been *replaced by cast steel*. This is because cast iron is saturated by a flux density of about 0.8 Wb/m^2 while saturation with cast steel is at about 1.5 Wb/m^2. Thus the cross-section of a cast iron frame is about twice that of a cast steel frame for the same value of magnetic flux. Hence, if it is necessary to reduce the weight of machine, cast steel is used. Another disadvantage with the use of cast iron is that its mechanical and magnetic properties are uncertain due to the presence of blow holes in the casting. Lately, rolled steel yokes have been developed with the improvements in the welding techniques. The *advantages of fabricated yokes are that there are no pattern charges and the magnetic and mechanical properties of the form are absolutely consistent.*

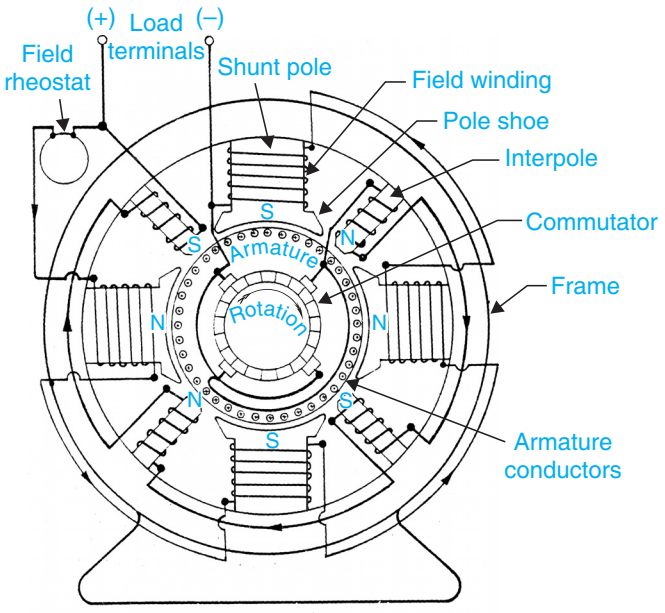


Fig. 12.6. Sectional view of a four pole D.C. machine.

It may be advantageous to use cast iron for small frames but for medium and large sizes usually rolled steel is used.

— If the armature diameter does not exceed 35 to 45 cm, then, in addition to the poles, end shields or frame-heads which carry the bearings are also attached to the frame. When the armature diameter exceeds 1 m, it is common practice to use pedestal-type bearings, mounted separately, on the machine bed plated outside the frame.

— The end shield bearings, and sometimes the pedestal bearings, are of ball or roller type. However, more frequently plain pedestal bearings are used.

— In machines with large diameter armatures a brush-holder yoke is frequently fixed to the frame.

Field poles :

— Formerly the poles were cast integral with the yoke. This practice is still being followed for small machines. But in present day machines *it is usual to use either a completely laminated pole, or solid steel poles with laminated pole shoe.*

— Laminated construction is necessary because of the pulsations of field strength that result when the notched armature rotor magnetic structure passes the pole shoe. Variations in field strength result in internal eddy currents being generated in a magnetic structure. These eddy currents cause losses ; they may be largely prevented by having laminated magnetic structures. Laminated structures allow magnetic flux to pass along the length of the laminations, but do not allow electric eddy currents to pass across the structure from one lamination to another. The assembled stack of laminations is held together as a unit by appropriately placed rivets. *The outer end of the laminated pole is curved to fit very closely into the inner surface of the main frame.*

— Fig. 12.7 shows the constructional details of a field pole. *The pole shoe acts as a support to the field coils and spreads out the flux in the air gap and also being of larger cross-section reduces the reluctance of the magnetic path.*

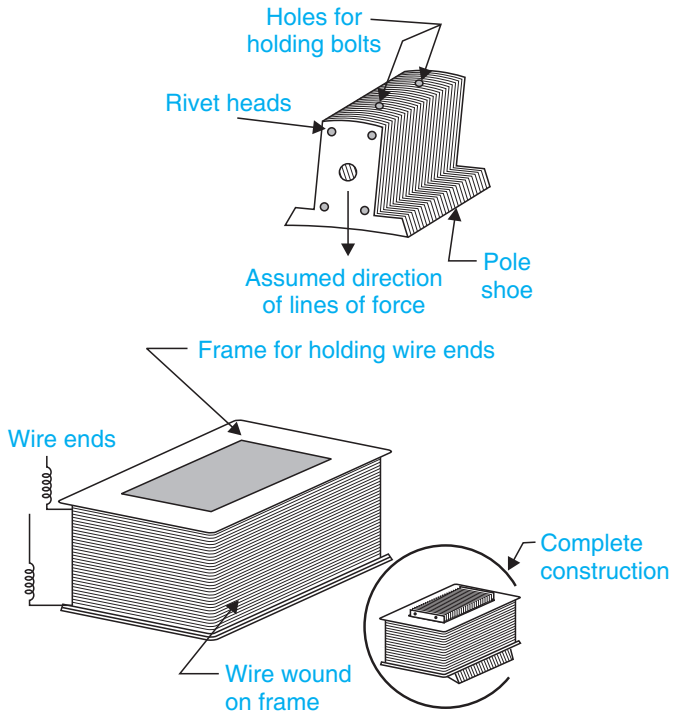


Fig. 12.7. Constructional details of a field pole.

— Different methods are used for attaching poles to the yoke. In case of *smaller sizes*, the back of the pole is drilled and tapped to receive pole bolts (*see* Fig. 12.8). In *larger sizes*, a circular or a rectangular pole bar is fitted to the pole. This pole bar is drilled and tapped and the pole bolts passing through laminations screw into the tapped bar (*see* Fig. 12.9).

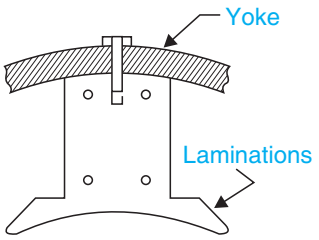


Fig. 12.8. Fixing pole to the yoke.

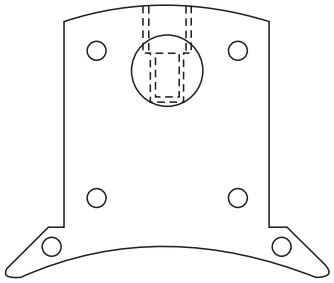


Fig. 12.9

Commutating poles :

— A commutating pole (also called *interpole*) is similar to a main pole and consists of core terminating in a pole shoe, which may have various shapes, and coil mounted on the core.

— The commutating poles *are arranged strictly midway between the main poles* and are bolted to the yoke.

— *Commutating poles are usually made of solid steel, but for machines operating on sharply varying loads they are made of sheet steel.*

Armature :

— The armature consists of core and winding. *Iron being the magnetic material is used for armature core.* However, iron is also a good conductor of electricity. The rotation of solid iron core in the magnetic field results in eddy currents. The flow of eddy currents in the core leads to wastage of energy and creates the problem of heat dissipation. *To reduce the eddy currents the core is made of thin laminations.*

— *The armature of D.C. machines (see Fig. 12.10) is built up of thin lamination of low loss silicon steel.* The laminations are usually 0.4 to 0.5 mm thick and are insulated with varnish.

— The armature laminations, in *small machines*, are fitted directly on to the shaft and are clamped tightly between the flanges which also act as supports for the armature winding. One end of flange rests against a shoulder on the shaft, the laminations are fitted and other end is pressed on the shaft and retained by a key.

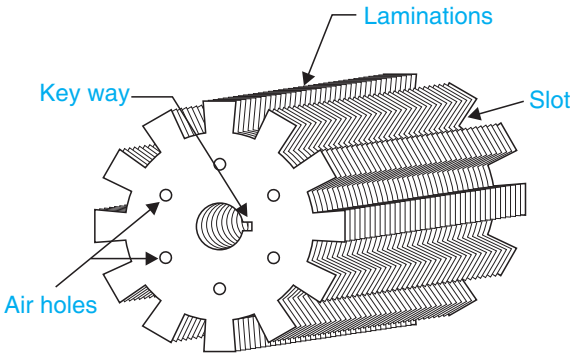


Fig. 12.10. Armature of a D.C. machine.

The core (except in small size) is divided into number of packets by radial ventilation spacers. The spacers are usually I sections welded to thick steel laminations and arranged to pass centrally down each tooth.

— For small machines the laminations are punched in one piece (*see* Fig. 12.11). These laminations are built up directly on the shaft. With such an arrangement, it is necessary to provide *axial ventilation holes* so that air can pass into ventilating ducts.

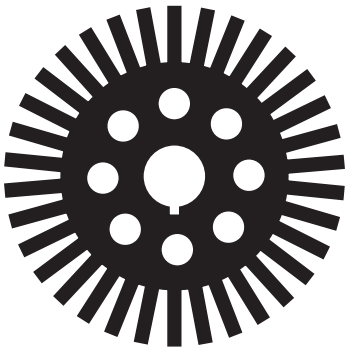


Fig. 12.11. Drum armature stamping with axial flow ventilation system.

— The armature laminations of medium size machines (having more than four poles) are built on a spider. The spider may be fabricated. Laminations up to a diameter of about 100 cm are punched in one piece and are directly keyed on the spider (*see* Fig. 12.12).

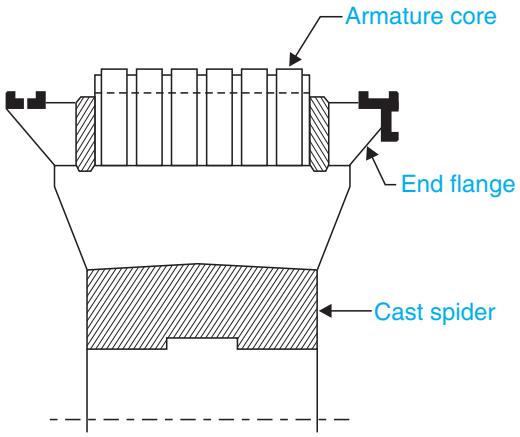


Fig. 12.12. Clamping of an armature core.

— In case of large machines, the laminations of such thin sections are difficult to handle because they tend to distort and become wavy when assembled together. Hence circular laminations instead of being cut in one piece are cut in a number of suitable sections or *segments* which form part of a complete ring (*see* Fig. 12.13). A complete circular lamination is made up of four or six or even eight segmental laminations. Usually two keyways are notched in each segment and are dove-tailed or wedge shaped to make the laminations self-locking in position.

— The armature winding is housed in slots on the surface of the armature. The conductors of each coil are so spaced that when one side of the coil is under a north pole, the opposite is under a south pole.

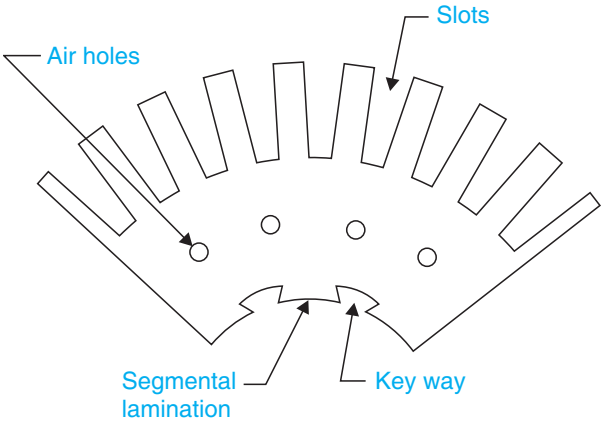


Fig. 12.13. Segmental stampings.

Fig. 12.14 shows the arrangement of conductors and insulation in a slot.

— *In D.C. machines two layer winding with diamond shaped coils is used.* The coils are usually former wound. In *small machines*, the coils are held in position by band of steel wire, wound under tension along the core length. In *large machines*, it is useful to employ wedges of fibre or wood to hold coils in place in the slots. Wire bands are employed for holding the overhang. The *equilizer connections* are located under the overhang on the side of the commutator. Fig. 12.15 shows a typical arrangement for equilizers. The equilizers can be accommodated on the other end of the armature also.

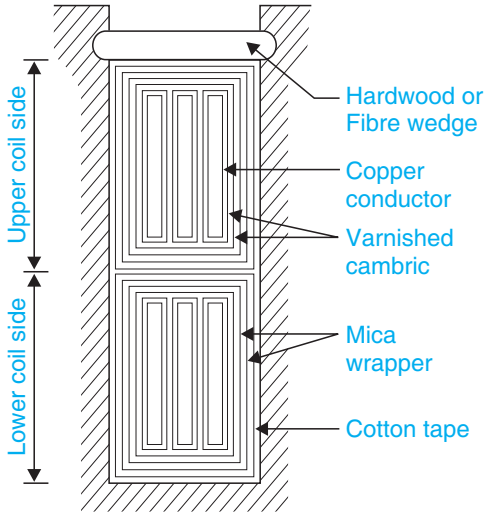


Fig. 12.14. Cross-section of an armature slot.

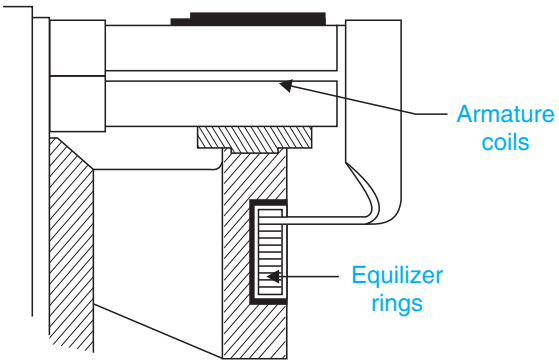


Fig. 12.15. Ring type equilizers.

Commutator :

— A commutator converts alternating voltage to a direct voltage.

— A commutator is a cylindrical structure built up of segments made of hard drawn copper. These segments are separated from one another and from the frame of the machine by *mica strips*.

The segments are connected to the winding through risers. The risers have air spaces between one another so that air is drawn across the commutator thereby keeping the commutator cool.

Fig. 12.16 shows the components of a commutator. The general appearance of a commutator when completed is as shown in Fig. 12.17 (*a*). The commutator and armature assembly is shown in Fig. 12.17 (*b*).

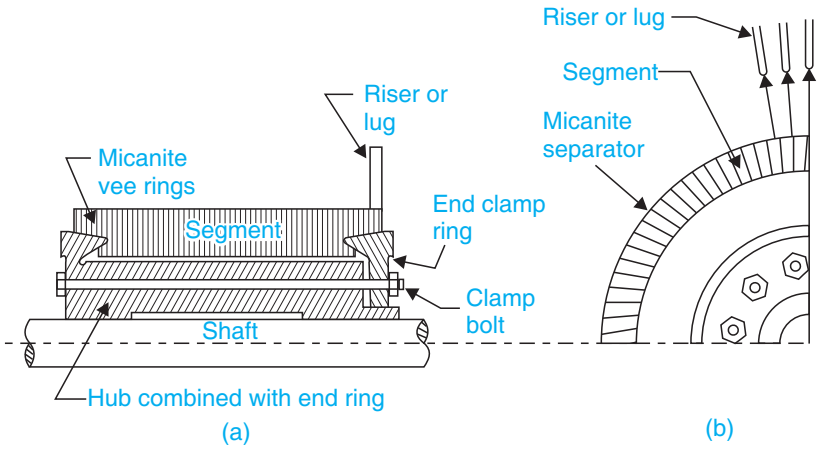


Fig. 12.16. Commutator components.

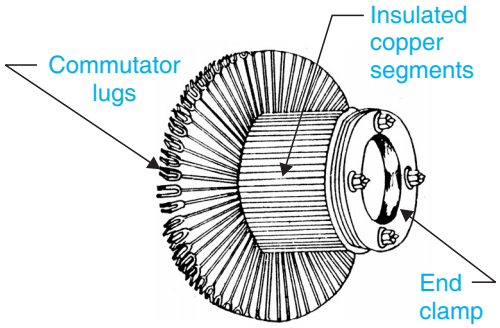


Fig. 12.17. (*a*) General appearance of a commutator after assembly.

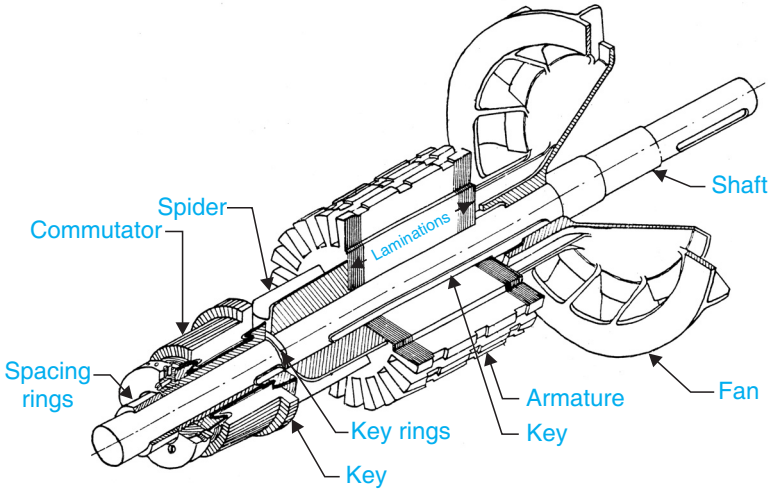


Fig. 12.17. (*b*) Commutator and armature assembly.

Brush gear. To collect current from a rotating commutator or to feed current to it use is made of *brush-gear* which consists of :

(*i*) Brushes (*ii*) Brush holders

(*iii*) Brush studs or brush-holder arms

(*iv*) Brush rocker

(*v*) Current-collecting bus bars.

Brushes. The brushes used for D.C. machines are divided into five classes :

(*i*) Metal graphite (*ii*) Carbon graphite

(*iii*) Graphite (*iv*) Electro-graphite

(*v*) Copper.

— The allowable *current density* at the brush contact varies from 5 A/cm^2 in case of carbon to 23 A/cm^2 in case of copper.

— The use of *copper brushes* is made for machines designed for *large currents at low voltages*. Unless very carefully lubricated, they cut the commutator very quickly and in any case, the wear is rapid. *Graphite and carbon graphite brushes are self lubricating and, are, therefore widely used.* Even with the softest brushes, however, there is a gradual wearing away of the commutator, and if mica between the commutator segments does not wear down so rapidly as the segments do, the high mica will cause the brushes to make poor contact with segments, and sparking will result and consequent damage to commutator. So to prevent this, the mica is frequently '*undercut*' to a level below the commutator surface by means of a narrow milling cutter.

Brush holders. *Box type brush holders* are used in all ordinary D.C. machines. A box type brush holder is shown in Fig. 12.18. At the outer end of the arm, a brush box, open at top and bottom is attached. The brush is pressed on to the commutator by a *clock spring*. The *pressure can be adjusted by a lever arrangement provided with the spring.* The brush is connected to a flexible conductor called *pig tail.* The flexible conductor may be attached to the brush by a screw or may be soldered.

— The brush boxes are usually made of *bronze casting* or *sheet brass.* In low voltage D.C. machines where the commutation conditions are easy galvanised steel box may be used.

— Some manufacturers use individual brush holders while others use multiple holders, *i.e.*, a number of single boxes built up into one long assembly.

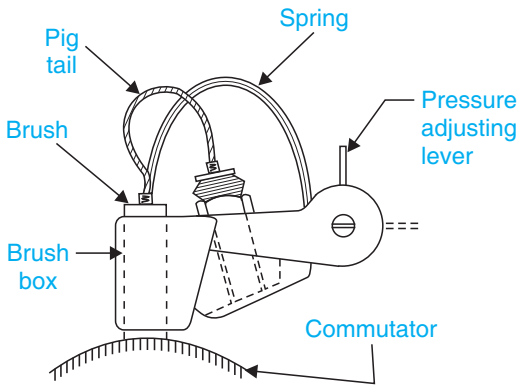


Fig. 12.18. Box type brush holder.

Brush rockers. Brush holders are fixed to brush rockers with bolts. The brush rocker is arranged concentrically round the commutator. *Cast iron is usually, used for brush rockers.*

Armature shaft bearings :

— *With small machines roller bearings are used at both ends.*

— For *larger machines roller bearings are used for driving end and ball bearings are used for non-driving* (commutator) *end.*

— The bearings are housed in the end shields.

— For large machines pedestal bearings are used.

Armature windings

The *armature winding* is very important element of a machine, as it directly takes part in the conversion of energy from one form into another. The requirements which a winding must meet are diverse and often of a conflicting nature. Among these requirements the following are of major importance.

— The winding must be designed with the *most advantageous utilisation of the material in respect to weight and efficiency.*

— The winding should *provide the necessary mechanical, thermal and electrical strength of the machine* to ensure the usual service life of 16–20 years.

— For D.C. machines proper current collection at the commutator (*i.e.* absence of detrimental sparking) must be ensured.

12.2.2.4. Characteristics of D.C. generators

The properties of generators are analysed with the aid of characteristics which give the relations between fundamental quantities determining the operation of a generator. These include the voltage across the generator terminals V, the field or exciting current I_f, the armature current I_a, and the speed of rotation N.

The three most important characteristics of D.C. generators are given below :

1. No load saturation characteristics $\left(\frac{E_0}{I_f}\right)$.

2. Internal or total characteristics $\left(\frac{E}{I_a}\right)$.

3. External characteristics $\left(\frac{V}{I}\right)$.

1. **No load saturation characteristic** $\left(\frac{\mathbf{E_0}}{\mathbf{I_f}}\right)$. It is also a known as magnetic or open circuit characteristic (O.C.C.). It shows the relationship between the no-load generated e.m.f. in armature, E_0 and field or exciting current I_f at a given fixed speed. The shaped of the curve is practically the same for all types of generators whether they are separately excited or self-excited. It is just the magnetisation curve for the material of the electromagnets.

2. **Internal or total characteristic** $\left(\frac{\mathbf{E}}{\mathbf{I_a}}\right)$. It gives the relationship between the *e.m.f. E actually induced* in the armature after allowing for the demagnetising effect of armature reaction and the *armature current* I_a. This characteristic is of interest mainly to the *designer*.

3. **External characteristic** $\left(\frac{\mathbf{V}}{\mathbf{I}}\right)$:

— This characteristic is also referred to as *performance characteristic* or sometimes *voltage-regulating curve*.

— It gives relation between the *terminal voltage V* and *load current I*.

— The curve lies below the internal characteristics because it takes into account the voltage drop over the armature circuit resistance. The *values of V are obtained by substracting* I_aR_a *from corresponding values of E.*

— This characteristic is of great importance in judging the *suitability of a generator for a particular purpose.*

The external characteristic can be obtained by the following two ways :

(*i*) By making simultaneous measurements with a suitable voltmeter and an ammeter on a loaded generator.

(*ii*) Graphically from the O.C.C. provided the armature and field resistances are known and also if the demagnetising effect of the armature reaction is known.

Separately excited generator :

— Fig. 12.19 shows the connections of a separately excited generator, a battery being indicated as the source of exciting current, although any other constant voltage source could be used.

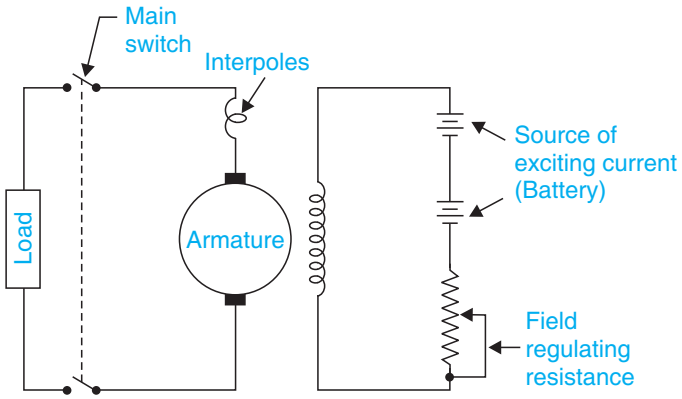


Fig. 12.19. Connection for a separately excited generator.

The field circuit is provided with a variable resistance and would normally contain a field switch and an ammeter, these being omitted from the diagram for simplicity. The armature is connected through 2-pole main switch to the bus bars, between which the load is connected.

(*a*) **No load saturation characteristic (or O.C.C.)**

— If the generator is run at constant speed with the main switch open, and the terminal voltage is noted at various values of exciting or field current then the O.C.C. shown in Fig. 12.20 can be plotted. This is also referred to as the '*magnetisation curve*' since the same graph shows, to a suitably chosen scale, the amount of magnetic flux, there being a constant relationship (depending upon speed of rotation) between flux and induced voltage.

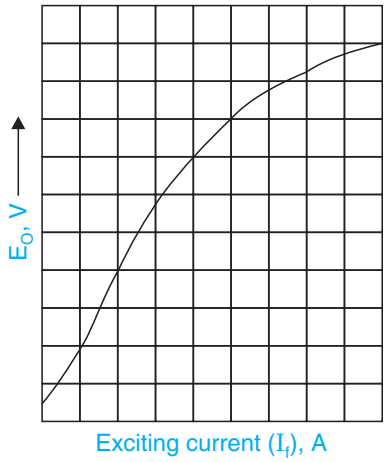


Fig. 12.20. Open-circuit characteristic of a separately excited generator.

— It will be noticed that a small voltage is produced when the field current is zero, this being due to a small amount of permanent magnetism in the field poles. This is called *residual magnetism* and is usually sufficient to produce 2 or 3 per cent of normal terminal voltage, although in some special cases it is purposely increased to 10 per cent or more.

— The *first part of the curve is approximately straight* and *shows that the flux produced is proportional to the exciting current ; but after a certain point, saturation of the iron becomes perceptible as the curve departs from straight line form.*

(*a*) Internal and external characteristics (or load characteristics)

— Load characteristics for a separately excited generator are shown in Fig. 12.21. The most important is the '*external characteristic*' (or total characteristic), which indicates the way in which the terminal voltage (V) varies as the load current is increased from zero to its full load value, the speed of rotation and exciting current being constant.

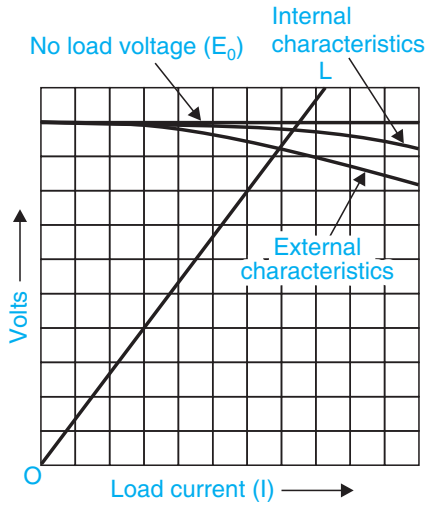


Fig. 12.21. Load characteristics of a separately excited generator.

The voltage drop (drop of volts) at any particular load current, *indicated by the vertical distance between the external characteristic and the no-load voltage* is brought about by two causes :

(*i*) *Armature reaction which has a demagnetising effect upon the field.*

(*ii*) *Resistance drop,* this being the product of the armature current and the total armature-circuit resistance, consisting of the armature resistance, interpole resistance and brush contact resistance.

— The '*internal characteristic*' is obtained by *calculating the resistance drop for a few values of current and adding this to the voltage shown by the external characteristics. The vertical distance between the internal characteristic and no load voltage then represents the effect of armature reaction alone.*

— When the resistance of load is R, then voltage across its terminals is $V = IR$, where I represents the current, so that if the value of V corresponding to various values of I are calculated, the values will all lie upon a straight line such as OL in Fig. 12.21. *The load current and terminal voltage corresponding to this resistance are given by the inter-section of the line OL with the external characteristics.*

Note. The great *advantage of separate excitation* over all other forms of excitation is that the *current is entirely independent of the load current in the armature*. It is, however, rather inconvenient to have to depend upon a separate source of supply and, therefore, the *method is used only in special cases, where the generator has to operate over a wide range of terminal voltage.*

Building up the voltage of self-excited shunt generator :

One of the simplest forms of 'self-excited' generator is the shunt-wound machine, the connection diagram (without load) of which is shown in Fig. 12.22. The manner in which a self-excited generator manages to excite its own field and build a D.C. voltage across its armature is described with reference to Fig. 12.23 in the following steps :

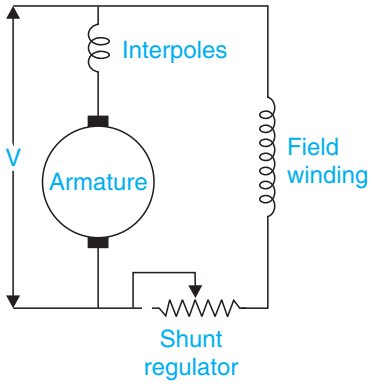


Fig. 12.22. Self-excited shunt generator.

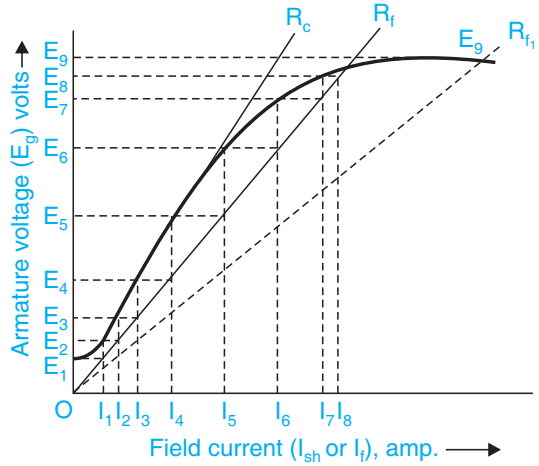


Fig. 12.23. Building up the voltage of a shunt generator.

— Assume that the generator starts from rest, *i.e.*, prime-mover speed is zero. Despite a residual magnetism, the generated e.m.f. E, is zero.

— As the prime mover rotates the generator armature and the speed approaches rate speed, the voltage due to residual magnetism and speed increases.

— At rated speed, the voltage across the armature due to residual magnetism is small, E_1, as shown in the figure. But this voltage is also across the field circuit whose resistance is R_f. Thus, the current which flows in the field circuit I_1, is also small.

— When I_1 flows in the field circuit of the generator of Fig. 12.22, an increases in m.m.f. results (due to $I_f T_f$, T_f being field turns, which aids the residual magnetism in increasing the induced voltage to E_2 as shown in Fig. 12.23.

— Voltage E_2 is now impressed across the field, causing a large current I_2 to flow in the field circuit. $I_2 T_f$ is an increased m.m.f., which produces generated voltage E_3.

— E_3 yields I_3 in the field circuit, producing E_4. But E_4 causes I_4 to flow in the field producing E_5 ; and so on, up to E_8, the maximum value.

— The *process continues until that point where the field resistance line crosses the magnetisation curve* in Fig. 12.23. Here the process stops. The induced voltage produced, when impressed across the field circuit, produces a current flow that in turn produces an induced voltage of the same magnitude, E_8, as shown in the figure.

Critical resistance :

— In the above description a particular value of field resistance R_f was used for building up of self-excited shunt generator. If the field resistance were reduced by means of adjusting the field reheostat of Fig. 12.22 to a lower value say R_{f_1}, shown in Fig. 12.23, the build-up process would take place along field resistance line R_{f_1}, and build-up a somewhat higher value than E_8, *i.e.,* the point where R_{f_1} intersects the magnetisation curve, E_9. Since the curve is extremely saturated in the vicinity of E_9, reducing the field resistance (to its limiting field winding resistance) will not increase the voltage appreciably. Conversely, increasing the field rheostat resistance and the field circuit resistance (to a value having a higher slope than R_f in the figure) will cause a reduction of the maximum value to which build-up can possibly occur.

— The field resistance may be increased until the field circuit reaches a *critical field resistance. Field circuit resistance above the critical field resistance will fail to produce build-up.* The critical field circuit resistance, R_c, is shown as tangent to the saturation curve passing through the origin, O, of the axes of the curve of Fig. 3.5. Thus a field circuit resistance higher than R_c will produce an armature voltage of E_1 approximately (and no more).

Reasons for Failure of Self-Excited Shunt Generator to Build-up Voltage :

The reasons why a self-excited generator may fail to build-up voltage are given below :

1. **No residual magnetism.** The start of the build-up process requires some residual magnetism in the magnetic circuit of the generator. If there is little or no residual magnetism, because of inactivity or jarring in shipment, no voltage will be generated that can produce field current. To overcome this difficulty, a separate source of direct current is applied to the field for a short period of time and then removed. The magnetic field should now be sufficient to allow the voltage to build-up. *The application of a separate source of direct current to the field is called 'flashing the field'.*

2. **Field connection reversed.** The voltage generated due to residual magnetism is applied to the field. Current should flow in the field coils in such a direction as to produce lines of flux in the same direction as the residual flux. If the field connections are reversed, the *lines of flux produced by the current flow will oppose the residual flux* so that the generated voltage will *decrease* rather than increase when the field circuit is closed. In this instance it is necessary to *reverse the field connections with respect to the armature.*

3. **Field circuit resistance too high.** A field circuit resistance greater than critical value will prevent an

appreciable build-up. At no load, resistance greater than the critical may be caused by the following :

— **Open field circuit connection.** The effects of an open circuit are apparent. The field circuit resistance is *much greater than the critical value*; hence *generator will not build-up.*

— **Dirty commutator.** A dirty commutator does not permit good contact between the brushes and the commutator. This poor contact shows up as a high resistance to the flow of current in the field circuit and produces the same effect as a high field circuit resistance.

Shunt generator characteristics :

In a shunt generator the field circuit is connected directly across the armature. Appliances, motors, light bulbs, and other electrical devices connected in *parallel* across the generator terminals represent a *load* on the generator. As more devices are connected in parallel, the load on the generator increases; that is, the generator current increases. Because the generator current increases, the terminal voltage of the generator decreases. There are three factors that cause this decrease in voltage :

(*i*) Armature-circuit resistance (R_a)

(*ii*) Armature reaction

(*iii*) Reduction in field current.

(*i*) **Armature-circuit resistance.** The armature circuit of a generator, like every electrical circuit, contains resistance. This resistance includes the resistance of : (*i*) *the copper conductors of the armature winding, (ii) the commutator, (iii) contact resistance between brushes and commutator*, and *(iv) the brushes themselves.* When no current flows through the armature, there is no *IR* drop in the armature and the voltage at the terminals is the same as the generated voltage. However, when there is current in the armature circuit, a voltage drop exists due to the armature resistance, and the terminal voltage is less than the generated voltage. The terminal voltage may be calculated from the following reaction :

$$V = E_g - I_a R_a$$

where V = voltage at terminals of generator

E_g = generated or induced voltage

I_a = total armature current

R_a = armature-circuit resistance.

(*ii*) **Armature reaction.** When current flows in the armature conductors a flux surrounds these conductors. The direction of this armature flux is such that it reduces the flux from the field poles, resulting in both a reduced generated voltage and terminal voltage.

(*iii*) **Reduction in the field current.** The field circuit is connected across the terminals of the generators. When the terminal voltage of the generator becomes smaller because of the armature-resistance volt drop and armature reaction, the voltage across the field circuit also becomes smaller and therefore field current will be less. A reduction in the magnitude of field current also reduces the flux from the field poles, which in turn reduces the generated voltage and also the terminal voltage.

External characteristic :

— See Figs. 12.24 and 12.25. The effect of the preceding three factors is shown in Fig. 12.25, which shows external (load-voltage) characteristic of a shunt generator.

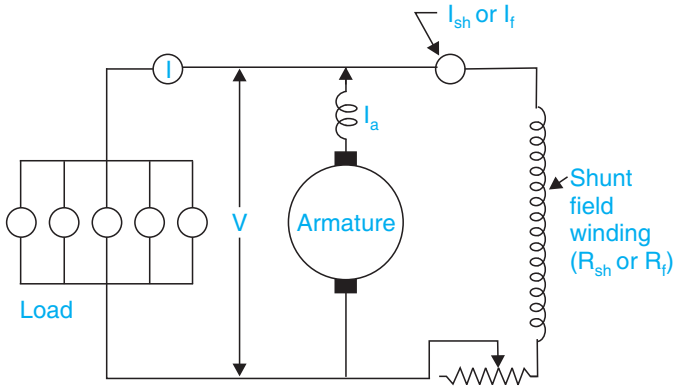


Fig. 12.24. Shunt generator under load.

— As shown in the circuit of Fig. 12.24, the readings of the voltage across the armature (and load), V are plotted as a function of load current, I. The voltage, V, is the same as E_g at no-load (neglecting the $I_a R_a$ and armature reaction drop produced by the field current). The effects of armature reaction, armature circuit voltage drop, and decrease in field current are all shown with progressive increase in load. Note that both the armature reaction and the $I_a R_a$ drop are shown as dashed straight lines, representing theoretically linear voltage directly proportional to the increase in load current. The drop owing to decreased field current is a curved line, since it depends on the degree of saturation existing in the field at the value of load.

— Generally, the external load-voltage characteristic decreases with application of load only to a *small extent up to its rated load* (current) *value*. Thus, the shunt generator is considered as having a fairly constant output voltage with application of load, and in practice, is *rarely operated beyond the rated load current value continuously for any appreciable time.*

— As shown in Fig. 12.25 *further application of load causes the generator to reach a breakdown point beyond which further load causes it to 'unbuild' as it operates on the unsaturated portion of its magnetisation curve. This unbuilding process continues until the terminal*

voltage is zero, at which point the load current is of such magnitude that the internal armature circuit voltage drop equals the e.m.f. generated on the unsaturated or linear portion of its magnetisation curve.

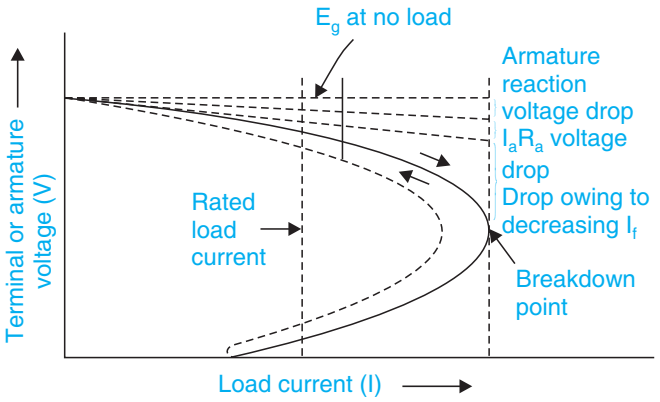


Fig. 12.25. Shunt generator load characteristics.

— It may be noted that if the *external load is decreased* (an increase of external load resistances), the *generator will tend to build up gradually along the dashed line* shown in Fig. 12.25.

Voltage regulation. The term '*voltage regulation*' is used to indicate the degree of change in armature voltage produced by application of load. If there is little change from no-load to full load, the generator or voltage-supplying device is said to possess good voltage regulation. If the *voltage changes appreciably with load, it is considered to have poor voltage regulation.*

'*Voltage regulation*' is defined as the *change in voltage from no-load to full load, expressed as a percentage of the rated terminal voltage* (armature voltage at full load).

i.e., per cent voltage regulation $= \dfrac{V_{nl} - V_{fl}}{v_{fl}} \times 100$ ...(12.1)

where V_{nl} = No load terminal voltage

V_{fl} = Full load (rated) terminal voltage.

Internal or total characteristic. To determine internal characteristic from external characteristic the following procedure is adopted [*see* Fig. 12.26 (*a*)].

Steps. 1. From the given data, draw the external characteristic (*I*).

2. Draw the shunt field resistance line *OL* and armature resistance line *OM*.

3. On the external characteristic take any point say *F*.

4. From point *F* draw vertical and horizontal lines intersecting *X* and *Y*-axes respectively. Let these lines be *FC* and *FA* respectively.

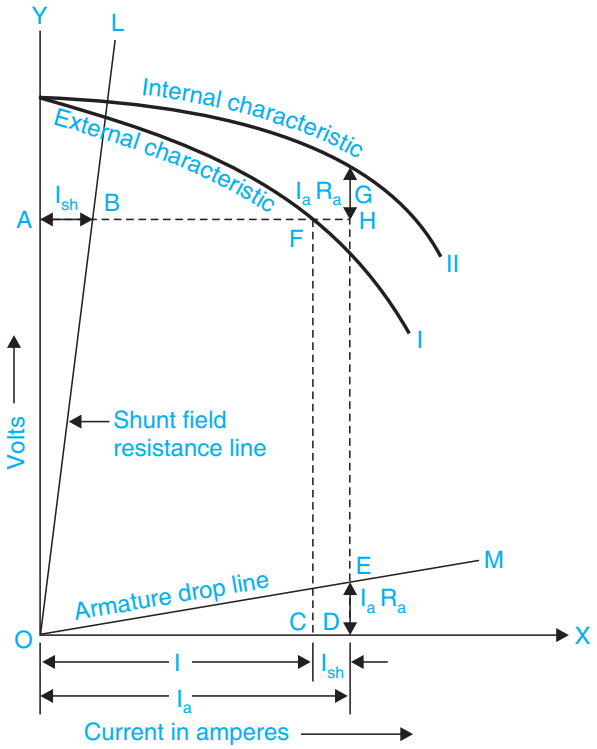


Fig. 12.26. (*a*) Determination of internal characteristic from external characteristic.

5. Take point *D* on *X*-axis so that *CD* = *AB* representing the shunt field current, I_{sh}.

6. From point *D* draw vertical *DE* and produce it intersecting line *AF* produced at *H*.

7. Take point *G* on line *DH* produced so that *HG* = *DE* (= I_aR_a) representing the armature drop.

8. Following the above procedure take a number of points on external characteristic and find corresponding points lying on internal characteristic.

9. Draw a curve passing through these points which is the required internal characteristic (*II*).

External characteristic and no-load saturation curve. The external characteristic of a shunt generator can be obtained directly from its no-load saturation curve as explained below. Following two cases will be considered:

(A) When armature reaction is so small as to be *negligible.* This is *more or less true for generators fitted with compoles.*

(B) When armature reaction is *not negligible.*

(A) Armature reaction negligible :

Steps. 1. From given data draw O.C.C. [*see* Fig. 12.26 (*b*)].

2. Draw shunt field resistance line (say *OS*) meeting O.C.C. at any point (say *A*).

3. From point *A* draw horizontal line intersecting *Y*-axis, say at point *B*.

Hence, *OB* is the maximum no-load or open circuit voltage.

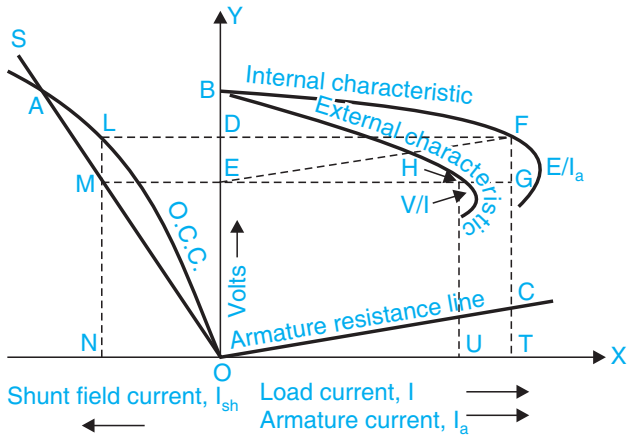


Fig. 12.26. (*b*) Determination of external and internal characteristic from O.C.C.

4. Take any point (say *L*) on the O.C.C. and draw an ordinate, say, *LMN* intersecting field resistance line at *M* and *X*-axis at *N*. Now *LN represents the generated e.m.f., MN represents the terminal voltage and LM represents voltage drop in armature.*

5. From points *L* and *M* draw horizontal lines cutting vertical axis say at point *D* and *E* respectively.

6. Draw armature resistance line *OC*.

7. From point *E*, draw line *EF* parallel to line *OC* cutting line *LD* produced at *F*. Hence, *F* is lying on the internal characteristic.

Similarly other points can be obtained and internal characteristic may be drawn through these points.

8. From point *F* draw vertical line intersecting produced line *ME* at any point *G* and *X*-axis say, at point *T*. Since *FG* = *LM* = *CT*, hence point *G* lies on the *curve representing relation between armature current and terminal voltage.*

9. Take *TU* = shunt field current (I_{sh}) *ON* (scale being different). *OU* represents the load current corresponding to armature current represented by *OT* and terminal voltage *OE*.

10. From point *U* draw a vertical line intersecting line *EG* at *H*. Point *H lies on the external characteristic.*

Similarly other points may be obtained and curve may be drawn, which is the required *external characteristic*.

(B) Taking armature reaction into account :

Here, in addition to considering the voltage drop in armature, voltage drop due to armature reaction is also taken into account.

Let I_aR_a = Voltage drop in armature, and
I_{sh} = Increase in shunt field current to counteract the demagnetising effect.

Now if a right-angled triangle say *lmn* is drawn as that *ln* = voltage drop in armature, and *mn* = shunt field current. The triangle *lmn* is called as the *drop reaction triangle.*

In order to draw external and internal characteristic repeat the process as in *A* with following modifications in steps 4 and 9 respectively.

4. Take any point *L* on the O.C.C. and draw line *LM* parallel to the line *lm* of triangle *lmn* and complete the triangle *LMN*. Now from the points *L* and *M* draw vertical lines cutting *X*-axis at points *N′* and *M′*. Now *LN′ represents the generated e.m.f. MM′* represents the terminal voltage, *LN represents the voltage drop in armature due to armature resistance ON′ is the shunt field current to induce an e.m.f. represented by LN′* and *N′M′* is the *increase in shunt field current to counteract the demagnetising effect.*

5. Take *TU* = shunt field current *ON′* (scale being different). *OU* represents the load current corresponding to the armature current represented by *OT* and terminal voltage *MM′*.

Voltage control of shunt generators :

— The terminal voltage of a shunt generator may be kept constant at all loads with the use of adjustable resistance, called a *field rheostat, connected in series with the shunt-field circuit.* By adjusting the resistance of the rheostat to suit the load on the machine, changes in terminal voltage with load may be prevented. When the load changes gradually, hand control of the rheostat may be used, although *automatic control* employing a *voltage regulator* is far more satisfactory.

— The terminal voltage may also be controlled *automatically* by the addition of a series-field winding. This method has the advantage of being *automatic, cheap* and *generally satisfactory*.

Series Generator :

The field winding of a series generator is connected in series with the armature winding as shown in Fig. 12.27. It consists of a *few series of heavy wire, capable of carrying the output current of the machine without overheating.* The characteristic curves of a D.C. series generator are drawn as given below :

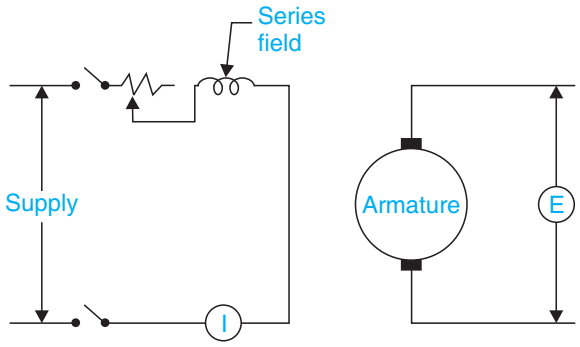


Fig. 12.27. Connection diagram for obtaining the saturation curve of a series generator.

— The *saturation* curve (1) may be obtained in a manner exactly similar to that already described for the shunt machine. The series-connected generator is illustrated in Fig. 12.27. The series connected generator illustrated in Fig. 12.28 must be capable of safely carrying the maximum current to be used, or about 125 per cent of rated load current. A plot of simultaneous readings of generated voltage and field current, taken at a rated speed, yields the magnetisation curve 1 of Fig. 12.29.

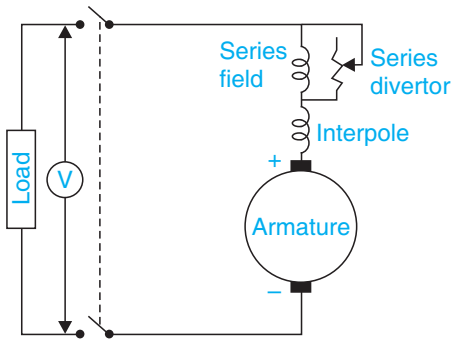


Fig. 12.28. Circuit for loading a series generator.

— **External characteristic (curve 2).** To obtain the data for this curve, the machine is connected to the load as shown in Fig. 12.28, ammeter and voltmeter being inserted to read the load current $I(= I_a)$ and the terminal voltage V respectively. The machine is run at constant (rated) speed, a series of simultaneous readings of voltage and current is taken while the load is varied from a minimum value to perhaps 125 per cent of rated load. When these readings are plotted, using V as co-ordinates and $I_a(= I)$ as abscissa curve 2 (*see* Fig. 12.29) is obtained.

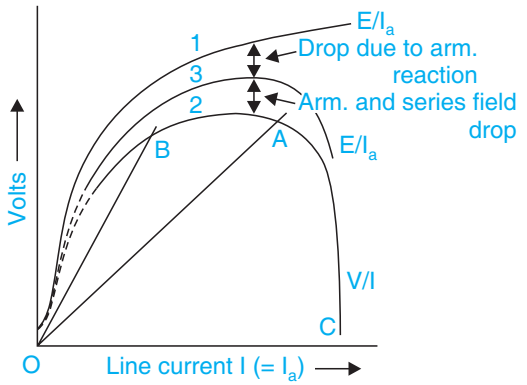


Fig. 12.29. Characteristic curves of a D.C. series generator.

It may be noted that the *readings cannot begin at zero load* as with the shunt generator, for if *the resistance of the circuit including armature, series field and load is increased beyond a certain critical value, the generator unbuilds and loses its load entirely*. Thus, if OA is the resistance line for the circuit the terminal voltage is the ordinate to the curve at A. When the *resistance of the circuit* is gradually *increased,* the *load falls off* along the curve, and A approaches B. When the resistance line finally becomes tangent to the curve, however, *operation becomes unstable,* and any slight further increase in the resistance causes the machine to unbuild its voltage and lose its load. The resistance that brings about this condition is called the critical resistance. Therefore, to *begin with*, the resistance of the circuit must be reduced below the critical value before the generator delivers any load.

— **Internal characteristic (curve 3).** This curve is obtained by adding the resistance drop $I_a(R_a + R_{se})$ to the external characteristic curve ; R_a and R_{se} being armature resistance and series field resistance respectively.

The difference between curves 1 and 3 is the *reduction in voltage caused by armature reaction.*

— It is worth noting that between A and C a considerable change in resistance brings about only a slight change in load current. Over this range the *voltage decreases rapidly*, owing to increasing armature reaction (particularly when the brushes are shifted forward), while the *current remains nearly constant.* Thus, between A and C the machine may be used to supply power to a *constant current variable-voltage circuit, such as series arc circuit.*

— Owing to initially *rising characteristic,* the series generator is often used as a *voltage booster* to give an increase of voltage practically proportional to the current.

— A series generator also finds applications in electric traction where '*dynamic braking*' is employed. The connections of the series traction motors are changed by means of a controller so that they act as generators ; the power absorbed in braking the vehicle being dissipated in resistances, which are also used for starting purposes when the machines are reconnected as motors.

Compound Wound Generator :

In case of a series generator the voltage regulation is very poor but the ability of the series field to produce additional useful magnetisation in response to increased load cannot be denied. This useful characteristic of the series field, combined with the relatively constant voltage characteristic of the shunt generator, led to the compound generator. Fig. 12.30 shows connection diagrams for a compound generator.

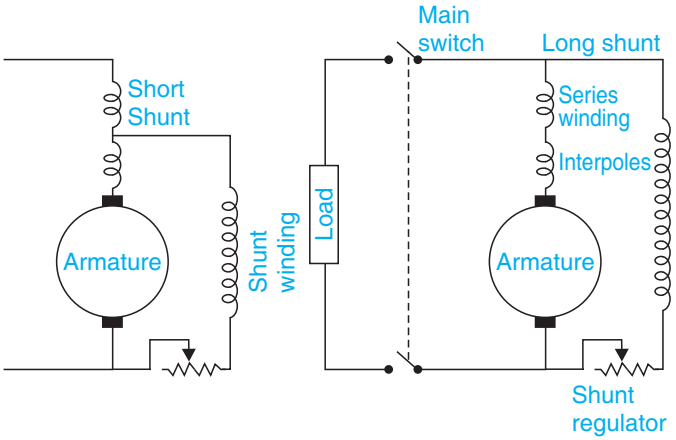


Fig. 12.30. Connection diagrams for a compound generator.

Regardless of the method of connection, the terminal voltage V of the short shunt or long shunt compound generator is same, $V = E_g - (I_{se} \,.\, R_{se} + I_a R_a)$.

The generator voltage, E_g, of a compound generator is the result of the combination of m.m.f.'s produced by the series ($I_{se}T_{se}$) and shunt ($I_{sh}T_{sh}$) ampere-turns due to current which flows in their field windings. In a compound generator, the *shunt field predominates and is much the stronger of the two. When the series field m.m.f. aids the shunt field m.m.f.*, the generator is said to be '*cumulatively compounded*' (*see* Fig. 12.31). When the *series field m.m.f. opposes the shunt field m.m.f.*, the generator is said to be '*differentially compounded*' [*see* Fig. 12.31 (*b*)].

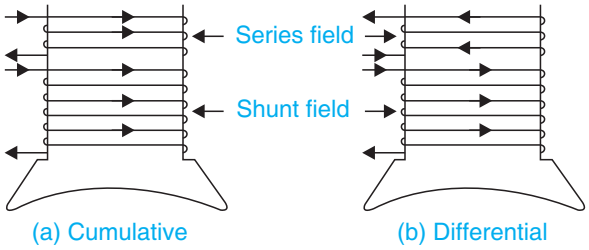


Fig. 12.31. Current directions in series and shunt-field coils of cumulative and differential-compound generator.

Characteristics of Cumulative Compound Generator :

See Fig. 12.32. Depending on the relative additional aiding m.m.f., produced by the series field there are three types of load characteristics possible for the *cumulative* compound generator. These types are called

(*i*) Overcompound (*ii*) Flat-compound
(*iii*) Undercompound.

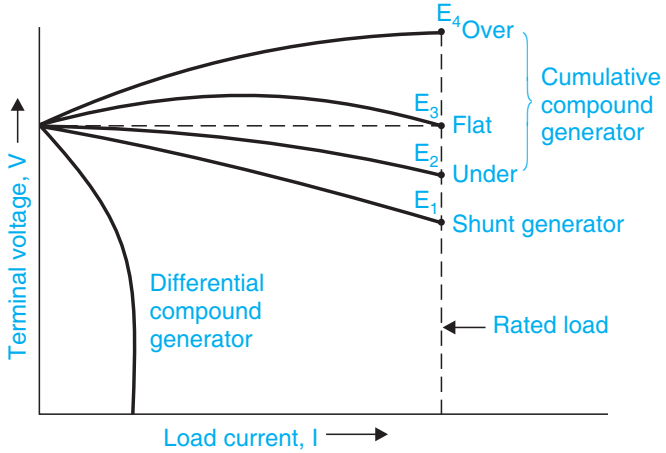


Fig. 12.32. External load voltage characteristics of cumulative and differential compound generators.

Over compound generator. An over compound generator is one whose terminal voltage *rises with the application of load* so that its full-load voltage *exceeds* its no-load voltage (*negative regulation*).

Flat compound generator. A flat compound generator has a load-voltage characteristic in which the no-load and full-load voltages are equal (*zero per cent regulation*).

Undercompound generator. An undercompound generator has a load characteristic in which the full load voltage is somewhat *less* than no-load voltage, but whose aiding series-field ampere-turns cause its characteristic to have *better regulation than an equivalent shunt generator*.

— Most commercial compound D.C. dynamos, whether used as generators or motors, are normally supplied by the manufacturer as *overcompound machines*. The *degree of compounding* (over, flat or under) may be adjusted by means of *diverter* which shunts the series field.

Characteristics of Differential Compound Generator :

— The *differential compound generator is defined as that compounding produced when the series field m.m.f. opposes the shunt field m.m.f.* The difference in current direction of the two windings is shown in Fig. 12.31 (*b*), where for the sake of clarity, the series field winding is shown above (rather than directly around) the shunt field winding.

— Fig. 12.33 shows the load characteristics of differential compound generator.

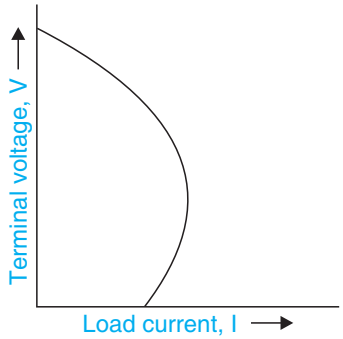


Fig. 12.33. Differential compound generator—load characteristic.

When the differential compound generator is *without load* it builds up and self-excites its shunt field in much the same manner as the shunt generator. However, *when a load is applied, the generated voltage* E_g *is now reduced by the* reduction in the main field flux created by the *opposing m.m.f. of the series field.* This reduction in E_g occurs *in addition to the armature and series circuit voltage drop, the armature reaction, and the reduction in field current produced by reduction of the armature voltage.* The result is a sharp drop in the terminal voltage with load as shown in Fig. 12.33, and as the field is below saturation and rapidly unbuilds.

— *The differential compound generator is used as a constant-current generator for the same constant-current applications as the series generator.*

Applications of D.C. Generators

Separately excited generators :

(*i*) The separately excited generators are usually *more expensive than self-excited generators* as they require *a separate source of supply.* Consequently they are generally used where self-excited are relatively unsatisfactory. These *are used in Ward Leonard systems of speed control, because self-excitation would be unsuitable at lower voltages.*

(*ii*) These generators are also used where quick and requisite response to control is important (since separate excitation gives a quicker and more precise response to the changes in the resistance of the field circuit).

Shunt generators :

(*i*) These generators are used to advantage, in conjunction with automatic regulators, *as exciters for supplying the current required to excite the fields of A.C. generators.* The regulator controls the voltage of the exciter by cutting in and out some of the resistance of the shunt-field rheostat, thereby holding the voltage at whatever value is demanded by operating conditions. This is one of the most important applications of shunt generators.

(*ii*) Shunt generators are used *to charge batteries.* In this application the voltage should drop off slightly as the load increases, because the voltage of a lead battery is lower when battery is discharged than when battery is charged. When it is discharged, however, the battery can stand a large charging current than when it is charged. *Because of its drooping characteristic the shunt generator is admirably suited to battery charging service*, for, in a general way, the voltage curve of the generator has the same shape as the voltage curve of the battery itself. In both cases, as the load falls the voltage rises.

— Shunt generators can be operated in parallel without difficulty, and the wiring of parallel-operated shunt machines is quite a bit simpler than the corresponding wiring for compound machines. When a slight drop in voltage is not objectionable, as when a motor load is fed directly from the generator terminals, shunt machines may be used to advantage.

Series generators. The field of application of series generator is limited. These are used for the following purposes :

(*i*) Series arc lighting.

(*ii*) Series incandescent lighting.

(*iii*) As a series booster for increasing the voltage across the feeder carrying current furnished by some other sources.

(*iv*) Special purposes such as supplying the field current for regenerative braking of D.C. locomotives.

Compound generators. The compound generator is used for more than any other type.

(*i*) It may be built and adjusted automatically to supply an approximately *constant voltage at the point of use,* throughout the entire range of load. This is *very great advantage.* It is possible to provide a constant supply voltage at the end of a long feeder by the simple expedient of *overcompounding* the generator, because the resistance

drop in the line is compensated for by the rising characteristic of the generator.

When the point of utilisation is near the generator, a flat-compounded machine may be used.

(*ii*) *Differentially compounded generator* finds an useful application *as an arc welding generator* where the generator is practically short circuited every time the electrode touches the metal plates to be welded.

(*iii*) Compound generators are used to supply power to :

— Railway circuits,
— Motors of electrified steam rail-roads,
— Industrial motors in many fields of industry,
— Incandescent lamps, and
— Elevator motors etc.

12.2.3. Alternator Current Generators

12.2.3.1. Introduction

— A *machine for generating alternating currents is referred to an alternator.*

— The term 'A.C. generator' is also frequently used, in place of alternator and this is often contracted to just 'generator' when it is obvious that as A.C. machine is meant. In older literature the term 'alternating current dynamo' will also be found, but the present tendency is to reserve the use of the word dynamo for D.C. generators.

— *High-speed* alternators driven by steam turbine differ considerably in their construction from the *slow speed* types and one distinguished by the use of the terms '*turbo-alternator*' whilst the slow engine-driven machines one often described as being of the '*flywheel-type*'.

12.2.3.2. Classification and operating principle

— In D.C. generators, the field poles are stationary and the armature conductors rotate. The *alternating* voltage induced in armature conductors is converted to a *direct* voltage at the brushes by means of the commutator.

— A.C. generators commonly called alternators, have *no commutators* as they are required to supply electrical energy with the *alternating* voltage. Therefore, it is not necessary that armature be the rotating member.

Alternators, according to their construction, are divided into the following two classifications :

1. Revolving armature type
2. Revolving field type.

1. Revolving armature type alternator

— It has stationary *field poles* and *revolving armature*.

— It is usually of relatively small kVA *capacity* and *low voltage rating*. It resembles a D.C. generator in general appearance except that it has *slip rings instead of a commutator*. The field excitation must be direct current, and therefore, must be supplied from an external direct current source.

2. Revolving field type alternator

— It has a *stationary* armature or *stator*, inside of which the *field poles rotate*.

— *Most* alternators are of the *revolving field type*, in which the '*revolving field structure*' or 'rotor' has slip rings and brushes to *supply the excitation current from an outside D.C. source.* The armature coils are placed in slots in a laminated core, called the '*stator*' which is made up of a thin steel punchings or laminations securely clamped and held in place in the steel frame of the generator. Usually the field voltage is between 100 and 250 volts and the amount of *power delivered to the field circuit is relatively small*.

The following are the *advantages* of the revolving field type alternators :

1. The armature windings are more easily braced to prevent deformation under the mechanical stresses due to short-circuit currents and centrifugal forces.

2. The armature (stator) windings must be insulated for a high voltage, while the voltage of field circuit is low (100 to 250 volts). *It is much easier to insulate the high voltage winding when it is mounted on the stationary structure.*

3. Only a small amount of power at low voltage is handled by the slip ring contacts.

4. It is easier to build and properly balance high-speed rotors when they carry the field structure.

5. The armature winding is cooled more readily because the stator core can be made large enough and with many air passages or cooling ducts for forced air circulation.

Operating principle (Revolving-field type). When the rotor rotates, the stator conductors (being stationary) are cut by the magnetic flux, hence they have induced e.m.f. produced in them. Because the magnetic poles are alternately N and S, they induce an e.m.f. and hence current in armature conductors, which first flows in one direction and then in the other. Hence, an alternating e.m.f. is produced in the stator conductors whose frequency depends on the number of N and S poles moving past a conductor in one second and whose direction is given by Fleming's right-hand rule.

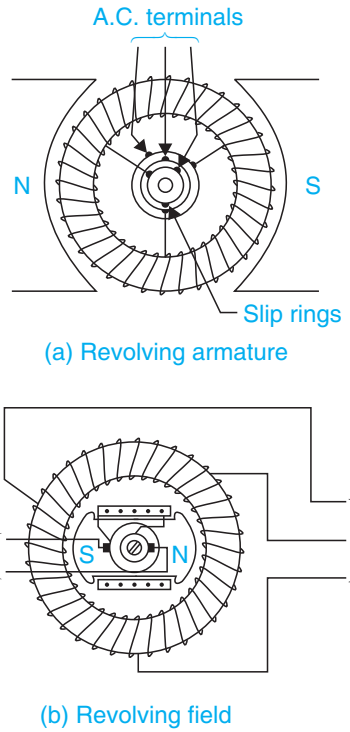


Fig. 12.34. Operating principle of a three-phase alternator.

Fig. 12.34 shows the operating principle of a three-phase alternator.

Note. All synchronous A.C. generators and motors require direct current for excitation. Excitation is supplied by a D.C. generator called an *exciter*. The capacity of the exciter is only a *small percentage* of the rated capacity of the alternator. The exciter may be directly connected to the shaft of the alternator, or it may be driven by a separate electric motor, water wheel, or small turbine. Large power stations usually have several exciters employing different methods of drive as insurance against the failure of excitation.

12.2.3.3. Constructional details

Refer to Fig. 12.7 on page 563.

Stator. The *stator* of an alternator consists essentially of a cast iron or a welded-steel frame supporting a slotted ring made of soft laminated sheet-steel punchings (Fig. 12.36) in the slots of which the armature coils are assembled.

— The *laminations* are analyzed and are insulated from each other by a thin coating of oxide and an enamel (as in D.C. machines, transformers etc.).

— *Open slots* are used, permitting easy installation of stator coils and easy removal in case of repair. Suitable spacing blocks are inserted at intervals between laminations to leave radial *air ducts,* open at both ends, through which cooling air may circulate.

— The *coils* are shaped much like the coils of a D.C. generator, the two sides of the coil being approximately a pole pitch apart. All coils are alike, and therefore, interchangeable. They are insulated before being inserted in the slots and are further protected by a horn-fibre slot lining. When in place on the stator, the coils are connected together in groups to form a winding of the required number of phases, three-phases star-connected windings being common.

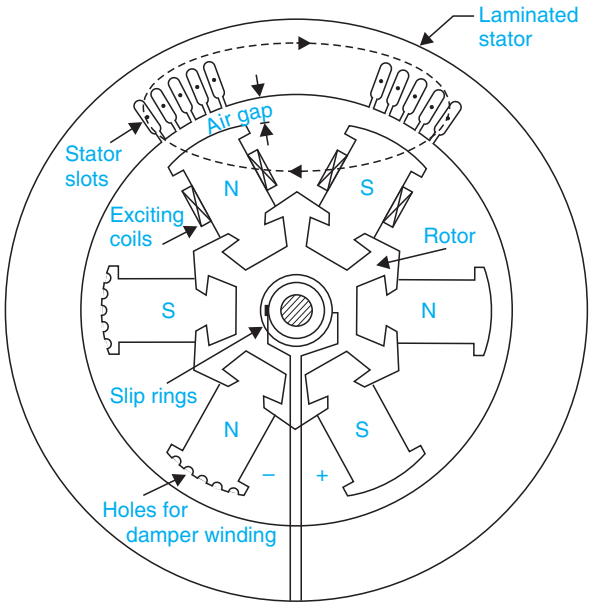


Fig. 12.35. Alternator.

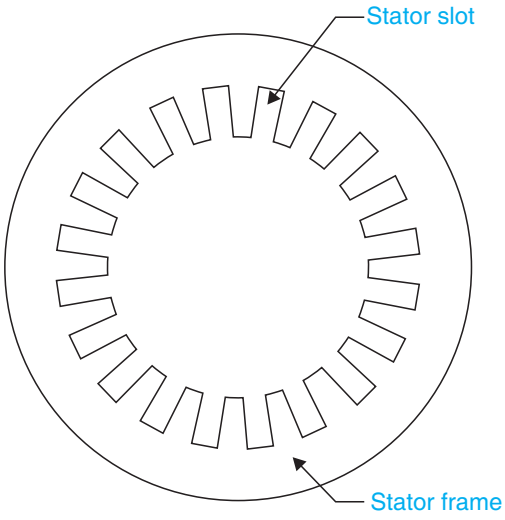


Fig. 12.36. Alternator stator.

— A fractional rather an *integral number of slots per pole is often used in order to eliminate harmonics in the waveform.*

Rotor. The revolving field structure is usually called the rotor. There are two types of rotors :

1. Salient pole type rotor.
2. Smooth cylindrical type rotor.

Salient pole type rotor. This type of rotor is used for *slow speed machines which have large diameters and small axial lengths.*

— The poles are made of thick steel laminations rivetted together and attached to a rotor by a devetail joint as shown in Fig. 12.37. The overhang of the pole gives mechanical support to the field coil.

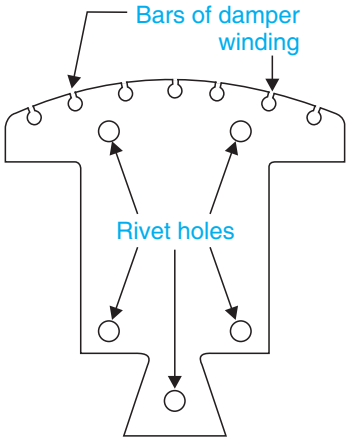


Fig. 12.37. Typical lamination of a salient pole rotor.

— In most of the alternators, where the oscillation or the limiting effect is very high, the *damper winding* in the pole faces is provided. The copper bars short circuited at both ends are placed in the specially provided holes. The relative velocity of the damping winding with respect to main field will be zero when the speed is steady but as soon as it departs from the synchronous speed, there will be relative motion between the damper winding and the main field. This will induce current in them. This induced current will exert a torque in such a way as to bring the alternator to operate at synchronous speed.

— *The pole face is so shaped that the radial air gap length increases from the pole centre to pole tips. This makes the flux distribution over the armature uniform to generate sinusoidal waveform of e.m.f.* (Fig. 12.38).

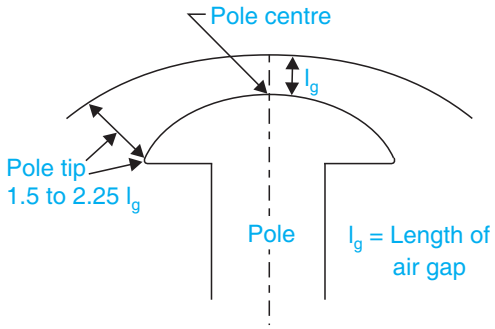
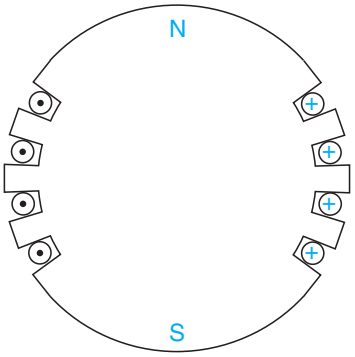


Fig. 12.38

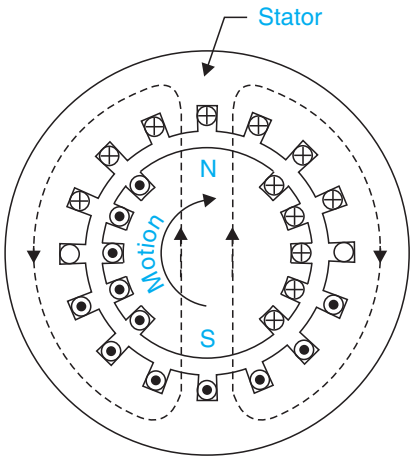
Smooth cylindrical rotor :

— This type of rotor is used for alternators which are coupled to *steam turbines* which run at very high speeds. To reduce the peripheral speed of the alternator the *diameter of the rotor is reduced and axial length is increased.* The number of poles of the rotor are *two* or *four*.

Figs. 12.38 and 12.39 show a cylindrical rotor and cylindrical rotor alternator respectively.



(a) Cylindrical rotor (two pole).



(b) Cylindrical rotor alternator (two pole).

Fig. 12.39

— These rotors are made from solid forgings of alloy steel. The outer periphery of rotor has slots in which the field winding is placed. About 2/3rd of rotor pole pitch is slotted, leaving the 1/3rd unslotted for the pole centre. Heavy wedges of non-magnetic steel are forced into the grooves in the teeth outside the field coils to keep the field coils in position.

— *Cylindrical rotor machines have always horizontal configuration.*

— Since the rotors have large lengths of core forced ventilation is necessary for proper cooling. *Forced air cooling is used up to about 50 MVA sizes and for bigger sizes hydrogen cooling is invariably employed because the conductivity of hydrogen is about 7 times that of air.*

Note. It may be worth mentioning that *cylindrical rotors* will most likely be located on alternates where *steam power* is readily available. *Salient-pole rotors* will be found where *water power* is the prime mover source of energy. Diesel engine, gas engine, and gas turbine prime movers are considered medium-speed machines, and their alternators will also have salient poles. Where alternators are driven by other electrical machines, either A.C. or D.C. motors, there are no such restrictions on the rotor construction. A design is developed that is compatible with the space limitations, speed considerations, and heat dissipation for both electrical machines. It may be noted here that the terms high-speed and low-speed rotors are sometimes used synonymously with cylindrical and salient-pole rotors, respectively.

Bearings

— Although antifriction bearings are occasionally used on alternators of the smaller ratings, the great majority are furnished with oil-lubricated babbitted bearings. For *horizontal shafts* these will be self-contained ring-oiled bearings wherever design conditions permit. At higher shaft peripheral speeds and higher bearing loadings ring oiling is supplemented with recirculation of externally cooled oil. The rings may be eliminated, or they may be retained to afford some degree of emergency oil supply in the event of a failure of the external system. *Lead-base babbits are commonly used for journal bearings,* although tin-base babbit may be employed for some heavy-duty application.

— Two principle types of *thrust bearings* are used on vertical alternators : the *pivoted shoe type* and the *spring type*.

Frequency

In case of a generator which has two poles, the induced e.m.f. passes through one complete revolution in one revolution of the machine. In a multipolar machine one cycle of e.m.f. would be generated when the field structure rotates through an angle subtended by a double pole pitch. Therefore, in a machine with poles, the number of cycle of e.m.f. in one revolution will be $p/2$. If a machine has a speed of N_s revolutions per minute, the frequency will be

$$\left(\frac{p}{2}\right) \times \frac{N_s}{60} \text{ per second.}$$

Thus, $$f = \frac{p}{2} \times \frac{N_s}{60} = \frac{N_s p}{120} \text{ Hz} \qquad ...(12.2)$$

In order to keep the frequency constant, the speed N_s must remain unchanged. Therefore, a synchronous generator (*i.e.*, alternator) runs at a constant speed known as synchronous speed.

12.2.3.4. Exciters

The alternator's field requires magnetism. The permanent magnets are unsuitable for the field of the alternator. Hence direct current is fed into the poles of the alternator so that one end is a north pole and the other a south pole. This direct current is supplied by a separate generator which is mounted on the same shaft as the alternator. Hence all alternators have a separate exciter which generally produce high current and low voltage. In case of large machines there are two exciters known as *main exciter* and pilot *exciter*. The *pilot exciter is a well-saturated constant voltage machine arranged to excite the main exciter.*

As the field strength depends on the D.C. exciting current in the field magnet coils, the exciting or field current is regulated accordingly to adjust the output voltage. In case of large machines the field current may be as high as 400 amperes. To regulate the exciting current is obtained by connecting the regulating resistance in the field circuit of the exciter where comparatively low current has to be handled. Fig. 12.40 shows such an arrangement.

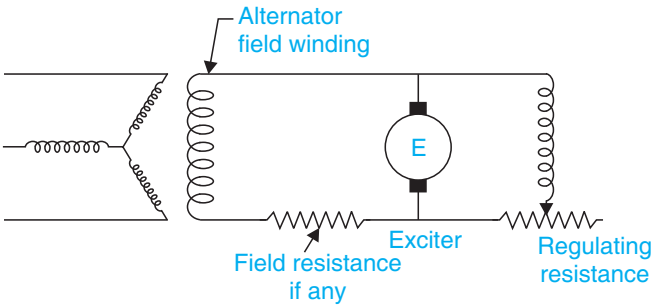


Fig. 12.40. Voltage control of an alternator.

It has been seen that the terminal voltage of the alternator depends not only the exciting current but also on the load current and the power factor of the load. If no-load terminal voltage is plotted against values of exciting current with the machine running at normal speed (field current) then the *open circuit characteristics* or *magnetisation curve* is obtained. The voltage is directly

proportional to the flux per pole. The magnetisation curve is determined by the properties of the magnetic circuit. If the excitation of an alternator is adjusted to give normal voltage at no-load and then a load is applied, the terminal voltage changes, even though the speed is kept constant. The voltage usually falls, but in certain circumstances it may actually rise. These changes may be due to (*i*) resistance of each phase winding, (*ii*) the reactance of each phase winding, (*iii*) the armature reactors.

The *exciter is generally a shunt wound D.C. machine*. For a new machine it is often necessary to apply the first excitation with a battery. Then later on the poles of the exciter have residual magnetism and thus require no external help. However in no case of bigger machines, the pilot exciter may be started by the battery (in case of new machines only) and then with the residual magnetism in the field magnets it will generate direct current.

An exciter may be either directly coupled to the alternator shaft or it may be driven through a belt or chain drive.

Advantages of directly coupled exciters :

1. The machine as a unit is complete in itself and independent of outside sources for its operation.

2. The voltage of the system can be maintained independent of any auxiliary source of supply and is not affected by faults there on.

Disadvantages :

1. Armature fitting, commutator stresses, brush chatter and ventilation, all require special attention.

2. Exciter troubles may sometimes necessitate shutting down of the main set.

3. With the high speeds in general use (1500 to 3000 r.p.m.) difficulties such as balancing, alignment of shaft and other problems crop up.

A.C. Exciters

To avoid commutation difficulties as well as commutator maintenance, A.C. exciters with silicon or germanium rectifiers have been developed for the largest turbo alternators as well as for smaller machines ; the current from the static floor mounted rectifiers is fed to the rotor of the main machine through conventional sliprings. The A.C. exciter is mounted on the main generator shaft and may be designed to operate at any economically convenient frequency, *e.g.* 100–150 Hz or more.

12.2.3.5. Alternator on load

When load on an alternator varies, its terminal voltage also varies. This variation in terminal voltage is due to the following reasons :

(*i*) Voltage drop due to armature resistance.

(*ii*) Voltage drop due to armature leakage reactance X_L.

(*iii*) Voltage drop due to armature reaction.

(*i*) **Armature resistance.** The voltage drop caused by armature resistance per phase R_a is IR_a and is in phase with current I. This drop, however, is practically negligible.

Effective resistance. The *effective resistance* of the armature winding is greater than the conductor resistance as measured by direct current. This is because additional energy over purely I^2R value is expended inside and sometimes outside of the conductor, owing to the alternating current.

The chief sources of this additional energy loss are :

(*i*) Eddy currents in the surrounding material ;

(*ii*) Magnetic hysteresis in the surrounding material ; and

(*iii*) Eddy currents or unequal currents distribution in the conductor itself.

In many cases it is sufficiently accurate to measure the resistance of an armature by direct current and increase it to a fictitious value, called the effective resistance, which is large enough to take care of these extra losses. The exact value can vary widely from 1.25 to 1.75, or more × D.C. resistance, depending upon design. *Extreme accuracy is not necessary in this factor*, since the voltage change due to resistance is small in comparison to the changes produced by leakage reactance and armature reaction.

(*ii*) **Armature leakage reactance.** The load current, flowing through the armature winding, builds up local flux which on cutting the winding *generates a counter* (or *reactance*) *e.m.f.* This effect gives the armature a *reactance* which is numerically equal to $2\pi fL$. L, in henries, is the leakage inductance of the winding. This armature reactance is called the *leakage reactance* X_L (also known as Potier reactance X_P) since the flux *which causes it is around the armature turns only and does not effect the feld flux directly*. This *leakage flux* (Fig. 12.41) is proportional to the armature current, since the magnetic path it covers is not normally saturated. X_L varies some what with the position of the armature and field poles. It is usually assumed to be constant.

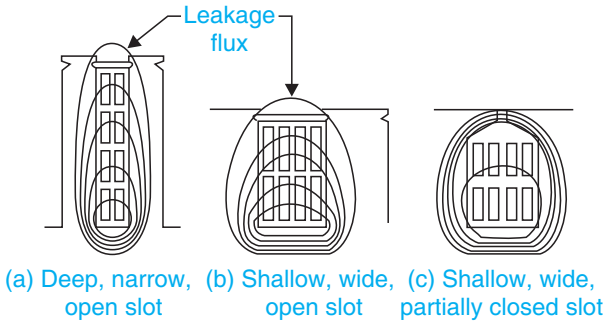


Fig. 12.41. Slot-leakage flux.

The voltage drop due to X_L is IX_L. A part of generated e.m.f. is used up in overcoming this voltage drop (reactance e.m.f.)

$$\therefore \qquad E = V + I(R_a + jX_L) \qquad ...(12.3)$$

This fact is illustrated in Fig. 12.42.

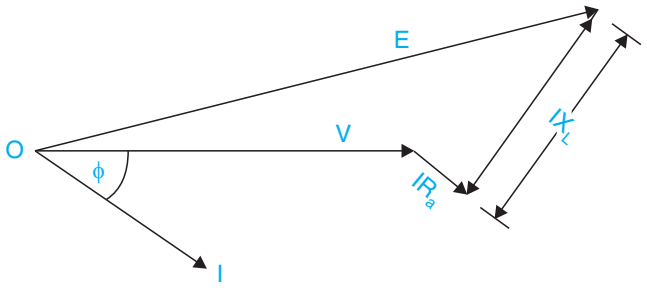


Fig. 12.42

(*iii*) **Armature reaction.** Armature reaction is the magnetomotive force produced by the armature currents in the armature conductors.

Unity power factor. At unity power factor, armature reaction consists of distortion of the main field flux.

Lagging power factor. When an alternator operates with a laging power factor a m.m.f. is set up by the current in the armature conductors which opposes the m.m.f. of the main field and causes a *decrease in the main flux*. This, in turn, results in decrease in the induced voltage. The *lower the value of lagging power factor*, the *greater will be the armature m.m.f. which will oppose and weaken the field*.

Leading power factor. In those limited applications where an alternator supplies a load with a leading power factor, the armature current sets up m.m.f. in the armature which aids the m.m.f. of the main field and *causes the main field flux to increase*. Therefore, the voltage of the alternator will increase with an increase in load current. The *lower the value of the leading power factor, the greater will be the armature m.m.f. aiding the m.m.f. of the main field to cause an increase in the main field flux*.

The following illustrations in Fig. 12.43 show how the main field flux is affected by the armature m.m.f. for different load power factors. For ease of illustration, a two-pole rotating type alternator is used. However, the same conditions take place in the revolving field type alternator.

A study of illustrations in Fig. 12.43 and vector diagrams for different power factor loads shows that the *voltage drop due to inductive reactance and armature reaction are the same in their effect on the termianl voltage*. Both of these effects are proportional to the armature current.

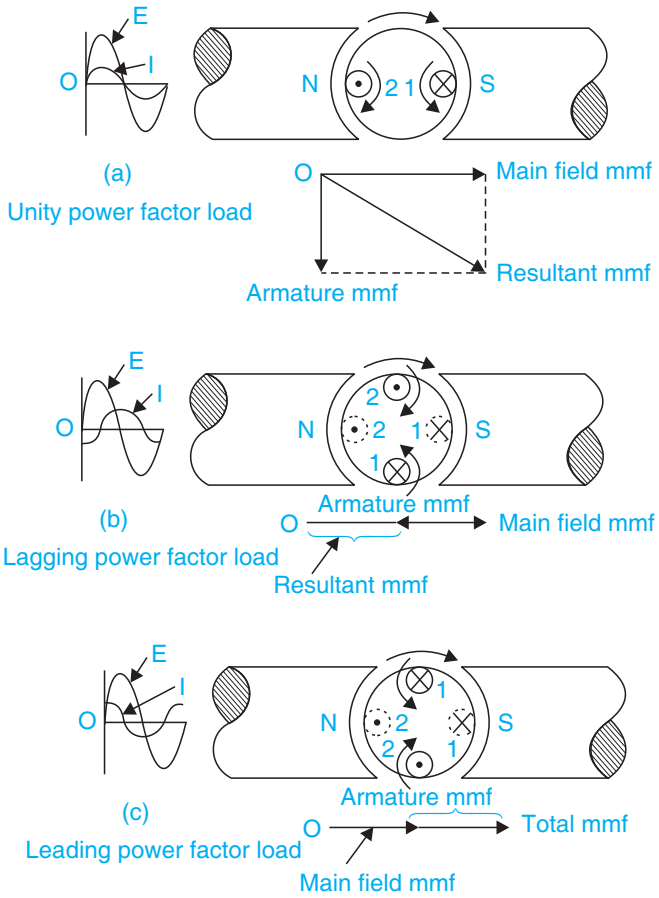


Fig. 12.43. Effects of armature reaction.

Synchronous reactance. The leakage reactance X_L (or X_P) and the armature reactance X_a may be combined to give '*synchronous reactance*' X_s.

Hence, $$X_s = X_L + X_a$$

[The ohmic value of X_a varies with the power factor of the load because armature reaction depends on load power factor].

From the above discussion, it is clear that for the same field excitation, terminal voltage is decreased from its no-load value E_o to V (for a lagging power factor). This is because of :

(*i*) Drop due to armature resistance IR_a.

(*ii*) Drop due to synchronous reactance IX_s.

Therefore, *total voltage drop* in an alternator under load is

$$= IR_a + jIX_s = I(R_a + jX_s) = IZ_s$$

where Z_s is known as '*synchronous impedance*'. (The word synchronous simply refers to the working conditions).

Fig. 12.44 shows the vector diagram for the above fact.

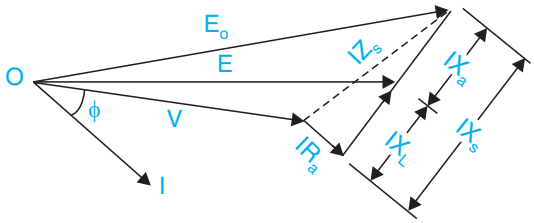


Fig. 12.44

Vector Diagrams of a Loaded Alternator. The vector diagrams for unity *power factor, for lagging power factor* and for *leading power factor* have been shown in Figs. 12.45, 12.46 and 12.47 respectively. All these diagrams apply to one phase of a 3-phase machine. Diagrams for the other phases can also be drawn in the same way.

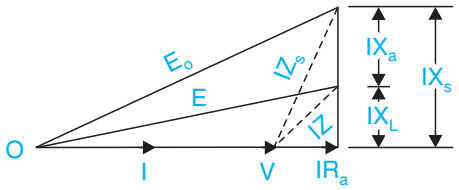


Fig. 12.45. Unity power factor.

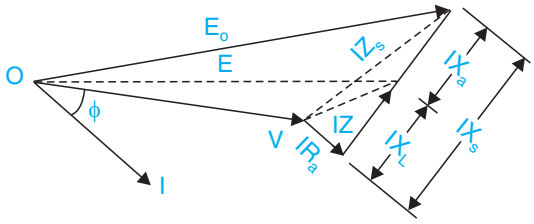


Fig. 12.46. Lagging power factor.

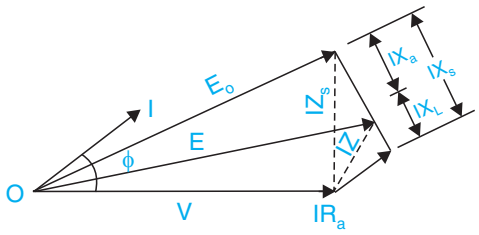


Fig. 12.47. Leading power factor.

In above diagrams :

E_o = No-load e.m.f. This being the voltage induced in armature in the absence of IR_a, IX_L and IX_a. Hence it represents the maximum value of induced e.m.f.

E = It is the induced e.m.f. after allowing for armature reaction. E is vectorially less than E_o by IX_a

V = Terminal voltage. It is vectorially less than E by IZ

where $Z = \sqrt{R^2 + {X_L}^2}$

I = Armature current/phase and

ϕ = Load power factor angle.

12.2.3.6. Voltage regulation

— When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, the amount of this variation determines the *regulation* of the machine. The numerical value of *regulation* is defined as *the percentage rise in voltage when full-load at the specified power-factor is switched off, the excitation being adjusted initially to give normal voltage*. Thus,

$$\% \text{ Regulation 'up'} = \frac{E_o - V}{V} \times 100 \qquad ...(12.4)$$

This gives a lower figure than the percentage drop in voltage when full-load is *switched on*, because in the latter case the excitation is only that required for normal voltage on open circuit. As actually defined, the excitation is greater, since it is that required to give normal voltage on full-load, and owing to the greater saturation of magnetic circuit in these circumstances, the rise in voltage when the load is switched off is less than the drop in voltage when the load is switched on.

— A normal alternator has a regulation of about 8 to 10 per cent at unity power factor, but the *voltage rise is considerably increased at lagging power-factors*. At 0.8 lagging power- factor the value lies between 25 and 35 per cent, or even more.

— *Close regulation is not desired, since such an alternator would deliver an excessive current if accidentally short-circuited. Coarse regulation adds to the protection of the machine*, and it is usual to design an alternator with a considerable amount of internal reactance, since this limits the short-circuit current, a most important point where alternators of high power are concerned. Indeed, large alternators are now designed to withstand a dead short-circuit with impunity. The disadvantages of coarse regulation is obviated by the usual practice of operating an alterantor in conjunction with an automatic voltage regulator, which maintains an approximately constant voltage at all loads.

Determination of Voltage Regulation. It is not usually possible or desirable to measure the regulation by direct experiment, indirect methods being adopted which do not necessitate the loading of the alternator. For this purpose, open circuit and short-circuit characteristics are required.

The following indirect methods are used to determine voltage regulation :

1. Synchronous impedance or E.M.F. method.
2. The Ampere-turn or M.M.F. method.
3. Zero power-factor or Potier method.

All these methods require :

(*i*) Armature (or stator) resistance R_a.

(*ii*) Open-circuit/no-load characteristic.

(*iii*) Short-circuit characteristic (but zero power factor lagging characteristic for Potier method).

(*i*) Value of R_a. Armature resistance R_a per phase can be measured directly by voltmeter and ammeter method or by using wheatstone bridge. The effective value of R_a, however, under working conditions is increased due to skin effect. The value of R_a so obtained is increased by 60 per cent or so to allow this effect. Generally, a value 1.6 times D.C. value is taken.

(*ii*) Open-circuit characteristic. This type of characteristic (as in D.C. machines) is plotted by running the machine on on-load and noting the values of induced voltage and field excitation current.

(*iii*) Short-circuit characteristic. Short-circuit characteristic is obtained by short-circuiting the armature (*i.e.*, stator) windings through a low resistance ammeter. The excitation is so adjusted as to give 1.5 to 2 times the value of full-load current. *The speed* (not necessarily synchronous) *is kept constant during the test*.

Synchronous Impedance Method. This method involves the following *steps* :

(*i*) Plot the open-circuit characteristic (O.C.C.) from a given data as shown in Fig. 12.48.

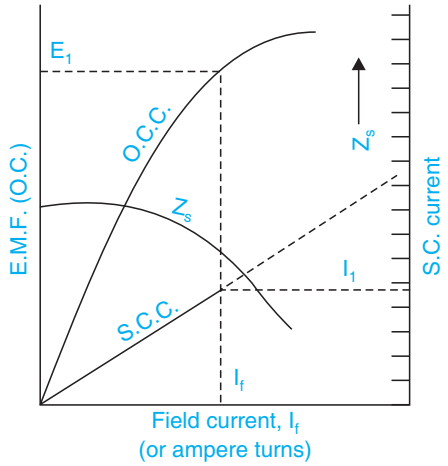


Fig. 12.48. O.C. and S.C. test curves of an alternator.

(*ii*) Plot short-circuit characteristic (S.C.C.) from the data given by short-circuit test.

Both these curves are drawn on a common field-current base.

Consider a field current I_f. Corresponding to this field current the O.C. voltage is E_1. When winding is short-circuited, the terminal voltage is zero. Hence, it may be assumed that the whole of this voltage E_1 is being used to circulate the armature short-circuit current I_1 against the synchronous impedence Z_s.

$$\therefore \qquad E_1 = I_1 Z_s$$

or
$$Z_s = \frac{E_1 \text{ (open-circuit)}}{I_1 \text{ (short-circuit)}}$$

(*iii*) Find synchronous reactance, X_s as follows

$$X_s = \sqrt{Z_s^2 - R_a^2}$$

(R_a can be found as discussed earlier)

(*iv*) After finding R_a and X_s vector diagrams for any load any power factor may be drawn. Three cases are considered in Fig. 12.49, (*a*) *unity power factor, (b) lagging power factor*, and (*c*) *leading power factor*.

— **Unity power factor.** Refer to Fig. 12.49 (*a*)

$$OC^2 = (OA + AB)^2 + BC^2$$

$$E_0^2 = (V + IR_a)^2 + (IX_s)^2$$

$$\therefore \qquad E_0 = \sqrt{(V + IR_a)^2 + (IX_s)^2} \qquad ...(12.5)$$

— **Lagging power factor.** Refer to Fig. 12.49 (*b*),

$$OC^2 = (OA + AB)^2 + (BD + DC)^2$$

$$= E_0^2 = (V \cos \phi + IR_a)^2 + (V \sin \phi + IX_s)^2$$

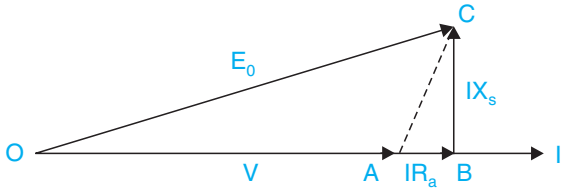
$$\therefore \qquad E_0 = \sqrt{(V \cos \phi + IR_a)^2 + (V \sin \phi + IX_s)^2} \qquad ...(12.6)$$

— **Leading power factor.** Refer to Fig. 12.49 (*c*),

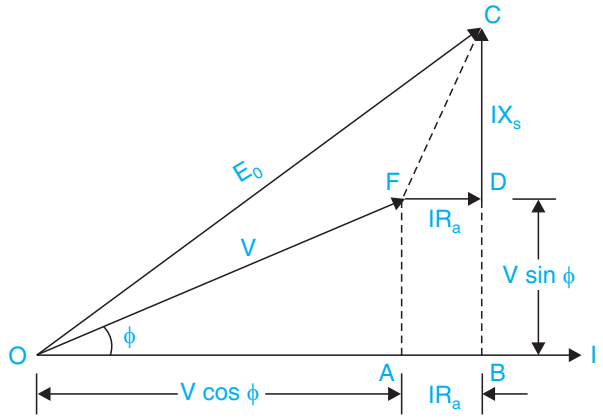
$$OC^2 = (OF + FD)^2 + (BD - BC)^2$$

$$E_0^2 = (V \cos \phi + IR_a)^2 + (V \sin \phi - IX_s)^2$$

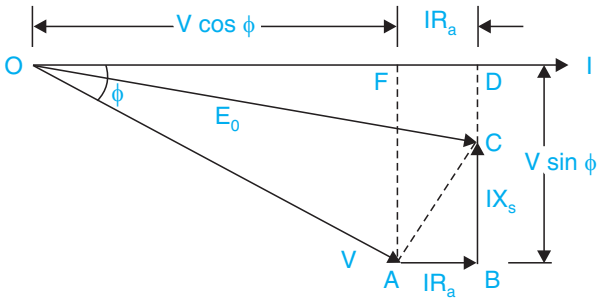
$$\therefore \qquad E_0 = \sqrt{(V \cos \phi + IR_a)^2 + (V \sin \phi - IX_s)^2} \qquad ...(12.7)$$



(a) Unity power factor



(b) Lagging power factor



(c) Leading power factor

Fig. 12.49. Regulation : (*a*) Unity p.f., (*b*) Lagging p.f., (*c*) Leading p.f.

The procedure is similar to that adopted in the case of transformers. The approximate method of calculating the total drop as was used for transformers *must not* be used for alternators where the *magnitudes involved are much greater in percentages*.

The results obtained by this method are *too high*, owing to the fact that the synchronous impedance determined at short-circuit condition is too *large due to a very low degree of saturation*. Hence this method is called the '*pessimistic*' method.

Assumptions Inherent in the Synchronous Impedance Method. The assumptions are as follows :

(*i*) *The effect of the armature-reaction flux can be replaced by a voltage drop proportional to the armature current*. The substitution of voltage for flux is the reason that the synchronous-impedance method is also called *e.m.f. method*.

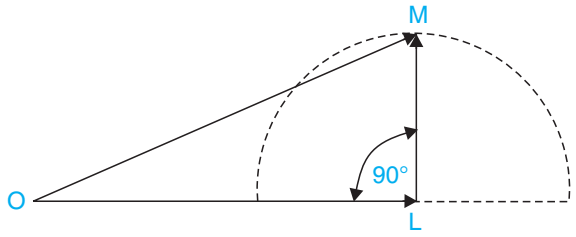
(*ii*) *Since the voltage caused by the main-field flux is added vectorially to that caused by the armature flux, it is also assumed that both fluxes have sinusoidal distribution*. Little error is introduced because of this with non-salient-pole machines, but the error is much greater in the case of the salient-pole ones which have concentrated field windings.

(*iii*) *The magnetic reluctance to the armature flux is constant regardless of the power factor*. This is substantially true for a non-salient, or round-rotor machine, whose air gap is almost constant but introduces considerable error with salient poles, since the position of the armature flux relative to the field poles is determined by the power factor.

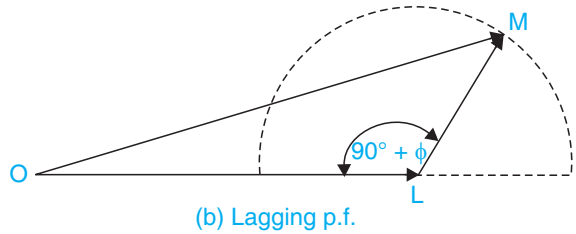
(*iv*) There is no saturation effect.

(*v*) The flux under test conditions is the same as that under load conditions.

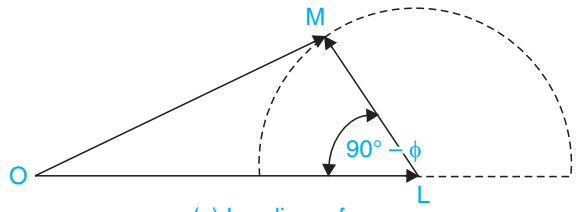
The Ampere Turn or M.M.F. Method. The graphs of open and short circuit tests are made use of in this method. The method is converse of the 'e.m.f. method' in the sense that *armature leakage reactance is treated as an additional armature reaction*.



(a) Unity p.f. ($\phi = 0$)



(b) Lagging p.f.



(c) Leading p.f.

Fig. 12.50

— From O.C. test field current I_f' is determined to give rated voltage V on no-load, neglecting armature resistance drop, and I_f'' is determined to cause-short-circuit current, equal to full-load current, on short-circuit.

— The field excitation I_f'', on short-circuit, *balances the impedance drop in addition to armature reaction on full-load*. But since R_a is usually very small and X_L is also small for low voltage on short circuit, so impedance drop can be neglected. Hence *power factor on short-circuit*

is almost zero lagging and field ampers turns are used entirely to overcome the armature reaction. Therefore, I_f'' gives demagnetising ampere-turns on full-load.

— Now let us consider a general case when the alternator supplies full-load current at a power factor of cos ϕ.

(*i*) Draw *OL* repressing I_f' to give full-load rated voltage, *V* (or more exactly $V + IR_a \cos \phi$).

(*ii*) Draw *LM* at an angle (90° ± ϕ) representing I_f'' to give full-load current on short-circuit (+ve sign for lagging p.f. and –ve sign for leading p.f.).

(*iii*) Find field current I_f, measuring *OM*, which will give open circuit e.m.f. E_0 which can be determined from open circuit characteristic (O.C.C.).

The percentage regulation then, can be obtained from the following relation :

$$\% \text{ Regulation} = \frac{E_0 - V}{V} \times 100.$$

— *Regulation given by this method is much lower than that given by the synchronous impedance method, but it is nearer the correct value. This method is called the 'Optimistic' method.*

Zero Power Factor or Potier Method. This method *gives more accurate results* since it is based on the *separation of armature-leakage reactance drop and the armature reaction effects*. The following experimental data is required in this method :

(*i*) No-load or open circuit curve.

(*ii*) Full-load zero power factor curve (not S.C.C.).

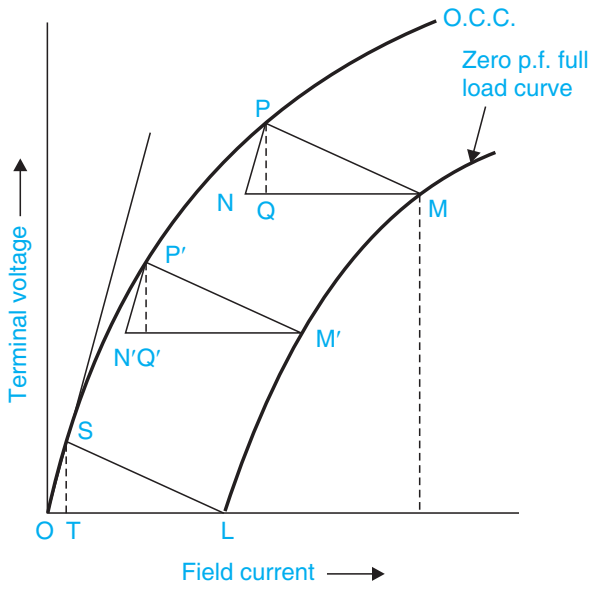


Fig. 12.51

From (*ii*) the reduction in voltage due to armature reaction is found out and voltage drop due to armature leakage reactance (also called Potier reactance) X_L is found from both (*i*) and (*ii*) both. By combining the two, E_0 can be calculated.

The above two curves are similar and displaced horizontally by the m.m.f. due to armature reaction in terms of the field current.

— Zero power factor, full-load voltage excitation characteristic can be drawn by knowing two points *L* and *M*. Point *L* is obtained from a short circuit test with full-load armature current. Hence *OL* represents field current (excitation) required to *overcome demagnetising effect of armature reaction and to balance leakage reactance drop at full-load*. Point *M* is obtained when full-load current flows through the armature and wattmeter reading is zero. *Zero power factor curve* may be drawn as follows :

(*i*) From *M* draw line *MN* equal and parallel to *OL*.

(*ii*) Through point *N* draw a line parallel to initial straight part of O.C.C. (parallel to *OS*), cutting the O.C.C. at *P*.

(*iii*) Join *PN* and drop a perpendicular *PQ* on *MN*.

(*iv*) Impose the triangle *MPQ* at various-points of O.C.C. to obtain corresponding points on the zero power factor curve.

In triangle *MPQ* :

Length *PQ* represents *leakage reactance drop* (IX_L).

Length *MQ* represents *armature reaction excitation*.

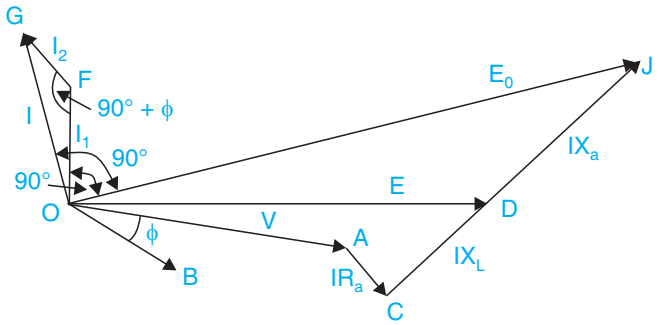


Fig. 12.52

Potier Regulation Diagram. Following is the procedure to draw Potier regulation diagram :

(*i*) Draw *OA* horizontally to represent terminal voltage *V* on full load and *OB* to represent load current (*I*) at a given power factor.

(*ii*) Draw *AC*(= IR_a), voltage drop due to resistance R_a (if resistance is given) parallel to *OB*.

(*iii*) Draw *CD* perpendicular to *AC* and equal to reactance drop IX_L.

Now *OD* represents generated e.m.f. *E*.

(*iv*) From O.C.C., find the field current I_1 corresponding to this generated e.m.f. *E* and draw *OF* (equal to I_1) perpendicular to *OD*. Draw *FG* parallel to load current *OB* (*i.e.*, *I*) to represent excitation (field current) *equivalent to full load armature reaction*.

OG gives *total field current* required.

(*v*) If the load is thrown off, then terminal voltage will be equal to generated e.m.f. corresponding to field excitation *OG*. Hence e.m.f. E_0 may be obtained from O.C.C. corresponding to field excitation *OG*. Vector *OJ* will lag behind vector *OG* by 90°. *DJ* represents *voltage drop due to armature reaction*.

Now regulation may be obtained from the following relation :

$$\% \text{ Regulation} = \frac{E_0 - V}{V} \times 100.$$

12.2.3.7. Losses and efficiency

Losses. The following losses occur in an alternator :

1. **Copper losses.** These losses occur in the armature winding and in the field coils.

2. **Core loss.** The core loss consists of eddy-current and hysteresis loss in the pole faces, teeth, and stator core due to the flux resulting from the combined rotor and armature fields.

3. **Friction and windage loss.** This loss is due to the bearing and brush friction and to the power required to circulate the cooling air.

4. **Load loss.** This is due to the *armature leakage flux* which causes eddy-currents and hysteresis in the iron surrounding the armature conductors. If, however, effective resistance is used to calculate the armature copper loss, then these load losses are also included in the calculation.

Efficiency. The efficiency of an alternator is calculated as follows :

Alternator efficiency

$$= \frac{\text{Output}}{\text{Output} + \text{Losses}} = \frac{\text{kVA(p.f.)}}{\text{kVA(p.f.)} + \text{Losses}}.$$

Maximum efficiency occurs at that load point where the constant losses (friction, windage, core loss and field copper loss) *are equal to variable losses* (armature copper and load loss). The maximum efficiency usually occurs at about 80% of full load.

Determination of losses. Losses may be determined by the following methods :

Measurement of losses method. As in most electric machines, efficiency measurement of an alternator by direct loading is rather impractical. It may also be a physical impossibility to obtain the required load, and even if it could be obtained the cost may be prohibitive. Also, the measurement of the mechanical power input is somewhat difficult, and any inaccuracy with measurement is *reflected directly in the final efficiency calculation*. Efficiency is therefore calculated by '*measurement of losses*' method which entails the following advantages :

(*i*) At any one time, only part of the losses need be provided. Therefore the source of power required for testing has a capacity of less than 5% of the rating of the alternator.

(*ii*) There is no need to put an electric load on the alternator.

(*iii*) Greater accuracy can be obtained since electrical instruments can be used for all measurements.

(*iv*) An inaccuracy that occurs in the test *is not directly reflected in the final efficiency calculation*, since the error occurs on only a small portion of the name plate rating.

Use of a calibrated D.C. motor to drive the alternator. A *quite accurate and simple method* of determining the losses is to use a calibrated D.C. motor to drive the alternator. The motor is calibrated in the sense that all its losses have been determined for varying conditions of operation, so that its output is then readily obtained.

This method involves the following procedural steps :

Step 1. Drive the alternator at synchronous speed, but *without field excitation*. The D.C. motor output is the alternator input, and hence its *friction and windage loss*.

Step 2. Repeat step 1, but this time *with field excitation*. The excitation should be that at which the alternator normally operates. If this is unknown, then the open-circuit voltage is adjusted to be equal to the rated voltage plus the internal voltage drops as determined by one of the methods used to calculate voltage regulation.

The difference between the motor output of step 2 and that of step 1 is the *core loss*.

Step 3. Short-circuit the armature and adjust the field current to obtain rated line current. The difference between this motor output and that of step 1 is the *armature copper loss plus load loss*. It is assumed that the flux density under short-circuit conditions is so low as to make the core loss negligible.

Step 4. The *field copper loss* is measured by simple D.C. measurement.

12.2.3.8. Parallel operation of alternators

Necessity. Alternators may be put in parallel because of the following reasons :

1. Local or regional power use may *exceed* the power of a *single* available generator.

2. Parallel alternators allow one or more units to be *shut down* for scheduled or emergency *maintenance* while the load is being supplied with power.

3. Generators are *inefficient at part load*, so shutting down one or more generators allows the remaining load to be carried with less machines that are efficiently loaded.

4. Load growth can be handled by *added* machines without disturbing the original installation.

5. Available machine prime movers and generators can be *matched* for economic first cost and flexible use.

Requirements for paralleling. The *requirements* for paralleling include the requirements for D.C. machines plus a few others.

1. The *voltages* must be the *same* at the *paralleling point* or junction even though not the same at the alternators.

2. The *phase sequence* for three phase (or any multiple phase) must be the *same* at the paralleling point.

3. The incoming machine must be *in phase* at the moment of paralleling. It will stay in phase under normal conditions after paralleling. It is important to recognize that *phase sequence* and *in phase* are *not the same thing*.

4. The line frequencies must be *identical* at the paralleling point. In the vast majority of cases, this means the same frequency at the generator because frequency changing is not economic. Mixed frequencies must be paralleled through some frequency conversion means for compatibility at the point of interconnection.

5. The primemovers must have relatively similar and *drooping speed-load characteristics*. This is to prevent a machine with a rising speed load characteristic from taking more and more of the load until if fails from overload.

Violation of these requirements for paralleling would result in circulating currents between the machines varying from uneconomic, to serious, to disastrous.

12.2.3.9. Alternator synchronising procedure

It may logically be assumed that one alternator is placed in parallel with one or more other alternators only when additional load requires it. Those alternators already carrying load are known as the *running machines*, while that which is to be placed in the system is known as the *incoming machine*. At the time of synchronizing, the following *conditions* must be met.

1. The effective voltage of the incoming alternator must be exactly equal to that of the others, or of the bus-bars connecting them.

2. The phase rotation, or sequence of the running and incoming alternators must be the same.

3. The individual phase voltages which are to be connected to each other must be in exact phase opposition. This is the same as saying that D.C. generators must be connected + to + and – to –.

4. The frequencies should be the same, although it is more desirable that the frequencies at the *instant* of paralleling be almost, but not quite, identical.

Synchronizing lamps :

— To satisfy the first condition of paralleling (*i.e.,* effective voltages be the same) a voltmeter can be used as shown in Fig. 12.53.

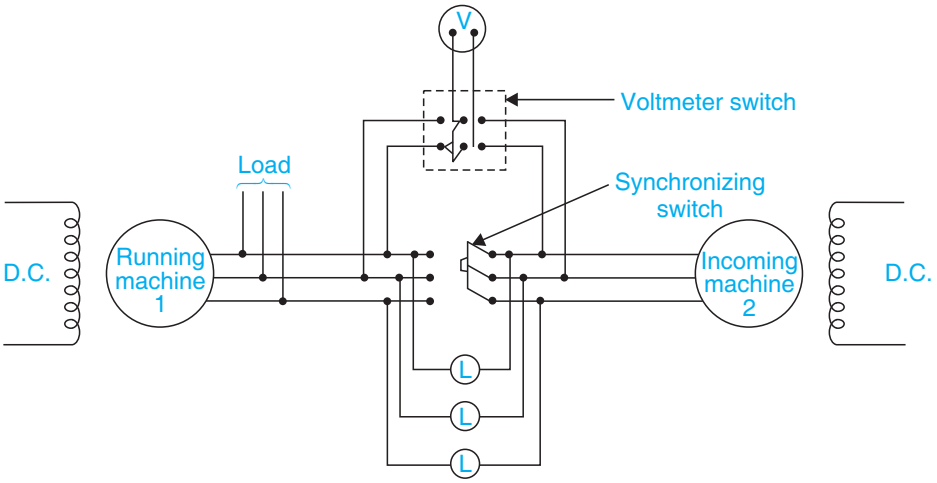


Fig. 12.53. Parallel operation of alternators : Synchronizing lamps and voltmeter.

— Satisfaction of the other conditions of *phase sequence, voltage opposition*, and *frequency* may be *determined by the use of the incandescent lamps connected between the two machines* (Fig. 12.53). The auxiliary equipment is omitted to simplify the sketch.

At any instant it is seen that the voltage across the lamp is the sum of the individual phase voltages.

The procedural steps for putting incoming alternator in parallel with the running machine are as follows :

Step 1. The prime mover of the incoming machine is started, and the alternator is brought up to near its rated speed.

Step 2. By adjusting the field current, the terminal voltage of incoming machine is made the same as that running alternator.

The lamp in the circuit will now flicker at a rate equal to the difference in frequency of the two alternators. *If the phases are properly connected, all lamps will be bright and dark at the same time*. If this is not the case, then it means that the phase sequences are not correct, and it is merely necessary to interchange two of the line leads of the incoming machine.

Step 3. Further adjustment of the incoming prime mover is now necessary, until the lamps flicker at a very low rate, *usually less than one dark period per second*.

Step 4. Final adjustment of the incoming voltage again made and the synchronizing switch is thrown in the middle of a dark period. The voltage across the lamps varies from zero to twice the phase voltage, and therefore, the lamps must be rated for this higher voltage. It is not convenient, however, to stock special lamps for this purpose, and two lamps of standard voltage ratings may be connected in series in each line.

The *lamp method* has the following *advantages* and *disadvantages*.

Advantages :

(*i*) Equipment is inexpensive.

(*ii*) Proper phase sequence is readily obtained.

Disadvantages :

(*i*) Lamps go dark at somewhat less than half their rated voltage, and so the synchronizing switch might be closed when there is a considerable phase difference between the machines, with a high circulating current resulting in possible damage to the machines. An experienced operator, however, can minimize this danger, since he can quickly learn to estimate the middle of the dark period.

(*ii*) The lamp filament can burn out.

(*iii*) The flicker of the lamps does not indicate which machine has the higher frequency.

There are two other lamp methods which are given below :

— If the lamps are connected across the phases, that is, P to Q', Q to R', R to P', they will again flicker in unison. This time, however, the proper synchronizing moment occurs when all three are in the middle of a bright period. This has the *advantage of avoiding synchronizing when the lamps may have burned out, but it is more difficult to estimate the middle of a bright period than the middle of a dark one*.

— In the third lamp method, known as the '*two-bright one-dark* method,' only two of the lamps are cross-connected. Thus the connections are phase P to P', Q to R' and R to Q'. This method supposedly *avoids the disadvantages of both previous lamps methods, but actually may be more confusing to the eye*.

In case of high-voltage alternators, the lamps are connected through transformers to obtain the nominal voltages for which lamps are rated.

Synchronoscope synchronization. In large central station installations, an additional device called a synchronoscope (Fig. 12.54) is used. A synchronoscope has a rotating hand and a dial labelled with slow and fast direction arrows to show the incoming machine speed relation. In addition, an index point shows the actual in-phase position. During synchronization, as the incoming machine rotational speed approaches near synchronism, the speed of the synchronoscope hand drops enough to become visible. The *hand speed is proportional to the difference in speed*. The slow indication is accompanied with an arrow showing that *counter-clockwise* hand rotation means *below* synchronous speed. Similarly *clockwise* rotation means above speed. When the speeds are matched as that the hand speed is very slow, the hand is matched until it points to the index mark, where upon the paralleling switch may be closed.

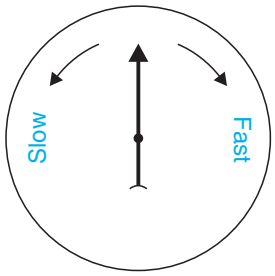


Fig. 12.54. Synchronoscope.

There are following three principal types of synchronoscopes :

(*i*) Polarized vane. (*ii*) Moving iron.

(*iii*) Crossed coil.

All are used similarly. However, *none* of the types will detect an *out-of-phase sequence condition*. They are used as a convenient and accurate means of routinely achieving synchronous speed and in phase indications. The phase sequence problem is really an original test problem since, once sorted out, the phase sequence will remain correct until repair or other circuit changes are needed.

12.2.3.10. Cooling of alternators

Necessity of cooling. Due to the various losses occurring in the alternator, there is a temperature rise in various parts of the alternator and winding insulation. To prevent the temperature rise exceeding the maximum permissible value, every alternator requires continuous cooling during its operation.

Cooling methods :

1. **Open system using air.** In this system the cold air is taken in from the atmosphere with the help of the fan and passed through the machine. The outcoming hot

air is either discharged to atmosphere or into the machine hall for station warming. Due to the difficulty of removal of all dust particles from the air entering the machine they are rarely used and that too on alternators having capacity upto 3 MW.

2. **Closed system using air.** In this system a given volume of air is circulated continuously through the alternator. The discharged hot air is cooled to about 40°C through heat exchangers before it is recirculated through the alternator. This system is universally used for *large machines*.

Advantages and disadvantages of closed system over open system :

Advantages :

1. Quieter operation of the station.
2. No filter is required.
3. Less possibility of dust and impurities deposition in the machine passages.
4. It is easier to combat a fire in an alternator since supply of fresh air is absent.
5. Appearance is quite good.

Disadvantages :

The only disadvantage is that this system is *costly*.

Hydrogen cooling

The gaseous hydrogen is better cooling medium than air (air-cooling is successfully used upto 100 MW generating units) and now-a-days it is universally used in almost all thermal power plants upto 200 MW capacity alternators.

The use of hydrogen gas as the cooling medium in closed circuit cooling offers the following

Advantages :

1. The thermal conductivity of hydrogen is almost seven times that of air. Its specific heat is 14.5 times that of air. The overall heat transfer with forced cooling may be as 2 to 3 times that of air.
2. *Less windage losses* since the density of hydrogen is $\frac{1}{14}$ th that of air.
3. Due to lower windage losses and better heat transfer in the cooler, *less cooling water is required.*
4. *Less space* is occupied by the hydrogen cooled machines.
5. The noise is considerably reduced due to lighter cooling medium and lower friction.
6. The fire risk is reduced in the event of electrical breakdown as oxygen is not present to maintain combustion of the insulation material.
7. The cooling surface required for H_2 cooling is considerable smaller than that needed for air coolers due to high heat transfer rates.
8. The reliability of the insulation increases and its life span is prolonged.
9. The 'corona' effects on the conductors in windings are less deleterious in hydrogen atmosphere than in air. This also increases the life of winding.

Disadvantages :

1. High cooling cost.
2. Overall capital and maintenance cost is high.
3. Gas may leak through the casing. For this reason the casing is made explosion proof against any pressure which can be developed by explosive mixture of hydrogen and air.
4. The major problem is to effectively seal the shaft glands at the alternator hourings.
5. A high degree of hydrogen purity is required to ensure high efficiency and avoid explosions, and this necessitates hydrogen purity, pressure and temperature recorders.

12.3. TRANSFORMERS

12.3.1. General Aspects

Although the transformer is not classified as an electric machine, the principles of its operation are fundamental for the induction motor and synchronous machines. Since A.C. electric machines are normally built for low frequencies only the low frequency power transformer will be considered in this text.

When energy is transformed into a higher voltage the transformer is called a *step-up transformer* but when the case is otherwise it is called a *step-down transformer*. Most power transformers operate at constant voltage, *i.e.*, if the power varies the current varies while the voltage remains fairly constant.

Applications. A transformer performs many important functions in prominent areas of electrical engineering.

— In *electrical power engineering* the transformer makes it possible to convert electric power from a generated voltage of about 11 kV (as determined by generator design limitations) to higher values of 132 kV, 220 kV, 400 kV, 500 kV and 765 kV thus permitting transmission of huge amounts of power along long distances to appropriate distribution points at tremendous savings in the cost of transmission lines as well as in power losses.

— At *distribution points* transformers are used to reduce these high voltages to a safe level of 400/230 volts for use in homes, offices etc.

— In *electric communication circuits* transformers are used for a variety of purposes *e.g.*, as an impedance transformation device to allow maximum transfer of power from the input circuit to the output device.

— In *radio and television circuits* input transformers, interstage transformers and output transformers are widely used.

— Transformers are also used in *telephone circuits, instrumentation circuits* and *control circuits*.

12.3.2. Basic Definitions

— A *transformer* is a *static electromagnetic device designed for the transformation of the (primary) alternating current system into another (secondary) one of the same frequency with other characteristics, in particulars, other voltage and current*.

— As a rule a transformer consists of a core assembled of sheet transformer steel and two or several windings coupled *electromagnetically*, and in the case of *autotransformer, also electrically*.

— A transformer with two windings is called *double-wound transformer* ; a transformer with three or more windings is termed a *triple wound* or *multi-winding* one.

— According to the kind of current, transformers are distinguished as single-phase, three-phase and poly-phase ones. A *poly-phase transformer winding is a group of all phase windings of the same voltage*, connected to each other in a definite way.

— **Primary and secondary windings.** The transformer winding to which the energy of the alternating current is delivered is called the *primary winding* ; the other winding from which energy is received is called the *secondary winding*.

— In accordance with the names of the windings, all quantities pertaining to the primary winding as for example, power, current, resistance etc., are also primary, and those pertaining to the secondary winding secondary.

— *h.v. and l.v. windings.* The winding connected to the circuit with the higher voltage is called the *high-voltage winding* (h.v.), the winding connected to the circuit with the lower voltage is called the *low-voltage winding* (l.v.). If the secondary voltage is *less* than the primary one, the transformer is called a *step-down transformer* and if *more-a step-up transformer*.

— A *tapped transformer* is one whose windings are fitted with special taps for changing its voltage or current ratio.

— **Oil and dry transformers.** To avoid the detrimental effect of the air on the winding insulation and improve the cooling conditions of the transformer its core together with the windings assembled on it is immersed in a tank filled with transformer oil. Such transformers are called *oil transformers*. Transformers not immersed in oil are called *dry transformers*.

12.3.3. Working Principle of a Transformer

A transformer operates on the principle of *mutual inductance*, between two (and sometimes more) inductively coupled coils. It consists of two windings in close proximity as shown in Fig. 12.55. *The two windings are coupled by magnetic induction*. (There is no conductive connection between the windings). One of the windings called *primary* is energised by a sinusoidal voltage. The second winding, called *secondary* feeds the load. The alternating current in the primary winding set up an alternating flux (ϕ) in the core. The secondary winding is linked by most of this flux and e.m.fs. are induced in the two windings. The e.m.f. induced in the secondary winding drives a current through the load connected to the winding. Energy is transferred from the primary circuit to the secondary circuit through the medium of the magnetic field.

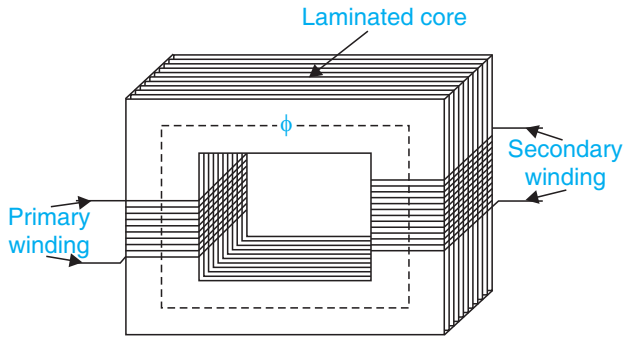


Fig. 12.55. Two winding transformer.

In brief, a transformer is a device that :

(*i*) transfers electric power from one circuit to another ;

(*ii*) it does so without change of frequency ; and

(*iii*) it accomplishes this by electromagnetic induction (or mutual inductance).

12.3.4. Transformer Ratings

The rated quantities of a transformer, its power, voltage, frequency, etc. are given in Manufacturer's name plate, which should always be arranged so as to be accessible. But the term 'rated' can also be applied to quantities not

indicated on the name plate, but relating to the rated duty, as for example, the rated efficiency, rated temperature conditions of the cooling medium, etc. :

— *The rated duty* of a transformer is determined by the quantities given in the name plate.

— The *rated power* of the transformer is the power at the secondary terminals, indicated in the name plate and expressed in kVA.

— *The rated primary voltage* is the voltage indicated in the transformer name plate ; if the primary is provided with taps, the rated tapped voltage is specially noted.

— *The rated secondary voltage* is the voltage across the transformer *secondary terminals at no-load* and with the rated voltage across the primary terminals ; if the secondary winding has taps, then their rated voltage is specially indicated.

— *The rated currents of the transformer*, primary and secondary, are the currents indicated in the name plate of the transformer and calculated by using the corresponding rated values of power and voltage.

12.3.5. Kinds of Transformers

The following kinds of transformers are the most important ones :

1. **Power transformers.** For the transmission and distribution of electric power.

2. **Auto-transformers.** For converting voltages within relatively small limits to connect power systems of different voltages, to start A.C. motors etc.

3. **Transformer for feed installations with static convertors.** (Mercury are rectifiers, ignitions, semi-conductor valves, etc.). When converting A.C. into D.C. (rectifying) and converting D.C. into A.C. (inverting).

4. **Testing transformers.** For conducting tests at high and ultra-high voltages.

5. **Power transformers for special applications.** Furnace, welding etc.

6. **Radio-transformers.** It is used in radio engineering etc.

Note. *Distribution transformers* should be designed to have maximum efficiency at a load much *lower than full-load (about 50 per cent)*.

Power transformers should be designed to have maximum efficiency *at or near full-load*.

12.3.6. Transformer Construction

All transformers have the following essential elements :

1. Two or more *electrical windings* insulated from each other and from the core (except in auto-transformers).

2. A *core*, which in case of a single-phase distribution transformers usually comprises *cold-rolled silicon-steel strip* instead of an assembly of punched silicon-steel laminations such as are used in the larger power-transformer cores. The *flux path in the assembled core is parallel to the directions of steel's grain or 'orientations'*. This results in a *reduction in core losses* for a given flux density and frequency, or *it permits the use of higher core densities* and *reduced size of transformers for given core losses*.

Other necessary parts are :

— A *suitable container* for the assembled core and windings.

— A *suitable medium* for insulating the core and its windings from each other and from the container.

— Suitable *bushings* for insulating and bringing the terminals of the windings out of the case.

The two basic types of transformer construction are :

1. The core type.
2. The shell type.

The above two types differ in their relative arrangements of copper conductors and the iron cores. In the '*core type*', the *copper virtually surrounds the iron core*, while *in the 'shell type', the iron surrounds the copper winding*.

12.3.6.1. Core type transformer

The completed magnetic circuit of the core-type transformer is in the shape of a hollow rectangle, exactly as shown in Fig. 12.56 in which I_0 is the no-load current and ϕ is the flux produced by it. N_1 and N_2 are the number of turns on the primary and secondary side respectively.

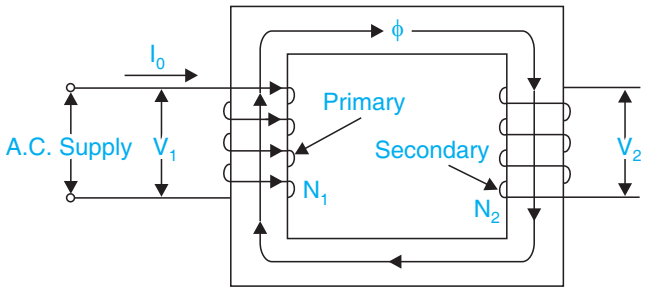


Fig. 12.56. Magnetic circuit of core-type transformer.

The core is made up of *silicon-steel laminations* which are, either rectangular or L-shaped. With the coils wound on two legs the appearance is that of Fig. 12.57. If the two coils shown were the respective high- and low-side coils as in Fig. 12.57, the leakage reactance would be much too great. In order to provide maximum *linkage* between windings, the group on each leg is made up of both high-tension and low-tension coils. This may be seen in

Fig. 12.58, where a cross-sectional cut is taken across the legs of the core. By placing the high-voltage winding around the low-voltage winding, only one layer of high-voltage insulation is required, that between the two coils. If the high-voltage coils were adjacent to the core, an additional high-voltage insulation layer would be necessary between the coils and the iron core.

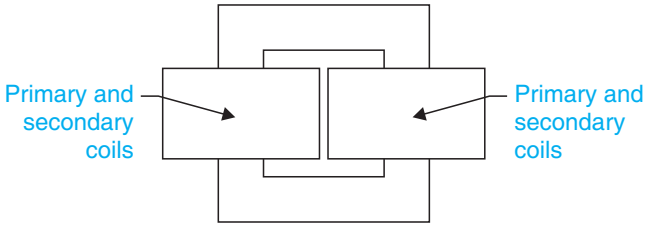


Fig. 12.57. Core-type transformer.

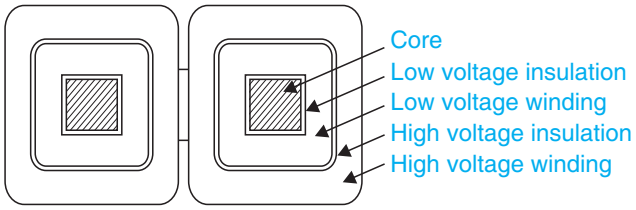


Fig. 12.58. Cross-section of core-type transformer.

Fig. 12.59 shows the coils and laminations of a core-type transformer with a cruciform core and circular coils.

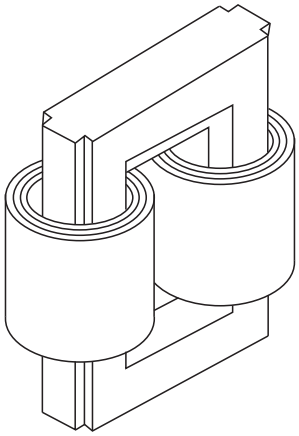


Fig. 12.59. Coils and laminations of a core-type transformer.

— Fig. 12.60 shows the different types of cores used in core transformers.

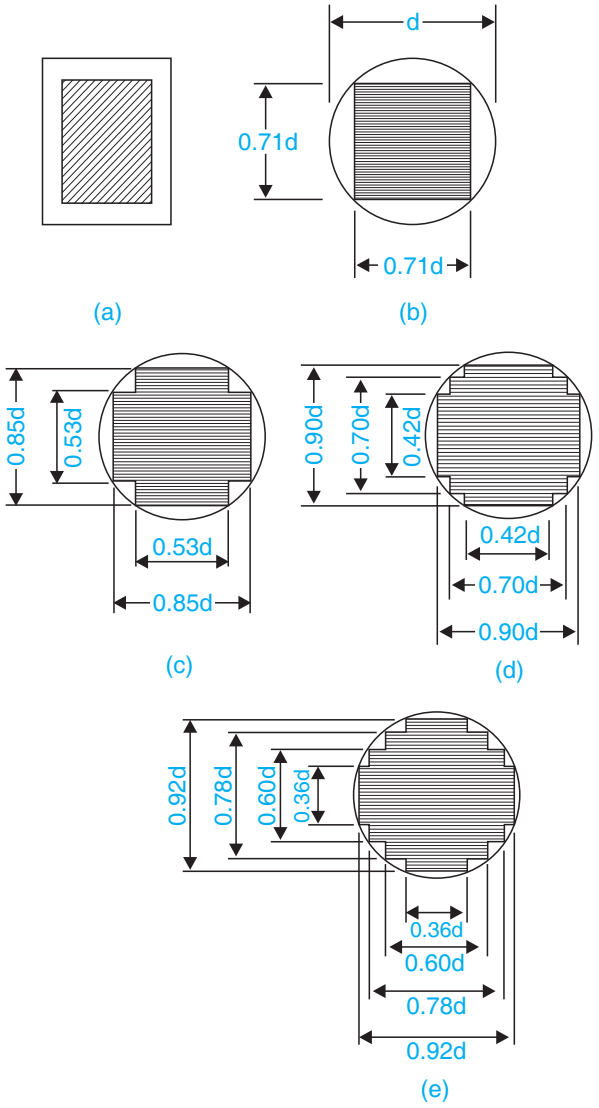


Fig. 12.60. Various types of cores.

Rectangular cores [Fig. 12.60 (*a*)] with rectangular cylindrical coils can be used for small size core-type transformers. For large size transformers it becomes wasteful to use rectangular cylindrical coils and so circular cylindrical coils are preferred. For such purpose, '*square cores*' may be used as shown in Fig. 12.60 (*b*) where circles represent the tubular former carrying the coils. Evidently, a considerable amount of useful space is still wasted. A common improvement on the square core is to employ a

'*cruciform core*' [Fig. 12.60 (*c*)] which demands, at least, two sizes of core strips. For *very large transformers*, further core stepping is done as in Fig. 12.60 (*d*) where at least three sizes of core plates are necessary. *Core stepping not only gives high space factor but also results in reduced length of the mean turn and the consequent I^2R loss. Three stepped core is the most commonly* used although more steps may be used for very large transformers as shown in Fig. 12.60 (*e*).

12.3.6.2. Shell type transformer

In the shell-type construction the iron almost entirely surrounds the copper (Fig. 12.61). The core is made up of E-shaped or F-shaped laminations which are stacked to give a rectangular figure eight. All the windings are placed on the centre leg, and in order to reduce leakage, each high-side coil is adjacent to a low-side coil. The coils actually occupy the entire space of both windows, are flat or pencake in shape, and are usually constructed of strip copper. Again, to reduce the amount of high-voltage insulation required, the low-voltage coils are placed adjacent to the iron core.

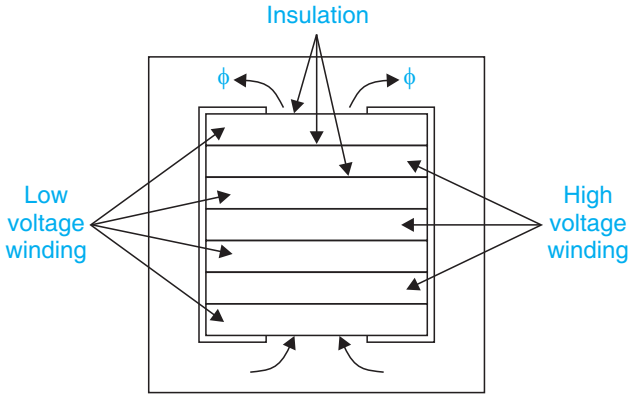


Fig. 12.61. Shell-type transformer.

Fig. 12.62 shows the coils and laminations of a typical shell-type transformer.

Choice of core or shell type construction. In general, the core-type has a longer mean length of core and a shorter mean length of coil turn. The core type also has a smaller cross-section of iron and so will need a greater number of turns of wire, since, in general, not as high a flux may be reached in the core. However, *core type is better adopted for some high-voltage service since there is more room for insulation*. The *shell type has better provision for mechanically supporting and bracing the coils*. This allows better resistance to the very high mechanical forces that develop during a high-current short-circuit.

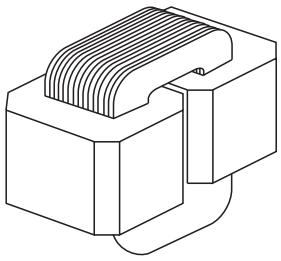


Fig. 12.62. Coils and laminations of a shell-type transformer.

The choice of core or shell type construction is usually one of *cost*, for similar characteristics can be obtained with both types.

Both core and shell forms are used, and selection is based upon many factors such as voltage rating, kVA rating, weight, insulation stress, mechanical stress, and heat distribution.

12.3.6.3. Spiral core transformer

The typical spiral core is shown in Fig. 12.63. The core is assembled either of a *continuous* strip of transformer steel wound in the form of a circular or elliptical cylinder or of a group of short strips assembled to produce the same elliptical-shaped core. By using this construction the core flux always follows along the grain of the iron. Cold-rolled steel of high silicon content enables the designer to use higher operating flux densities with lower loss per kg. *The higher flux density reduces the weight per kVA*.

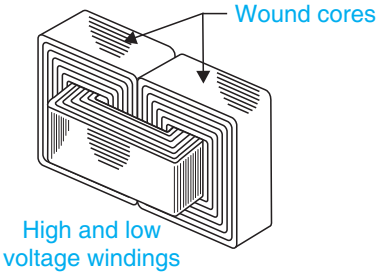


Fig. 12.63. Spiral-core transformer.

12.3.7. Transformer Windings, Terminals, Tappings and Bushings

12.3.7.1. Transformer windings

The most important requirements of transformer windings are :

1. The winding should be economical both as regards initial cost, with a view to the market availability of copper, and the efficiency of the transformer in service.

2. The heating conditions of the windings should meet standard requirements, since departure from these

requirements towards allowing higher temperature will drastically shorten the service life of the transformer.

3. The winding should be mechanically stable in respect to the forces appearing when sudden short circuit of the transformer occurs.

4. The winding should have the necessary electrical strength in respect to over voltages.

The different types of winding are classified and briefly discussed below :

1. **Concentric Windings :**

(*i*) Cross-over (*ii*) Helical

(*iii*) Disc.

2. **Sandwich Windings :**

Concentric windings. Refer to Fig. 12.64. These windings are used for core type transformers. Each limb is wound with a group of coils consisting of both primary and secondary turns which may be concentric cylinders. The l.v. winding is placed next to the core and h.v. winding on the outside. But the two windings can be subdivided and interlaced with high tension and low tension section alternately to reduce leakage reactance. These windings can be further divided as follows :

(*i*) **Cross-over windings.** Cross-over windings are used for currents up to 20 A and so they are suitable for h.v. winding of small transformers. The conductors are either cotton covered round wires or strips insulated with paper.

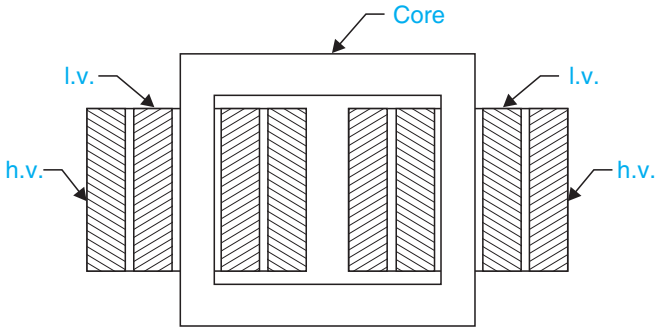


Fig. 12.64. Concentric coils.

Cross-over coils are wound over formers and each coil consists of a number of layers with a number of turns per layer. The complete winding consists of a number of coils connected in series. Two ends of each coil are brought out, one from inside and one from outside. This inside end of a coil is connected to the outside end of the adjacent coil.

(*ii*) **Helical winding.** A helical winding consists of rectangular strips wound in the form of a helix. The strips are wound in parallel radially and each turn occupies the total radial depth of winding.

Helical coils are well suited for *l.v. windings of large transformers*. They can also be used for h.v. windings by putting extra insulation between layers in addition to insulation of conductors.

(*iii*) **Continuous disc winding.** This type of winding consists of a number of flat strips wound spirally from inside (radially) outwards. The conductor is used in such lengths as are sufficient for complete winding or section of winding between tappings. The conductor can either be a single strip or a number of strips in parallel, wound on the flat. This gives a robust construction for each disc. The discs are wound on insulating cylinders spaced from it by strips along the length of cylinder. The discs are separated from each other with press board sectors attached to the vertical strips. The vertical and horizontal spacers provide ducts for free circulation of oil which is in contact with every turn.

Sandwich coils. Sandwich coils (Fig. 12.65) are employed in transformers of shell type. Both high and low voltage windings are split into a number of sections. Each high voltage section lies between the low voltage sections.

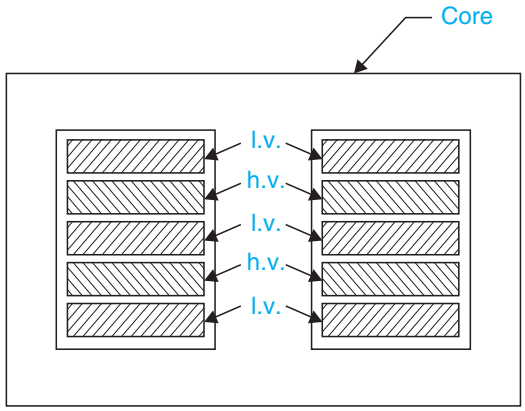


Fig. 12.65. Sandwich coils.

The *advantage of sandwich coils is that their leakage can be easily controlled and so any desired value of leakage reactance can be had by the division of windings.*

12.3.7.2. Terminals and leads

The connection to the windings are of insulated copper rods or bars. The shape and size of leads is important in high voltage transformers owing to dielectric stress and corona which are caused at bends and corners. Connections from windings are directly taken to the busbars in the case of air-cooled transformers while they are taken to insulated bushings in the case of coiled-cooled transformers.

12.3.7.3. Tappings

In a supply network the voltage can be controlled by changing the transformation ratio. This can be done by tapping the winding in order to alter the number of turns. The change in number of turns may be effected when the transformer is out of circuit (known as off load tap changing)

or when on load (known as on load lap changing). The tappings are provided on the high voltage winding because a fine voltage variation is obtained owing to large number of turns. It is difficult to obtain voltage variation within close percentage limits in low voltage winding as there are few turns and voltage per turn is a large percentage of the total voltage.

In transformers, the tappings can be provided at :

(*i*) phase ends ; and

(*ii*) neutral point or in the middle of the windings.

— The advantage of providing tappings at *phase ends* is that the number of bushing insulators is reduced, this is important where the cover space is limited. Some transformers have reinforced insulation at the phase ends. It is essential that in such cases either the tapping should not be provided at end turns or the reinforcement should be carried beyond the lower tap.

— When the tappings are made at the *neutral point* the insulation between various parts is small. *This arrangement is economical especially in the case of high voltage transformers*.

12.3.7.4. Bushings

The bushings are *employed for insulating and bringing out terminals of the winding from the container to the external circuit*. For low-voltage transformers this is accomplished by employing *bushings of porcelain around the conductor at the point of entry*. For high voltages it is necessary to employ bushings of larger sizes. In modern transformers the problem is met by using *large porcelain* or *composition bushings for voltages as high as 33 kV, above that oil filled or condenser type bushings are used*.

12.3.8. Transformer Cooling

12.3.8.1. Cooling methods

The transformers get heated due to iron and copper losses occurring in them. It is necessary to dissipate this heat so that the temperature of the winding is kept below the value at which the insulation begins to deteriorate. The *cooling of transformers is more difficult than that of rotating machines because the rotating machines create a turbulent air flow which assists in removing the heat generated due to losses*. Luckily the losses in transformers are comparatively small. Nevertheless the elaborate cooling arrangements have been devised to deal with the whole range of sizes.

As far as cooling methods are concerned, the transformers are of following two types :

1. Dry type
2. Oil immersed type.

Dry Type Transformers. Small transformers upto 25 kVA size are of the dry type and have the following cooling arrangements :

(*i*) **Air natural.** In this method the natural circulation of surrounding air is utilized to carry away the heat generated by losses. A sheet metal enclosure protects the winding from mechanical injury.

(*ii*) **Air blast.** Here the transformer is cooled by a continuous blast of cool air forced through the core and windings (Fig. 12.66). The blast is produced by a fan. The air supply must be filtered to prevent accumulation of dust in ventilating ducts.

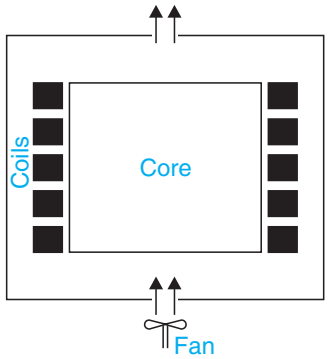


Fig. 12.66

Oil Immersed Type Transformers. In general most transformers are of oil immersed types. The *oil provides better insulation than air and it is a better conductor of heat than air*. Mineral oil is used for this purpose.

Oil immersed transformers are classified as follows :

(*i*) **Oil immersed self-cooled transformers.** The transformer is immersed in oil and heat generated in cores and windings is passed to oil by conduction. Oil in contact with heated parts rises and its place is taken by cool oil from the bottom. The natural oil transfers its heat to the tank walls from where heat is taken away by the ambient air. The oil gets cooler and falls to the bottom from where it is dissipated into the surroundings. The tank surface is the best dissipator of heat but a plain tank will have to be excessively large, if used without any auxiliary means for high rating transformers. As both space and oil are costly, these auxiliary means should not increase the cubic capacity of the tank. The heat dissipating capacity can be increased by providing (*i*) corrugations, (*ii*) fins, (*iii*) tubes (Fig. 12.67), and (*iv*) radiator tanks.

The *advantages of 'oil natural' cooling is that it does not clog the ducts and the windings are free from effects of moisture*.

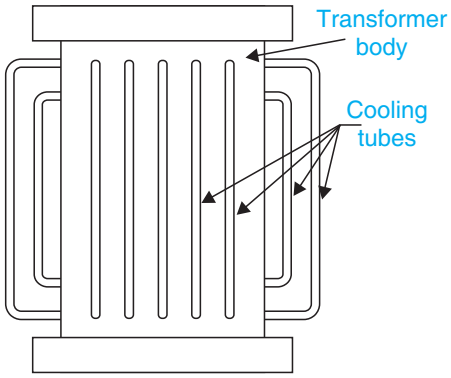


Fig. 12.67. Transformer with cooling tubes.

(*ii*) **Oil immersed forced air-cooled transformers.** In this type of cooling, air is directed over the outer surfaces of the tank of the transformer immersed in oil.

(*iii*) **Oil immersed water-cooled transformers.** Heat is extracted from the oil by means of a stream of water pumped through a metallic coil immersed in the oil just below the top of the tank. The heated water is in turn cooled in a spray pond or a cooling tower.

(*iv*) **Oil immersed forced oil cooled transformers.** In such transformers heat is extracted from the oil by pumping the oil itself upward through the winding and then back by way of external radiators which may themselves be cooled by fans. The *extra cost of oil pumping equipment must of course be economically justified but it has incidentally the advantage of reducing the temperature difference between the top and bottom of enclosing tank*.

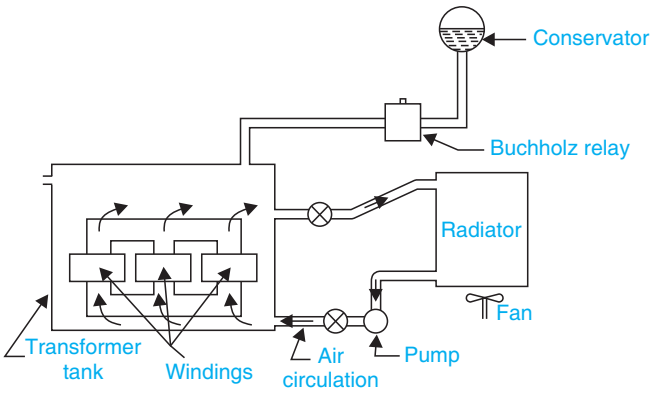


Fig. 12.68. Air blast cooling of radiator.

Fig. 12.68 shows the cooling of transformers having capacities from 10000 kVA and higher. In such cases air blast cooling of radiator is used.

12.3.8.2. Transformer oil

It is a mineral oil obtained by refining crude petroleum. It serves the following purposes :

(*i*) Provides additional insulation.

(*ii*) Carries away the heat generated in the core and coils.

(*iii*) Protects the paper from dirt and moisture.

The transformer oil should possess the following properties :

1. High dielectric strength.
2. Low viscosity to provide good heat transfer.
3. Good resistance to emulsion.
4. Free from inorganic acid, alkali and corrosive sulphur.
5. Free from sludging under normal operating conditions.
6. High flash/fire point.

12.3.8.3. Conservator and breather

Conservator. The oil should not be allowed to come in contact with atmospheric air as it may take up moisture which may spoil its insulating properties. Also air may cause acidity and sludging of oil. To prevent this, many transformers are provided with conservators. The *function of a conservator (Fig. 12.68) is to take up contraction and expansion of oil without allowing it to come in contact with outside air*. The conservator consists of an air tight metal-drum fixed above the level of the top of the tank and connected with it by a pipe. The main tank in completely filled with oil when cold. The *conservator is partially filled with oil*. So the oil surface in contact with air is greatly reduced. The sludge thus formed remains in the conservator itself and does not go to the main tank.

Breather. When the temperature changes, the oil expands or contracts and there is a displacement of air. When the transformer cools, the oil level goes down, and air is drawn in. This is known as *breathing*. The air, coming in, is passed through an apparatus called breather for the purpose of extracting moisture. The *breather consists of a small vessel which contains a drying agent like silica gel crystal impregnated with cobalt crystal*.

Note. *Sludging* means the slow formation of solid hydrocarbons due to heating and oxidation. The sludge deposit itself on the windings and cooling ducts producing overheating. This makes transformer still hotter producing more sludge. This process may continue till the transformer becomes unusable due to overheating. So the contact of oil with air should be avoided as the air contains oxygen.

12.3.9. Three Phase Transformer

12.3.9.1. Three-phase transformer connections

Virtually all power distribution is by poly-phase system of voltages. Three-phase transformations may be made with the use of properly connected single-phase transformers.

These connections are in extensive commercial use. The most frequently used connections are the following :

(*i*) Primary *Y*—secondary *Y*.

(*ii*) Primary Δ—secondary Δ.

(*iii*) Primary Δ—secondary *Y*, or *vice versa*.

(*iv*) Primary and secondary open Δ.

(*v*) Primary *T*—secondary *T* (Scott connection)

Thus the most common connections are *Y*-*Y*, Δ-Δ, *Y*-Δ, Δ-*Y*, open delta or *V*-*V* and Scott connection or *T*-*T* connection.

The Y-Y connection. Fig. 12.69 shows a bank of three transformers connected in *Y* on both the primary and secondary sides. If the ratio of transformation of each transformer is *K*, the same ratio will exist between the *line* voltages on the primary and secondary sides. This *connection will give satisfactory service only if the three-phase load is balanced* ; when the load is unbalanced, the electrical neutral will shift from its exact centre to a point that will make the line-to-neutral voltages unequal.

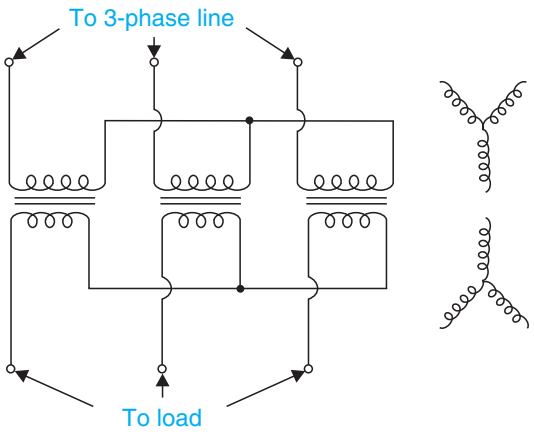


Fig. 12.69. The *Y*-*Y* connection of transformers.

Advantages :

1. This type of connection requires fewer turns per winding since the voltage across each is $\frac{1}{\sqrt{3}}$ times the line voltage ; hence it is *cheaper*.

2. The phase or winding current being equal to the line current, the cross-section of the winding wire is large, therefore, the winding is stronger to bear stresses imposed upon it during heavy load or short circuit.

3. There is less dielectric stress on the insulating materials owing to lesser voltage *i.e.*, $\frac{1}{\sqrt{3}}$ of line voltage.

The above advantages are enumerated with the understanding that, other things being equal, its rival is the delta-delta connection.

Disadvantages :

1. In case the load on the secondary side is unbalanced, as in the case of distributing network, the potential of the star-point will assume any value if the star-point is not earthed. This may impose full-line voltage on secondary windings. The shifting of the neutral point must be prevented by connecting the primary star-point to the star-point of the alternator winding.

2. In spite of grounding the star-point, if there is a third harmonic in the form of the alternator voltage, the third harmonic will appear in the voltage of the secondary side. This will cause triple frequency currents in the three-phase circuits. These currents when they flow in the neutral wire are additive and do not cancel out. Hence they will *cause interference to telephone lines located along the same route*.

3. The magnetising current in a transformer has third harmonic components. These currents will find a return path via the connection between the primary star-point of transformer and the neutral point of the alternator. However, if this connection is missing, these components will distort the flux wave which will produce a voltage having a third harmonic in each of the transformer, both on the primary and secondary sides. And, as before, if the star-point on the secondary is earthed, or grounded, triple harmonic currents will appear in the secondary circuit, and they will flow through the neutral wire causing interference to telephone lines in the vicinity.

4. If the star-points of both the primary and the secondary sides are not earthed, the regulation of the phases will be very poor if the load happen to be unbalanced as in the case of distribution network.

The Δ-Δ connection. Fig. 12.70 shows a bank of transformers connected in Δ on both the primary and secondary sides. *This arrangement is generally used in systems in which the voltages are not very high and especially when continuity of service must be maintained even though one of the transformers should fail.*

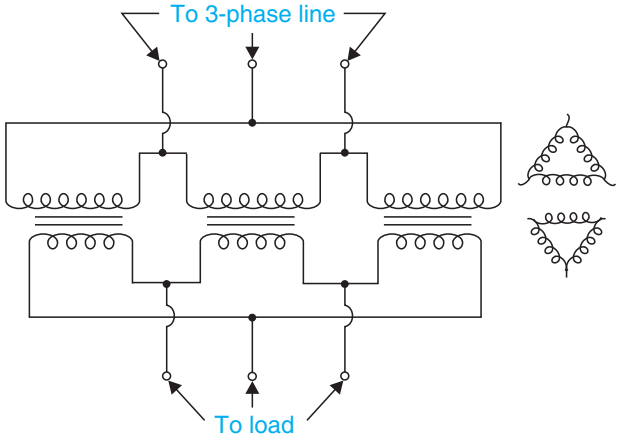


Fig. 12.70. The Δ-Δ connection of transformers.

Advantages :

1. The system voltages are more stable in relation to an unbalanced load.

2. If one transformer fails it may be switched out of the line and operation continued at a reduced power level. This is known as open-delta or *V-V* operation.

3. There is no distortion of flux, because the third harmonic component of magnetising current can flow in the delta connected primary windings without flowing in the line wires.

4. No difficulty is experienced due to unbalancing of loads on secondary side.

Disadvantages :

1. In comparison to *Y-Y* connections it requires more insulation.

2. The absence of star-point may be disadvantageous. If one line gets earthed due to fault, maximum voltage between windings and core will be full line voltage.

The Y-Δ connection. The *Y*-Δ connection is shown in Fig. 12.71.

It is principally used where the voltage is to be stepped down, as for example, at the end of a transmission line. It is also employed in *moderately low-voltage distribution circuits for stepping down* from transmission voltages of 4000 or 8000 V to 230 (and 115 V).

— The *Y* connection takes advantage of the fact one leg of a *Y*, or the line-to-neutral voltage, is less than the line-to-line voltage by a $\sqrt{3}$ factor. This is especially important when the primary voltage is a few hundred thousand volts.

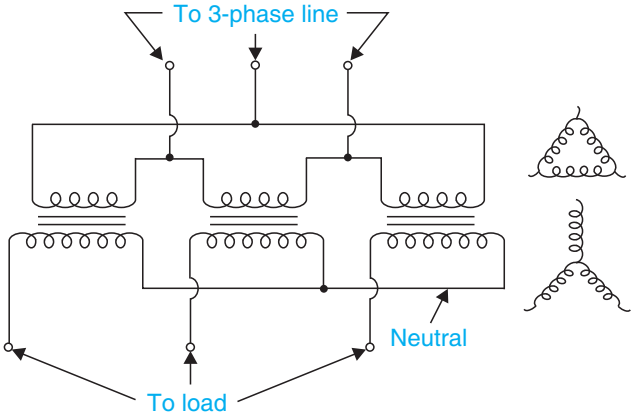


Fig. 12.71. The *Y*-Δ connection.

— The *Y*-Δ does have a phase shift between the primary and secondary voltages. This 30° phase shift means that a *Y*-Δ transformer bank *cannot* be paralleled with either a *Y-Y* or a Δ-Δ. The phasor voltage differences between the two systems would be around sin 30° = 0.5 times the secondary voltages. This would cause an excessive circulating current between transformer banks.

The Δ-Y Connection

— The three-phase Δ-*Y* connections are shown in Fig. 12.72.

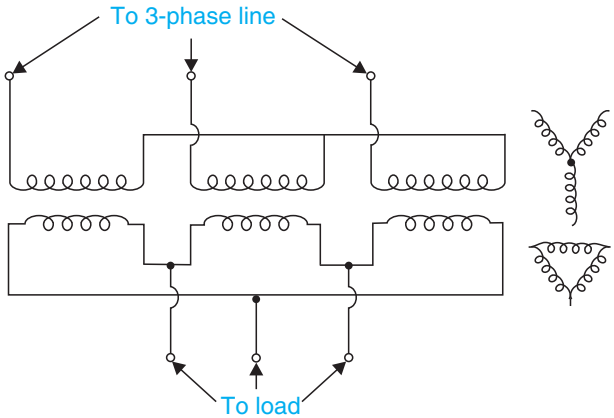


Fig. 12.72. The Δ-*Y* connection of transformers.

— This type of connection is employed where it is necessary to *step up the voltage*, as for example, at the beginning of a high-tension transmission system.

— The ratio of secondary to primary voltage is $\sqrt{3}$ times the transformation ratio of each transformer.

— The neutral of the secondary is grounded for providing 3-phase 4-wire service. This connection is popular since it can be used to serve both the 3-phase power equipment and single-phase lighting circuit.

— This connection is not open to the objection of a floating neutral and voltage distortion because the existence of a Δ-connection allows a path for the third-harmonic currents. It would be observed that the primary and secondary line voltages and line currents are out of phase with each other by 30°. Because of this 30° shift, it is impossible to parallel such a bank with a Δ-Δ or *Y-Y* bank of transformers even though the voltage ratios are correctly adjusted.

The V-V (open-Δ) Connections. Fig. 12.73 shows the *V-V* connection.

If one of the transformers of a Δ-Δ bank is removed and a three-phase source is connected to the primaries (as shown in Fig. 12.73), three equal three-phase voltages will be measured at the secondary terminals at no-load. This method of transforming three-phase power, using two transformers, is called the open-delta, or *V-V* connection.

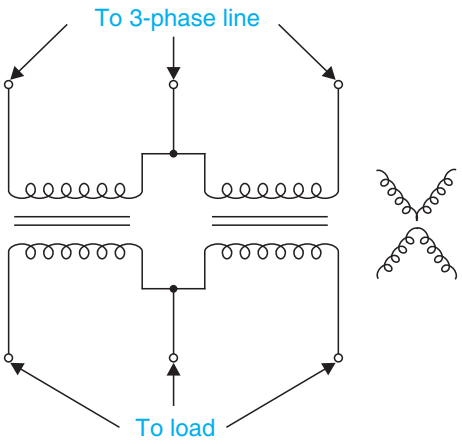


Fig. 12.73. The *V-V* (open Δ) connection of transformers.

This type of connection is used in the following cases :

(*i*) When the three-phase load is comparatively small so that the installation does not warrant a three transformer bank.

(*ii*) When one of the transformers in a Δ-Δ bank fails, so that the service may be continued until the faulty transformer is repaired or a good one is substituted.

(*iii*) When it is anticipated that the future load will increase to warrant the chosing of the open Δ at some time later.

V-V connection has a number of *features* that are advantageous.

— Upon failure of the primary or secondary of one transformer of a complete Δ-Δ transformer circuit, the system reverts to a *V-V* circuit, so this is an *automatic stand by*. The power-handling capacity of a *V-V* circuit is $\frac{1}{\sqrt{3}}$ times the capacity of a full Δ-Δ of the same transformers. This feature works both ways, so a circuit is sometimes installed as *V-V* with the understanding that its power handling may be multiplied by $\sqrt{3}$ by adding one more transformer.

— Open delta or *V-V* circuits do introduce some voltage unbalance due to the non-symmetry of the voltage regulation effects under load. However, the small degree of unbalance is not normally noticed by a motor load or other types of commercial load.

Disadvantages of V-V connection

1. The secondary terminal voltages tend to become unbalanced to a great extent when the load is increased, this happens even when the load is perfectly balanced.

2. The average factor at which the *V*-bank operates is less than that of the load. This power factor is actually *86.6 per cent of the balanced load factor*. Another important point to note is that, except, for a balanced unity power factor load, the two transformers in the *V-V* bank operate at different power factors.

Uses of V-V connection

(*i*) The *V-V* circuit is frequently used for two *auto-transformers*. Here advantage is taken of power handling of auto-transformers and their superior voltage regulation and efficiency.

(*ii*) Another major use of *V-V* transformer banks is in *A.C. motor starting*.

Scott or T-T connection. The connection of one polyphase system into another polyphase system is possible by suitably connecting the windings of transformers. One of the early types that was used is Scott or *T-T* connection, by which a 2-phase system is available from a 3-phase system or *vice-versa*.

Fig. 12.74 shows two single-phase transformers *M* and *T*, the primaries of which are connected to a 3-phase supply. The secondary of *M* forms one phase and the secondary of *T* the other phase of a true 2-phase system. *M* is called the *main transformer* and *T* is called the *teaser*. One end of the teaser primary is connected to the mid-point of the main primary. The two ends of the main primary are connected to two lines wires of a 3-phase, 3-wire system, and the third line wire is connected to a tapping *X* on the teaser primary.

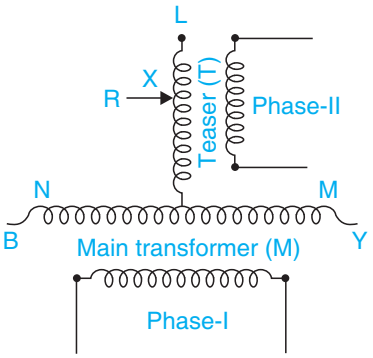


Fig. 12.74. Scott or *T-T* connection.

If the supply voltages are assumed symmetrical, the triangle of voltages is equilateral as shown in Fig. 12.75. The vertical line $LS = \frac{\sqrt{3}}{2} NM$, so that it gives the relationship between the number of turns of two primaries, as

$$\frac{\text{Number of turns for the main transformer M}}{\text{Number of turns for the teaser T}} = \frac{100}{86.6}$$

Hence, if two identical single-phase transformers are to be used for Scott-connection, the primary one must have a tapping point brought out from its *mid-point of the primary*, and the second transformer must have a tapping *X* brought out from *86.6%* of *its primary turns*.

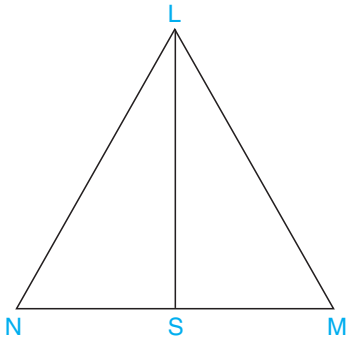


Fig. 12.75

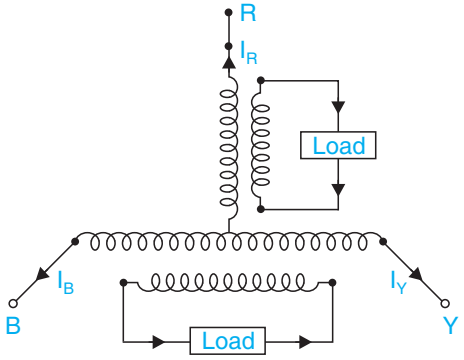


Fig. 12.76

As the two-phase side is asymmetrical, there cannot be perfect balanced conditions on the three-phase side. However, neglecting the impedance of the windings, it can be shown that if load on the 2-phase side is balanced the 3-phase side is also balanced (Figs. 12.76, 12.77 and 12.78).

— Fig. 12.76 shows the connection diagram. The 2-phase side has equal load impedances.

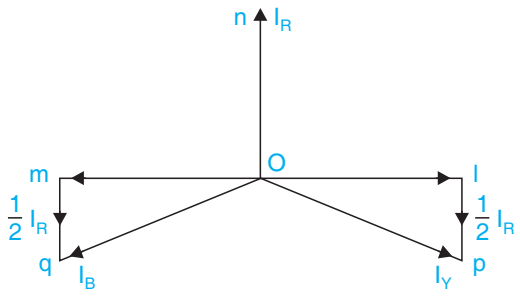


Fig. 12.77

— In Fig. 12.77, the vector diagram is drawn for *unity power factor load*. The secondary currents are not shown. *On* is the *teaser* primary current, and since it flows at the mid-point of the *main transformer*, it divides itself equally in two halves. The resultant current in the lines *B* and *Y* is the vector sum of the balancing amperes of the main primary and $\frac{1}{2}$ the current of the teaser primary. Hence *op* and *oq* are the line currents. Below is the proof that *ol* = *om* = *on*, and that each one of these currents is at 120° from the other two.

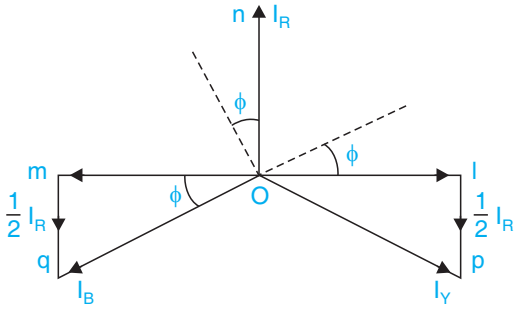


Fig. 12.78

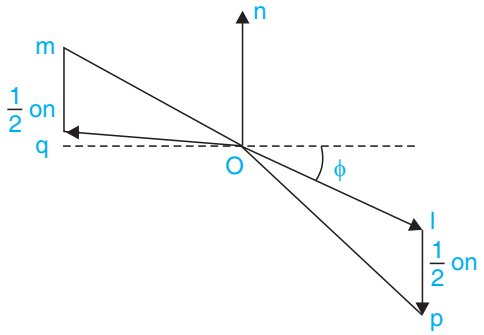


Fig. 12.79

Proof. Let us assume that the ratio of turns of the *main* transformer be 100 : 100 (primary to secondary) and that of teaser 86.6 : 100. If the secondary load-currents are 100 A at unity power factor, the primary balancing amperes of the main transformer will be 100 and lie along *ml*. The *teaser* balancing amperes will be $\frac{100}{86.6} \times 100 = 115.4$ and will lie along *on*. The *teaser* primary current splits into half at 0 and flows in the two halves of the main primary. Hence the line current in *Y* and *B* is given by $\left[(100)^2 + \left(\frac{115.4}{2}\right)^2\right]$ since these two components are at right angles to each other. Now $\left[(100)^2 + \left(\frac{115.4}{2}\right)^2\right]^{1/2}$ = 115.4 A and the angle between *ol* and *op* is ϕ such that $\phi = \tan^{-1}\frac{57.7}{100} = 30°$ (Fig. 12.77). Hence *op* lags *on* by 90° + 30° = 120°. Q.E.D.

— In Fig. 12.78, the vector diagram is drawn for a condition when the *load power factor is cos* ϕ. The same proof can be applied to this case as was done for the case of unity power factor. If the loads are unbalanced and have different power factors, such as cos ϕ_1, and cos ϕ_2, primary side becomes unbalanced. The vector diagram of Fig. 12.79 shows the extent of unbalanced when the *teaser* load is of unity power factor and the *main* transformer load has a power factor of cos ϕ (lag).

12.3.9.2. Three-phase transformer construction

— The windings of three single-phase transformers can be wound on a common core. The *advantages* and *disadvantages* are given below :

Advantages :

1. One 3-phase transformer is *cheaper* than three single-phase transformers.

2. It has *slightly better efficiency and regulation*.

3. A 3-phase transformer takes *less floor space*.

On the other hand, from the point of view of stand by, or same capacity, it is economical to have 3 single-phase transformers *plus* one spare rather than two 3-phase transformers one of which is a spare. However, in large central stations 3-phase transformers are often advantageous.

Disadvantages :

1. Three-phase transformers are much more difficult and costly to repair than are single-phase units.

2. When failure does occur and it becomes necessary to substitute a replacement unit to maintain service, the cost of spare is much greater than it would be were a single-phase transformer to be used as a replacement in a three-transformer bank.

3. There is a difficulty in transporting a heavier three-phase transformer compared with the moving of each of the three single-phase transformers.

— Two general kinds of three-phase transformers are recognized, similar to single-phase transformers, depending upon the relative arrangements of windings and cores. These are the *core type* and the *shell type*.

Three-phase core type transformer. Fig. 12.80 shows three core-type transformers placed together so that they have a common path for the return magnetic circuit. Although the windows should be entirely filled by primary and secondary coils on each of the legs, only primary coils are shown on the outside legs. This simplifies the diagram, while it in no way changes the actual theory that follows, since the primary coils set up the flux. If the three transformers are identical in all respects, a balanced three-phase system of voltages will produce three fluxes in the cores which have the same maximum value, but differ in time phase by 120°. In the common leg of the three cores of Fig. 12.81, the three fluxes add, and the net flux is therefore always zero. The common leg may then be eliminated, with a subsequent saving in core material and size of transformer. A single polyphase transformer would be of impractical construction if it were the same as Fig. 12.80 with the centre leg omitted. Instead, the core-type polyphase transformer is manufactured so that it looks

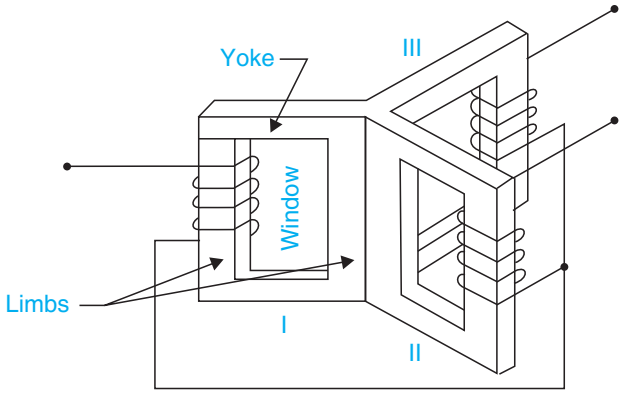


Fig. 12.80. Core-type transformers for polyphase transformation.

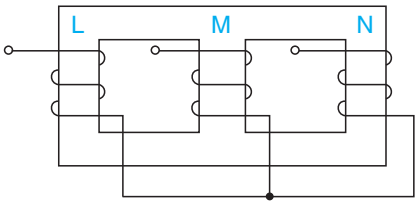


Fig. 12.81. Core-type three-phase transformer.

like that shown in Fig. 12.81. Actually, what we have done is, that axes of three coils have been moved into one plane. This causes the magnetic reluctance of coil M to differ somewhat from that of L and N. This produces a slight unbalance in the three magnetizing currents, but the effect is not serious, especially under load.

Three-phase shell type transformer

— In Fig. 12.82 are shown three shell-type transformers stacked one above the other, with only the primary coils shown.

— In Fig. 12.82 (a) the three coils are wound in the same direction. The flux in the common core area between adjacent phases such as the shaded portions is thus equal to the *difference* of two of the phase fluxes. Since the fluxes are 120° apart in time, this mutual flux is equal to $\sqrt{3} \times (\frac{1}{2}\ \phi)$, or 0.866 of the flux in the centre leg. If the same flux density is maintained throughout, less iron is required in the common

leg. Now, however if the centre coil, phase *M* is reversed, the flux in the common core is equal to the *sum* of the fluxes of two adjacent phases. This is shown in Fig. 12.82 (*b*). As in any three-phase system, the sum of two fluxes is equal to either flux alone, which in this case is 0.5 ϕ. This represents a further saving in iron, and for this reason shell-type three-phase transformers are *usually wound with centre coil opposing the two outside ones*.

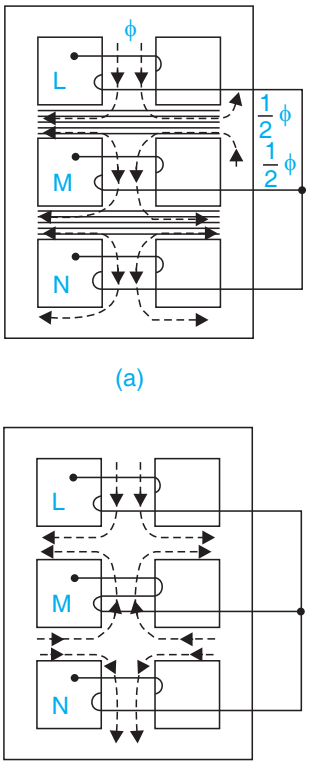


Fig. 12.82. Shell-type three-phase transformer (*a*) coil *M* wound in the same direction, (*b*) coil *M* wound in opposite direction.

12.3.9.3. Parallel operation of 3-phase transformers

The conditions for paralleling 3-phase transformers are same as that required for parallel operation of single-phase transformer with the following additions :

(*i*) *The voltage ratio must refer to the terminal voltage of primary and secondary*.

(*ii*) *The phase displacement between primary and secondary voltages must be the same for all transformers which are to be paralleled*.

(*iii*) *The phase sequence must be the same*.

Following points are worth noting while dealing with 3-phase transformers :

— The calculations are made for one phase only. The value of equivalent impedance used is the equivalent impedance per phase referred to secondary.

— When the impedances of primary and secondary windings are given separately, then primary impedance must be transferred to secondary by multiplying it with (transformation ratio)^2.

— In case of *Y*/Δ or Δ/*Y* transformers the voltage ratios as given in the questions, refer to terminal voltages and are quite different from turn ratio.

12.3.10. Instrument Transformers

It is not practicable to connect instruments and meters directly to the lines in high voltage circuits. Instead instrument transformers are used. The following are the *two basic advantages* inherent in this method :

(*i*) Standard rated instruments may be used.

(*ii*) Operating personnel coming in contact with the instruments are not subject to high voltage and current of the lines, and so there is less danger to them. Even with a low-voltage system, instrument transformers are used for measuring large currents, so that heavy leads to the instrument panel and to the ammeter and other current terminals are avoided.

The principle of the instrument transformer is fundamentally the same as that of the power transformer. The instrument transformers are classified as follows :

1. Potential transformers.
2. Current transformers.

12.3.10.1. Potential transformers (P.T.)

— A potential transformer is a *step down transformer* used along with a low range voltmeter for measuring a high voltage. The primary is connected across the high voltage supply and the secondary to the voltmeter or potential coil of the wattmeter. Since the voltmeter (or potential coil) impedance is very high, the secondary current is very small and the potential transformer behaves as an ordinary two winding transformer operating on no-load. Fig. 12.83 shows a potential transformer used to measure the voltage of a circuit. It may be noted that the secondary is grounded. This is done so that if the insulation breaks down, the high voltage does not endanger personnel who may be reading the meters.

— These transformers are *made with high quantity iron core operating at very low flux densities so that the magnetising current may be very small*. Careful design ensures minimum variation of voltage ratio with load and minimum phase shift between input and output voltages. Potential

transformer secondaries are commonly designed for an output of 110 V.

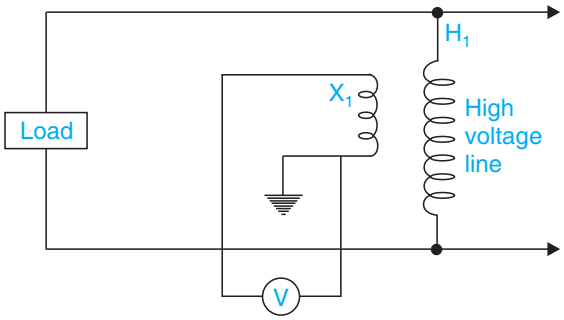


Fig. 12.83. Potential transformer connections.

12.3.10.2. Current transformers (C.T.)

— Just as a shunt extends the range of a D.C. ammeter, so does the current transformer perform the same function in A.C. circuits. Thus a *high magnitude alternating current can be easily measured by a combination of a current transformer and a low range ammeter*.

— The primary of a current transformer (C.T.) consists of a few turns of thick cross-section connected in *series* with the high current line. Very often the primary is just one turn formed by taking the line conductor through the secondary winding (Fig. 12.84). The secondary winding consists of a large number of turns of fine wire designed for either 5 A or 1 A rating. Thus a current transformer is *step-up* transformer. The current transformer has the secondary effectively short-circuited through the low impedance of the ammeter. Fig. 12.85 shows the current transformer connections.

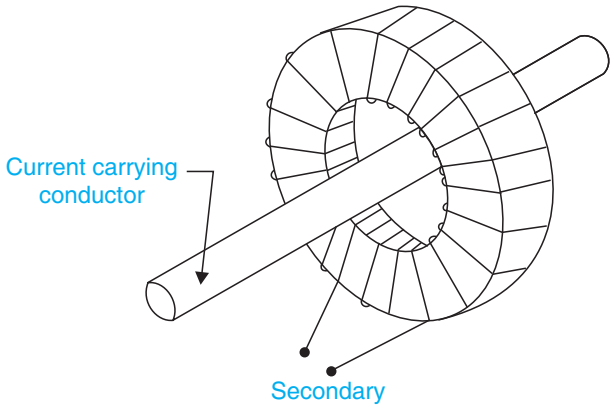


Fig. 12.84. Line conductor acting as primary.

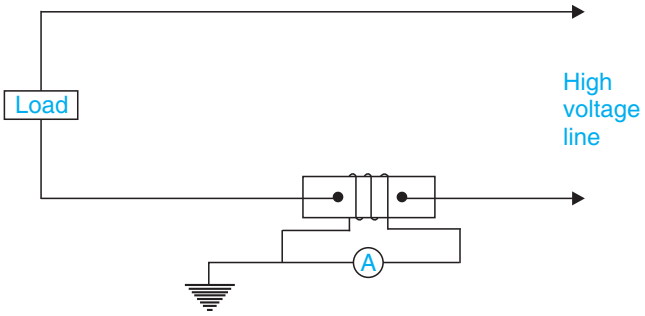


Fig. 12.85. Current transformer connections.

— The *current transformer ratio is not equal to the ratio of secondary to primary turns, mainly because of the effect of the magnetising current*. The primary current can be thought of as the sum of two currents, the first to balance secondary current so that primary and secondary m.m.fs. may balance and the second being the no-load current I_0. The component I_0 besides being responsible for a slight error in the current ratio, is also responsible for a phase angle error. The transformer *must be carefully designed to minimise the ratio and phase angle error*.

— It may be noted that current transformer must never be operated on open-circuit for the following two reasons :

(*i*) There will be no secondary m.m.f. and since the primary current (and m.m.f.) is fixed, the core flux will increase enormously. This will cause large eddy current and hysteresis losses and the *resulting high temperature may damage the insulation or even the core*.

(*ii*) A very high voltage will be induced in the multi-turn secondary and this high voltage may be dangerous both to life and to the insulation.

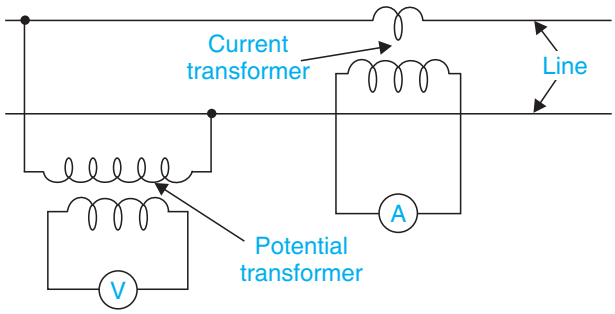


Fig. 12.86. Wiring diagrams for potential and current instrument transformers.

Fig. 12.86 shows the wiring diagrams for potential and current instrument transformers.

12.3.11. Constant Current Transformers

A constant-current transformer is used for *supplying power to street lights which are connected in series*. The *primary of this transformer receives power at constant voltage and varying current and the secondary supplies power at constant current and varying voltage*, which depends upon the number of lamps in series.

Principle of operation. The principle of operation of a constant-current transformer is illustrated in Fig. 12.87.

— One coil is stationary while the other one is movable, and its weight is partly balanced by a counter-weight *W*. Either coil may be the movable coil.

— The openings through the coils are much longer than the core. This permits a large leakage flux to be set up through the coils when the currents are maintained in them.

— It is clear from Fig. 12.87 that a mechanical force of repulsion exists between the coils. This force tends to drive the movable coil upward on the core, and owing to the counter weight, a relatively small force produces motion. *At maximum load the movable coil is close to the stationary one and the voltage induced in the former is a maximum*. When the secondary load is *reduced* by cutting out some of the lamps in the series circuit, the current in the remaining units increases momentarily. This cause the force of repulsion to increase. The *floating coil then moves upward and thereby increases the equivalent leakage reactance of the transformer, reduces the secondary voltage*, and *brings the current back to normal. The coil comes to rest when the terminal voltage is properly reduced to suit the lesser number of lamps and the current attains its correct constant value*.

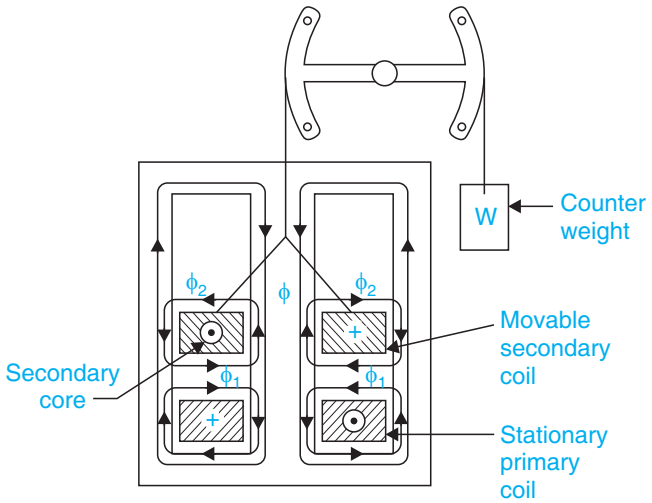


Fig. 12.87. Constant-current transformer.

— The *rating* is usually given in kW, and the secondary current. The standard values of current are 6.6, 7.5 and 20 A. The load power factor is almost 100%. The *regulation* is expressed as *the percentage of the current (secondary) from its rated value. The regulation should not exceed 1%*.

12.4. SWITCHGEAR

The switchgear constitutes all parts or equipments of the power plant whose function is to receive and distribute electric power. It comprises of the following :

(*i*) Assemblies of switching apparatus

(*ii*) Protective and indicating metering devices

(*iii*) Interconnecting bus bar systems and relevant accessories.

12.4.1. Functions of a Switchgear

The functions performed by a switchgear are listed below :

1. To localise the effects of faults by operation of protective equipment and so automatically disconnect faulty plant from the system.

2. To break efficiently short circuits without giving rise to dangerous conditions.

3. To facilitate redistribution of loads, inspection and maintenance on the system.

12.4.2. Switches

The most important types of switches fall in one of the following classes :

(*i*) Knife switches (*ii*) Disconnecting switches

(*iii*) Air-break switches (*iv*) Control switches

(*v*) Auxiliary switches (*vi*) Oil switches

(*vii*) Magnet impulse switches.

(*i*) **Knife switches.** These switches are used to open and close circuit of *low voltage and current capacity*. They are extensively used in lighting and small power circuits. In order to protect such low capacity circuits against overloads and short circuits, it is necessary that proper fuses be connected in series with the switch blades.

(*ii*) **Disconnecting switches.** For power circuits it is necessary to use some type of circuit breaker to open or close the circuit. In order to isolate the circuit breakers it is generally considered good practice to connect knife switches in series with the circuit breakers. Such knife switches are known as *disconnecting switches*. They *should never be opened until the circuit breaker in the same circuit has been opened, and should always be closed before the circuit breaker is closed*. They are *not designed to break currents* and should therefore, *never, be opened while current is flowing in the line*.

(*iii*) **Air-break switches.** By "*air-break*" switches are meant switches designed to *open circuits under load*.

They are generally used outdoors for circuits of medium capacity, such as lines supplying an industrial load from a main transmission line or feeder. In order to take of the arc that occurs on opening such a switch, special arcing horns are provided, so that the arc may rise and be ruptured. Air-break switches are built for about 135,000 volts maximum but their use is in general confined to lower voltages. *These switches are not designed to operate under abnormal conditions, such as short circuits*.

(*iv*) **Control switches.** Under this class are included all the switches that are used to *control the operation of other equipment*. As a general rule, they are designed for operating voltages less than 250 volts and very small current capacities.

(*v*) **Auxiliary switches.** Under this class are included all switches or contractors that are *actuated by some other control switch or device*. In the control of power equipment, such as circuit breakers, it is impracticable to handle the operating current through the control switches on the switch-board, hence an auxiliary operating switch is placed near the circuit breaker, this switch being electrically operated by a control switch that may be located at any desired distance from the circuit breaker. Thus, the control circuits may be designed for very small currents, while the operating circuits as a general rule must handle much large currents and very often at higher voltages.

(*vi*) **Oil switches.** For certain applications at high voltages and large current capacities it is desirable to immerse the switch contacts under oil. The effect of the oil is to cool and quench the arc that tends to form when the circuit is broken.

(*vii*) **Magnet impulse switches.** In this type of switch the arc is extinguished by blowing it magnetically into arc chutes where it is lengthened, cooled, and interrupted. The magnetic effect is produced by the circuit current which is passed through suitable coils, setting up a strong magnetic field across the space between the switch contacts as they are opened. The basic principle involved in lengthening the arc is that of a simple motor, in which force is directly proportional to the product of magnetic flux and current.

12.4.3. Fuses

Fuses are used to protect circuits of small capacity against abnormal currents such as overloads or short-circuits.

There is a large variety of fuses on the market, but the most important types that are used for power purposes are :

1. Cartridge fuses
2. Transformer fuse blocks
3. Expulsion fuses.

1. **Cartridge fuses.** These fuses are composed of a strong fibre casing inside of which is enclosed a fuse wire, generally an alloy of lead. The fuse voice is fastened to copper caps which are fastened to each end of the casing. Fuses of general type are available for circuits upto about 25000 volts. There are on the market a large number of fuses of the general type, the particular details of construction being very varied. They are used as a protective device in low-capacity circuits, such as small lighting and power lines, and on the secondary of instrument-potential transformers, when used for metering or relay protection.

Fig. 12.88 shows a HRC—cartridge type fuse. HRC stands for high-rupturing-capacity. In its simplest form it consists of a heat resisting ceramic body having metal (brass) end caps to which are welded fusible silver (or bimetallic) current carrying elements. The complete space within the body surrounding the elements is filled with a powder, usually quartz, which acts as an arc extinguishing agent.

When the fuse is carrying normal rated current, the temperature of the fuse element does not reach melting point. On occurrence of a fault short circuit current flows through the fuse element and the fuse element melts before the fault current reaches its first peak. As the heat is produced, the melted fuse element will vapourize. The chemical reaction between silver vapour and filling powder tends to establish the high resistance. The high resistance acts as an insulator because the fault current decreases along with the high pressure created within the fuse by the fault (excessive) current. Thereafter a transient voltage is created at the instant of fault current interruption on account of sudden release of energy.

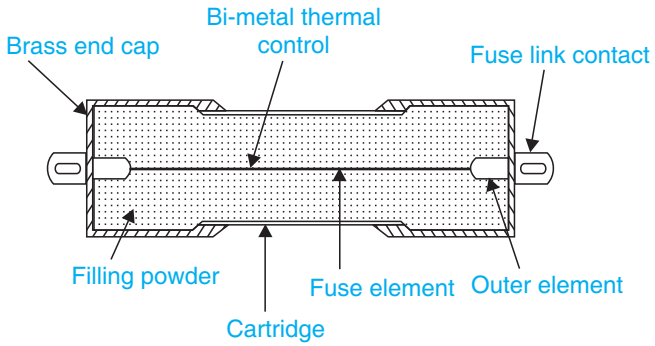


Fig. 12.88. High rupturing capacity catridge fuse.

2. **Transformer fuse block and cut-out.** The proper protection of distribution circuits has for years been recognized as best fulfilled by means of fuses. Distribution transformers are as a general rule placed on poles, towers, or in manholes and any automatic protection would be entirely too complicated and expensive. Fuses offer a simple and cheap method of protection. It is common practice to place these fuses in the *secondary of such transformers*, thereby protecting the transformers against short circuits or overloads. There are two types of fuses that are generally used for the purpose. Both types include a *porcelain*

housing, enclosing the fuse and contact points. In *one type* the fuse is carried on a plug that is provided with an insulating porcelain knob in order that it may be removed for re-using. A *second type* consists of a rectangular porcelain receptacle with a removable front door that carries the fuse.

3. **Expulsion fuse.** For higher voltages such as found in power circuits or main feeders, there is often a demand for a fuse, on account of its simplicity. The expulsion-type fuse has been developed for such service.

This device consists of a hollow tube, made of some heat resisting substance such as fiber with a lining of asbestos or some other material, through which is passed a fuse wire. One end of the tube is closed and connected to the line, the other end is opened and allows the fuse wire to project out and connect to the other terminal. When a short circuit or overload occurs, the fuse is blown and a certain amount of gases form inside the tube. These gases in escaping to the air cause the arc, which is generally produced, to be blown out. Since there is always a tendency for an arc to occur, these fuses are adaptable only to outdoor use. They may be obtained for practically any modern transmission line voltage.

12.4.4. Circuit Breakers

There is probably no other part of a power system that is more important than the *equipment that controls the system*. All the control devices discussed above are suitable for only relatively small capacities, but for large capacities it is necessary to employ more dependable means of control, such as is obtained by the use of circuit breakers.

12.4.4.1. Function of a circuit breaker

The *function of a circuit breaker is to break a circuit when various abnormal conditions arise and create a danger for the electrical equipment in an installation*. The heaviest duty a circuit-breaker has to perform is to interrupt a short-circuit current which may reach a value of several tens of thousands and even more ($> 10^5$ amperes) in a large capacity power system. At the same time, in order to quickly eliminate the source of the fault, the circuit-breaker must open the circuit with least possible delay.

12.4.4.2. Principle of circuit breaker

The breaking of circuit means *rapid conversion of predetermined section of circuit from a conductor to insulator*. When the current carrying contacts are separated, an arc (which contains an ionized gas) is produced between them. This arc provides for the gradual change-over from current carrying to voltage isolating states of the contacts. Therefore, it plays an important part in circuit interruption process. The arc has to be carefully controlled because a good deal of energy in the form of heat is generated in it. The produced arc may be extinguished by high resistance or low resistance methods.

12.4.4.3. Classification of circuit breakers

Circuit breakers may be classified as follows :

1. Low voltage circuit breakers
2. High voltage circuit breakers
   (*a*) Oil circuit breakers
   (*i*) Bulk oil circuit breakers
   (*ii*) Low oil contact circuit breakers
   (*b*) Oil-less circuit breakers
   (*i*) Air blast circuit breakers
   (*ii*) Water circuit breakers
   (*iii*) Hard gas circuit breakers.

Characteristics of High Voltage Rating Circuit Breakers

The high voltage rating circuit breakers should possess the following characteristics :

1. They should have high reliability-electrically and mechanically.

2. They should be capable of interrupting inductive and capacitive circuits and fault currents of all values within their rating.

3. The opening *i.e.*, the time interval between receipt of tripping impulse and contact separation should be the minimum mechanically possible.

Oil circuit breakers (O.C.B.)

These are the most common type of circuit breakers used in power stations. The rating range of these circuit breakers lies between 25 MVA at 2.5 kV and 5000 MVA at 250 kV. The ***advantages*** of using oil as a quenching medium are :

1. It has high dielectric strength.
2. It absorbs arc energy while decomposing.
3. Good cooling property of gas formed (as a result of decomposition of oil).
4. Surrounding oil in close proximity to the arc presents a large cooling surface.
5. It acts as an insulator between live part and earth.
6. The ability of cool oil of high dielectric strength to flow into the arc space after the current is zero.

Disadvantages :

1. It is easily inflammable.
2. It can cause explosion by mixing with air.
3. It requires maintenance and periodic replacement.

Plain break oil circuit breaker :

Fig. 12.89 shows the arrangement of this breaker. There is a strong weather tight earthed metal tank, containing oil upto a predetermined level, and an air cushion above the oil. The oil pressure is this breaker tank is solely due to the head of oil above the contacts which are enclosed in the tank.

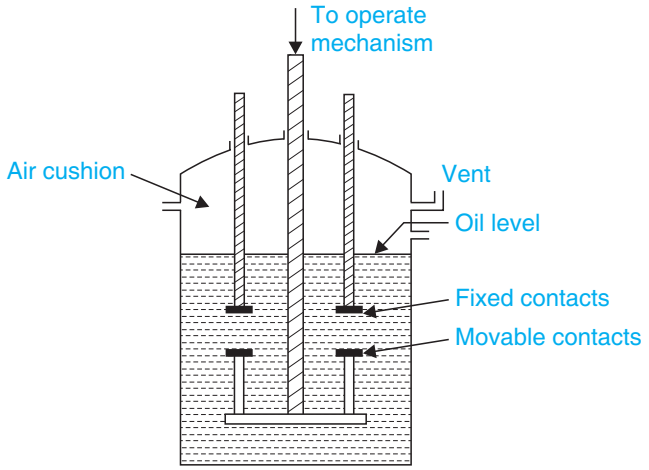


Fig. 12.89. Plain oil circuit breaker.

When the contacts separate an arc is struck. This vaporizes oil into gas. The sudden formation of the gas by arc may dissipate heat generated as a result of arc.

The major drawback of this breaker that it suffers from the defect of *permitting rather long and inconsistent arcing times*. In view of this limitation, such circuit breakers are suitable only for low current and low voltage operations not exceeding 150 MVA at 11 kV.

Air circuit breakers :

In air circuit breakers the compressed air at pressure around 15 kgf/cm^2 is used for extinction of arc. Fig. 12.90 shows a typical air-blast circuit breaker. The extinction of arc is caused by flow of air around the moving circuit. The breaker is closed by applying pressure at the lower opening, and opened by applying pressure at the upper opening. When the contacts separate, the cold air rushes round the movable contact and blows out the arc.

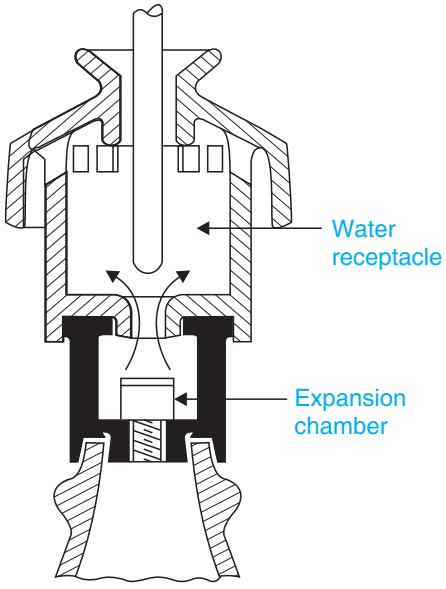


Fig. 12.90. Air blast circuit breaker.

Advantages :

An air circuit breaker claims the following advantages over oil-circuit breaker :

1. Fire hazards due to oil are eliminated.
2. Operation takes place quickly.
3. There is less burning of contacts since arc duration is short and consistent.
4. Facility of high speed re-closure.
5. Suitable for frequent operation (since the cooling medium is replaced constantly).

Limitations

1. Sensitivity to restriking voltage.
2. Current chopping.
3. A compressor is constantly required to remain in operation.
4. The leakage of air at the pipe line fittings creates problems.

Water circuit breaker

The principle of the water circuit breaker is shown in Fig. 12.91. The contacts are in water, which is turned into steam by the arc and rushes past the opening to blow out the arc.

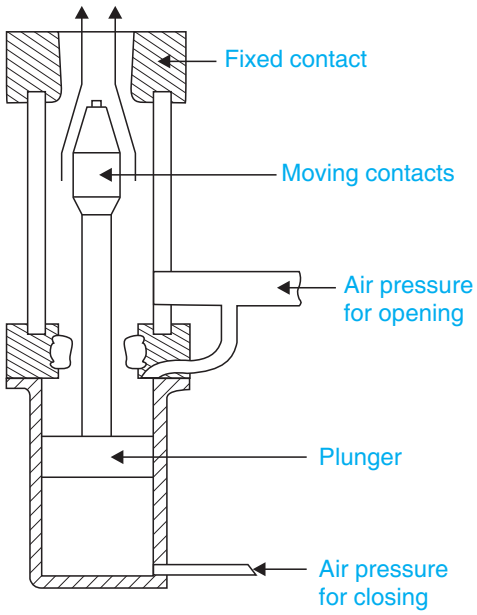


Fig. 12.91. Water circuit breaker.

12.4.4.4. Principles of layout of switchgear

The following principles should be followed while carrying out layout of switch gear :

1. The layout should be such that any section may be isolated without unduly affecting the service.
2. There should be an easy and safe access for general routine inspection and for maintenance.

3. The individual units should be so designed that the risks of failure are reduced to minimum.

4. Fire protection arrangement must be made adequately.

5. To keep the breaking duty within the capacity of the circuit breakers reactors should be used where necessary.

12.4.5. Types of Switchgear

The various types of switchgear are enumerated and discussed below :

1. Cellular 2. Cubicle
3. Truck 4. Metal clad
5. Outdoor switchgear.

1. **Cellular.** The components of this type of switchgear are enclosed in *cells* made of brick, concrete or moulded stone. These components can be easily inspected and modifications can be made without any difficulty. The cellular type gear has the following *disadvantages* :

(*i*) The erection of a cellular type gear is a lengthy process.

(*ii*) It occupies large space.

(*iii*) The interlocking systems may be complicated.

2. **Cubicle.** The whole of the equipment, in this case, is enclosed in steel plate cubicles with complete or partial sub-dividing barriers. It entails the following *advantages* :

(*i*) It requires relatively small floor area.

(*ii*) It presents a neat and simple layout.

3. **Truck.** In this type of switchgear a movable truck carries the circuit breaker moving isolator contacts, and the potential and current transformers. The front panel of the truck fits into the stationary steel cubicle which houses the busbars, cable box, and fixed isolator contacts. When inspection is to be carried out, the truck is withdrawn from the cubicle.

4. **Metal clad.** Here all conductors and insulators are *enclosed by an earthed metal case*. A metal clad switchgear is of two types :

(*i*) Horizontal draw out

(*ii*) Vertical drop down.

A metal clad switch gear has the following *advantages* :

(*i*) As all the live parts are enclosed in metal it ensures safety to operators and reduces maintenance charges.

(*ii*) Maintenance work can be easily carried out (since working parts are easily and safely accessible).

(*iii*) To prevent operating mistakes simple and efficient interlocks can be installed.

(*iv*) Erection on the site can be easily carried out.

(*v*) Since it occupies less space, therefore, building cost in reduced.

5. **Outdoor switchgear.** The following points are worthnoting :

(*i*) Although it requires large ground space but there is a saving in building cost.

(*ii*) Maintenance work is at the mercy of the weather.

(*iii*) The damage from lightning is likely to be more since the equipment is exposed.

(*iv*) Frequent insulation cleaning.

(*v*) As compared to an indoor switchgear its maintenance cost is more.

12.5. PROTECTION OF ELECTRICAL SYSTEMS

12.5.1. General Aspects

Fig. 12.92 shows a typical power system. In such a power system the function of relays and circuit breakers is to prevent or limit damage to the system due to faults or overloads and to isolate the faulty section from the remainder of the system.

The function of the relay system is to recognize the fault and to initiate the operation of devices or circuit breakers to isolate the defective element with the minimum disturbance to the service.

Typical system protective zones are shown in Fig. 12.92. These zones might be classified as :

(*i*) Generators (*ii*) Low-tension busses
(*iii*) Transformers (*iv*) High-tension busses
(*v*) High-tension transmission lines
(*vi*) Feeders.

The speed with which relays and circuit breakers operate has a direct bearing on :

(*i*) The quality of service to consumers

(*ii*) The stability of the system

(*iii*) The amount of power that may be transmitted without exceeding the stability limit

(*iv*) The damage done by a short circuit and consequently the cost and delay in making repairs

(*v*) Safety to life and property.

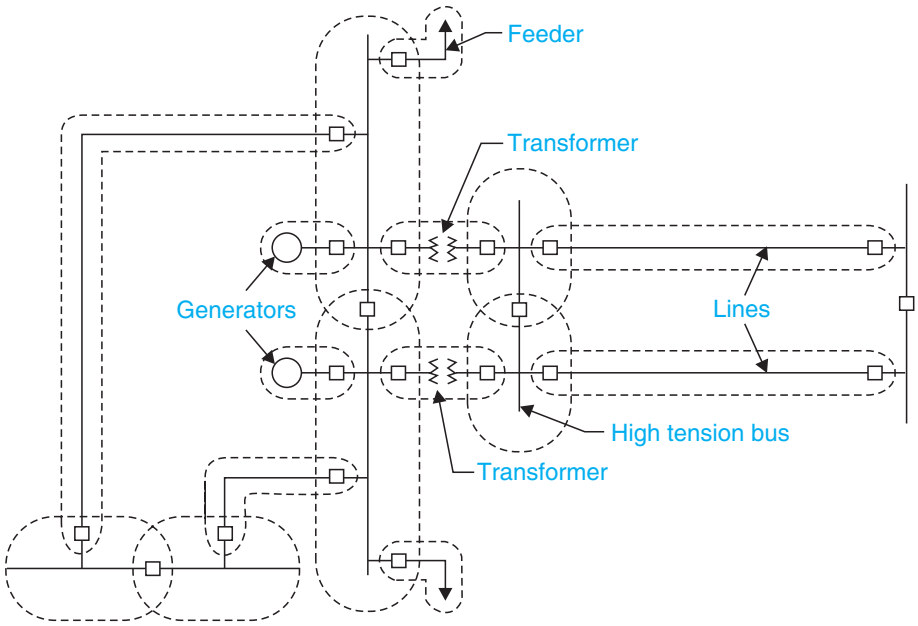


Fig. 12.92. Typical system showing zones of protection.

The successful operation of the modern power system is to a great extent due to the modern high-speed circuit breakers.

Relays have been developed for practically all types of system disorders, which may be listed as follows :

1. **Rotating machines**
   - (*i*) Short-circuits in machine
   - (*ii*) Open circuits in machine
   - (*iii*) Over current
   - (*iv*) Overheating
   - (*v*) Motoring of generator
   - (*vi*) Loss of field
   - (*vii*) Over speed
   - (*viii*) Bearing over heating
   - (*ix*) Single-phase and unbalanced current operation.
2. **Transformers**
   - (*i*) Short-circuits
   - (*ii*) Open circuits
   - (*iii*) Overloads.

3. **Busses.** Bus failures are somewhat remote compared with failures in other parts of a system. An insulator support may fail, producing a line-to-ground fault, or in remote cases a bus-to-bus short-circuit may occur.

4. **Transmission lines.** Transmission and distribution lines, because of their length and exposed nature, are the source of most trouble. Several causes may imitate trouble, such as : (*i*) overloads and (*ii*) any type of short circuit, caused by the breaking of the conductors or falling trees etc.

12.5.2. Different Types of Relays

All relays are essentially composed of three elements :

(*i*) An actuating element
(*ii*) A movable element
(*iii*) A set of contacts.

Relays may be classified as follows :

1. **According to their time action**
   - (*i*) Instantaneous (*ii*) Definite time limit
   - (*iii*) Inverse time.
2. **According to their mechanical details or principle of action**
   - (*i*) Plunger type (*ii*) Induction type.
3. **According to their application**
   - (*i*) Current relays (*ii*) Directional relays
   - (*iii*) Voltage relays (*iv*) Auxiliary relays
   - (*v*) Differential relays
   - (*vi*) Distance or impedance relays.

Requirements of relay

1. Definite operation with accuracy
2. Selective operation
3. Flexibility
4. Sensitivity.

Description of Commonly used Relays

1. **Plunger type relay.** Refer to Fig. 12.93. It consists of a core or plunger which is movable within a solenoid. When sufficient amount of current is passed through the winding, the core is pulled up, thus causing the cone-shaped disc at the top to bridge the gap between

stationary contacts. The position of the plunger with respect to coil is adjustable ; the lower its position, the more current is required to pull it into the closing position, and by adjusting its position it may be set to take any predetermined value of current within the range of the coil.

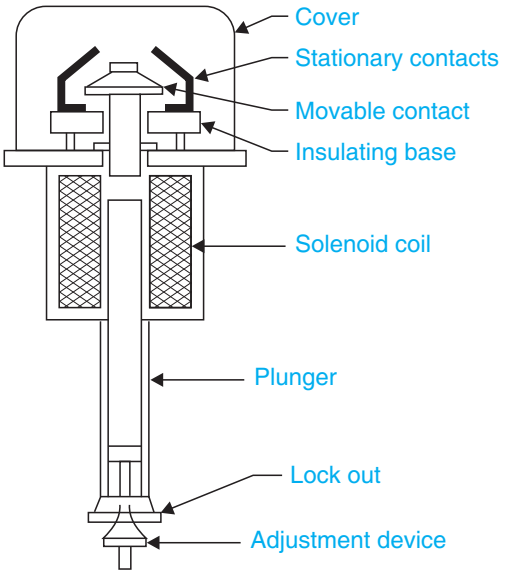


Fig. 12.93. Plunger type relay.

2. **The Over-current (Induction type) relay.** This type of relay is shown in Fig. 12.94. The output of the current transformer is supplied to the winding on the central part of *E* shaped core. The second winding from this place is connected to two windings on poles of the *U*-shaped core. The disc is mounted in between the cores. It carries contacts and is free to rotate against a mechanical restraining torque. Currents are induced in the disc due to the magnetic flux across the air gaps. Flux is also produced by the lower magnet. The combined effect produces a rotational torque. The speed of the disc is controlled by using brake magnet. The *operation line varies inversely with the current supplied to the relay by the current transformer*.

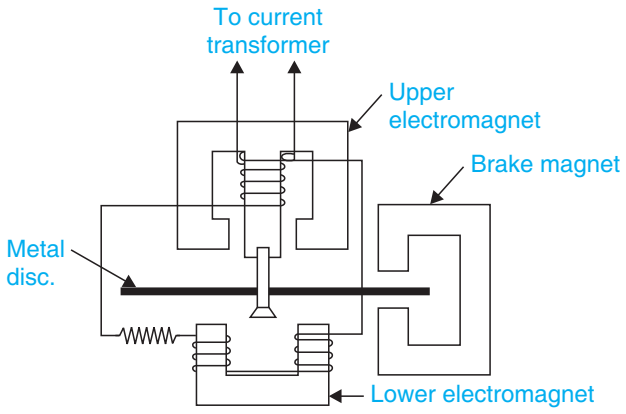


Fig. 12.94. Induction type over-current relay.

3. **Current balance relays.** This type of relay is commonly used. It operates on the principle of *current balance in which two currents are compared on a proportionate basis*. The principle of this type of relay is shown in Fig. 12.95.

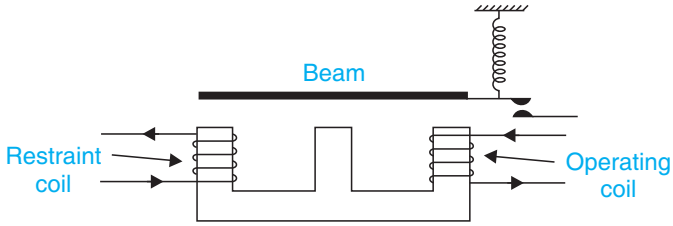


Fig. 12.95. Current balance relay.

4. **Differential relays.** As the name implies, these relays *depend for their operation on the difference in currents that might flow in two parts of a system*. In the Fig. 12.96 is shown an elementary circuit diagram of a standard differential relay. It is composed of *three* windings, the two outside ones being known as the *restraining coils* and the inner one as the *operating coil*. They are so made and connected that the *two restraining coils exert a downward pull, while the operating coil exerts an upward pull on the armature*. In Fig. 12.96 is shown how the three windings, are connected.

Coils '*a*' and '*b*' are connected to their respective current transformers in the power circuit so that under normal conditions the sum of the current through them in *zero*, and hence the operating coil '*c*' will not exert any force upon the moving mechanism. When the difference in the current in the two lines protected becomes great enough to overcome the weaker of the two retaining windings, the moving contact mechanism will rise and throw to one side, thereby completing the circuit of the trip coil of the oil circuit breaker.

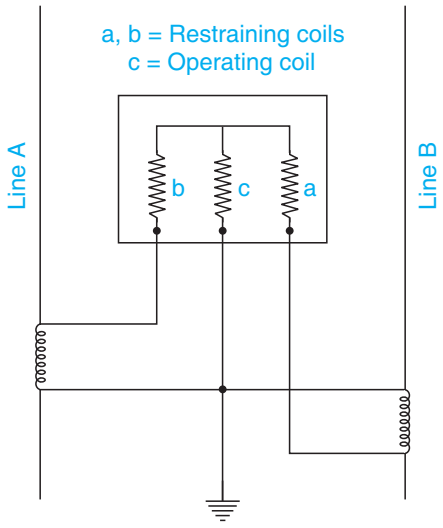


Fig. 12.96. Differential relay.

12.5.3. Alternator Protection

There are two possible ways of protecting alternators against damage due to excess current due to a short-circuit. These are :

1. Overload protection
2. Differential protection.

1. **Overload protection.** In Fig. 12.97 is illustrated the method of obtaining overload protection for alternators. The disadvantage of using overload relays for alternators is due to the fact that when synchronizing several machines to the same bus, there might be a large momentary circulating current present, which will open the alternator circuit breakers and thereby cause a delay in synchronizing.

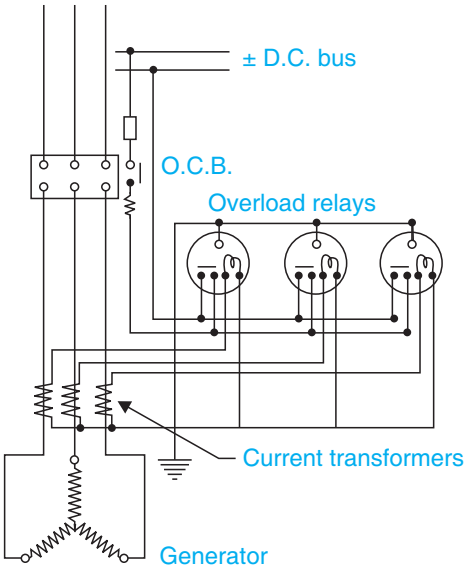


Fig. 12.97. Overload protection for alternators.

In the design of power equipment modern tendency is to build alternators with very high values of internal impedance, so that they will stand a complete short circuit at their terminals without causing any damage to themselves. Such alternators need not have any overload protection ; as a matter of fact, the operating engineer, as a general rule, does not want any overload protection, as such protection might disconnect the alternators from the power-plant bus on account of some momentary trouble outside the plant and therefore interfere with the continuity of the electric service. For such alternators the sole protection required must be one that will only recognize an internal fault in the machine.

2. **Differential protection.** Differential protection is illustrated in Fig. 12.98 where the complete diagram of connections is shown for the case of a *Y*-connected alternator, and only part of the system for a delta-connected alternator. At each end of each phase of the armature windings identical current transformers are placed. In Fig. 12.98 (*c*) is shown the elementary diagram. If the transformers are connected as shown, there cannot be any

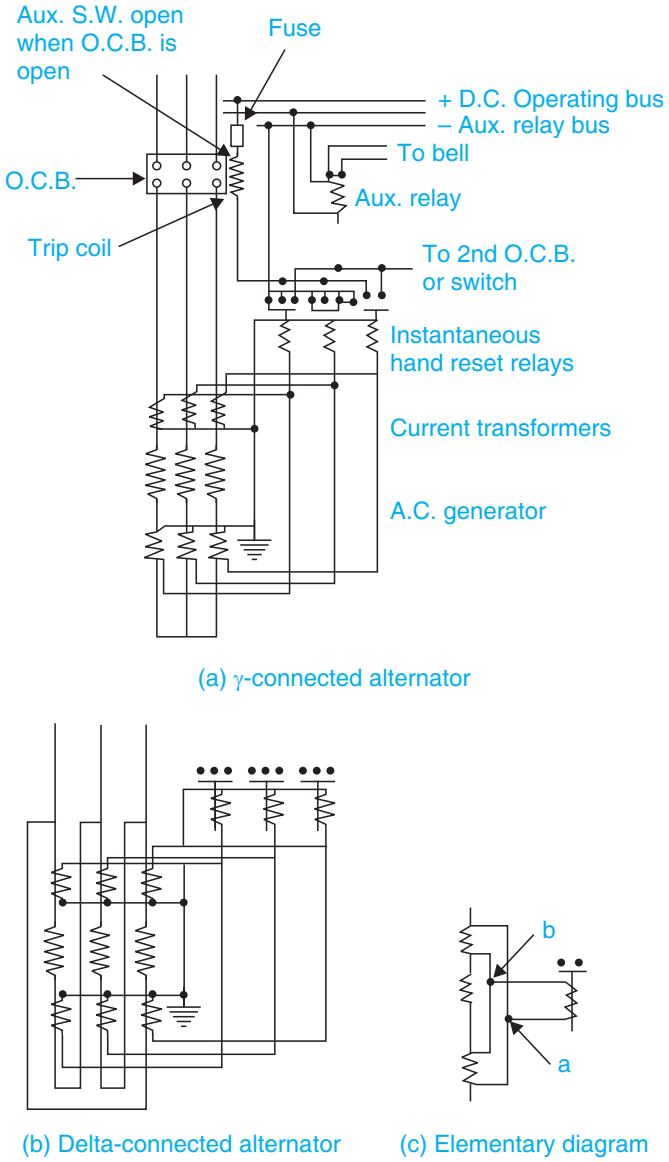


Fig. 12.98. Differential protection of alternators.

potential between the points *a* and *b* unless there is a difference of current in the secondaries of the two current transformers. Under normal conditions ; the current entering the winding is equal to current leaving the winding, hence there will be no difference of potential across '*a*' and '*b*' and hence there can be no current flow through the relay coil. As soon as an internal short circuit or ground occurs on the winding, the currents flowing in the two current transformers are unequal, and a potential will be established across '*a*' and '*b*' and therefore current will flow through the relay coil causing its contacts to close.

12.5.4. Transformer Protection

The protection that is most common for transformer banks is similar to the differential protection of alternators (see Fig. 12.99). There is one important modification. Since the primary and secondary voltages are not alike, it is necessary to use relays having two separate coils or current transformers of different turn ratio for the primary and secondary sides of the power transformers. These coils must be so designed that when connected to their respective current transformers their pulls on the plunger of each relay is neutralized. In case of a short or ground in either the high or low tension side of the transformers, the pulls exerted upon the plunger will no longer be neutralized and the relay contacts will be closed, opening the oil circuit breakers on both sides of the transformer. In case the relay coils are identical, such a system requires current transformers of different primary to secondary ratios in order that the currents acting in the two coils of one relay be equal. These two *currents must be inphase*, hence this type of protection can be used only in case the *power transformers are similarly connected on both sides*.

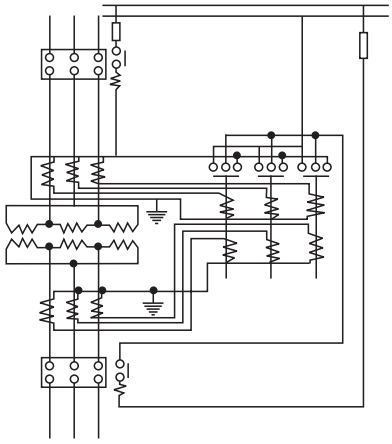


Fig. 12.99. Differential protection for transformers. High and low tension sides connected alike.

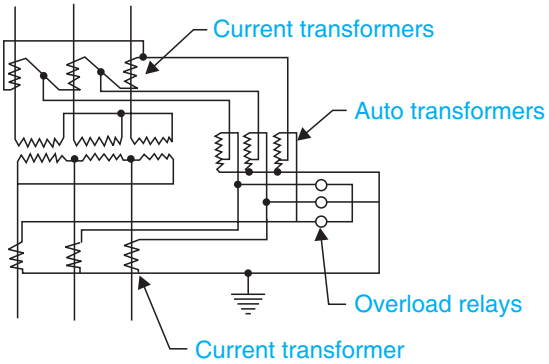


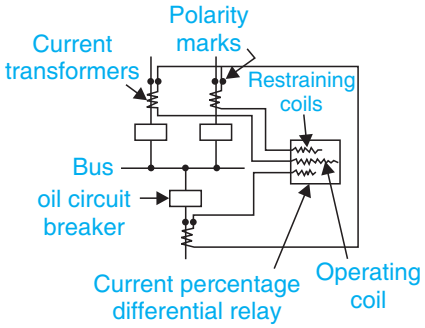
Fig. 12.100. Differential protection for transformers. High and low tension sides connected differently.

A typical method of protecting a star-delta transformer bank is shown schematically in Fig. 12.100.

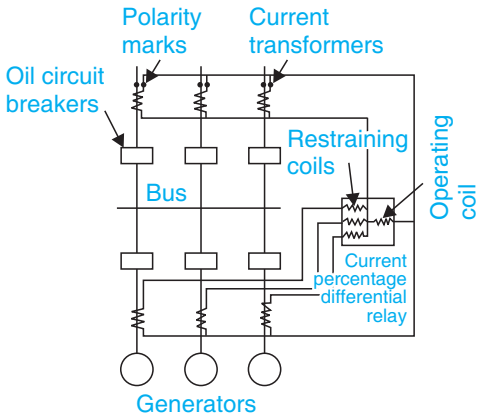
12.5.5. Bus Protection

Fig. 12.101 shows three examples of bus protection. In all three cases the protection is based on the fundamental proposition that for an external fault the vector summation of all currents flowing to a bus is equal to zero, and therefore, the relay will remain in its balanced position. On the other hand, when an internal fault occurs on the bus, the summation of the currents will no longer be zero and the current will flow through the relay, causing it to operate and thereby open all circuit breakers connected to the bus. An auxiliary multicontact relay is often used to trip the several circuit breakers.

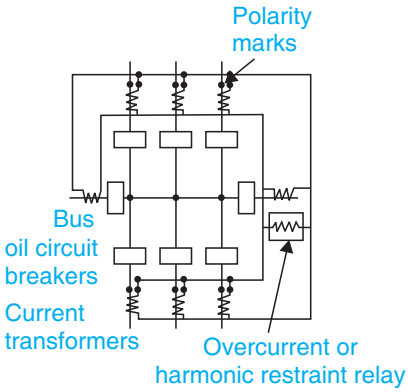
In case of a few connecting lines, it is possible to use percentage differential relays [see Fig. 12.101 (*a*) and (*b*)]; for the case of many lines it becomes more desirable to use standard over current relays [see Fig. 12.101 (*c*)].



(a) Schematic one-line diagram of current-differential protection of buses using percentage differential relay.



(b) Schematic one-line diagram of current-differential protection of buses using percentage differential relay.



(c) Schematic one-line diagram of current-differential protection of buses using over current relay.

Fig. 12.101

12.5.6. Protection of Transmission Lines

The requirements of line protection can be summarised as follows :

1. In the event of a short circuit the circuit breakers nearest the fault should open, all other circuit breakers remaining in a closed position.

2. In case the nearest breaker to the fault should not open fast enough, back up protection should be secured from adjacent circuit breakers.

3. Line circuit breakers should not trip due to loss of synchronism or hunting of generators.

4. The relay time should be just as short as possible in order to preserve system stability, without unnecessary tripping of circuits.

Common Methods of Line Protection Against Short-Circuits

1. Overcurrent protection.
2. Distance or impedance protection.
3. Pilot protection and carrier current protection.
4. Balanced current or balanced power protection.

Some of the above methods are discussed below :

Overcurrent protection. This type of protection is the most elementary type of line protection available. It generally employs the induction-type inverse-time relay. Fig. 12.102 illustrates such an application to a radial system involving one generating station and four substations. The relay-time settings are adjusted so that the first circuit breaker to trip in the event of a fault, is the one nearest the fault. The selectivity between substations is obtained by the time interval '*S*'.

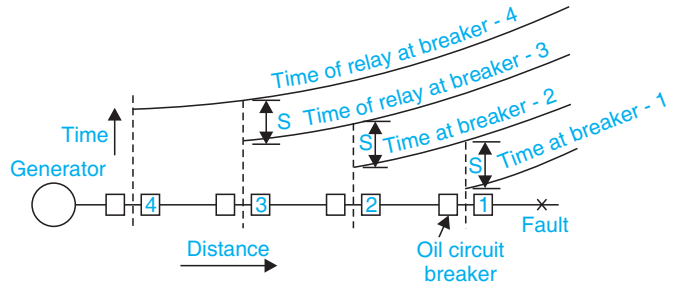


Fig. 12.102

Distance protection. For line to ground faults, the simple overcurrent protection is probably more satisfactory than distance protection. However, for *phase to phase faults, the distance protection is applicable, since the circuit impedance is quite constant and not subjected to seasonal changes, as is the case with earth impedances.*

Fig. 12.103 illustrates the application of this method of protection to a radial system.

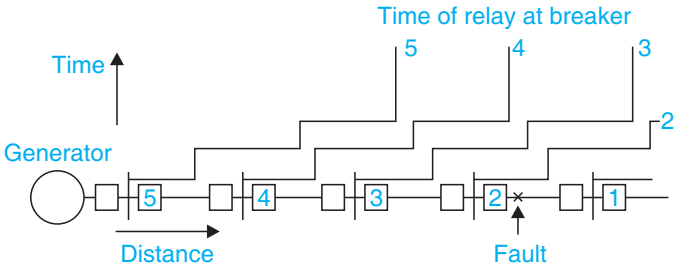


Fig. 12.103

Pilot wire protection. In the case of a short line it is possible to obtain very positive protection by the so-called "pilot wire" method. The method is essentially differential protection applied to the transmission lines. Current transformers are placed in each phase at both ends of the line and connected by means of pilot wires, as shown in Fig. 12.104. Only one phase is shown in order not to obscure the fundamental principle involved. It is evident from the above diagram that this is identical in its principle of operation with the differential protection applied to alternators. A short circuit at any point between the current transformers will cause the oil circuit breakers at both ends of the line to open. The relays used may be of either the induction or plunger type but probably the induction inverse-time relay is the most common for this type of installation. The natural objection to pilot wires is in the fact that they are likely to be broken or damaged. The expense of placing pilot wires on the transmission towers should also be considered. In *the case of long lines in which the capacity effect is appreciable, this method of protection cannot be used.*

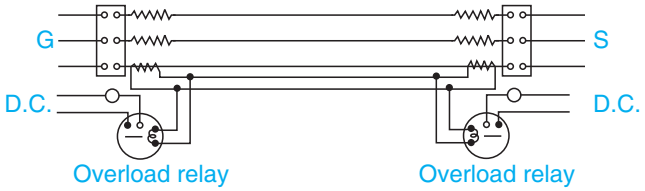


Fig. 12.104. Pilot-wire method of protection.

12.6. SHORT-CIRCUITS IN ELECTRICAL INSTALLATIONS AND LIMITING METHODS

A '*short-circuit*' is any *solid contact established between the different phases of an electrical installation or any bridging of them by a very low resistance*. When a *short-circuit* takes place a short circuit current starts flowing which is usually many times excess of normal rated current in the currents carrying parts, circuit apparatus and even the alternators.

Cause of short-circuits :

Primarily a short circuit is *caused due to failure or breakdown of the insulation between phases which allow the conductors to come into electrical contact with each other*. In electrical equipment and installations the insulation failures take place due to the following :

(*i*) Defects in material

(*ii*) Poor workmanship

(*iii*) Natural ageing

(*iv*) Mechanical injury and various causes.

Effects of short-circuits :

1. During a short-circuit a large amount of current (exceeding the normal load current) flows causing *overheating* which can prove very harmful to the electrical equipments. To avoid overheating of the current conducting parts it is generally *necessary to considerably increase their cross-section areas*.

2. Supply to the consumers is interrupted.

3. The generator e.m.f. and the voltage in the stator winding drop due to considerable large short circuit current flow through the circuit. As a consequence of the drop in the generator e.m.f., and also as a result of considerable voltage drop in the stator winding due to the flow of large short-circuit current, *every short circuit is found to cause a serious drop in voltage at the busses of the generating stations and in power circuit*.

4. Due to short circuit when there is significant decrease in voltage the motors may stall ; to prevent the stalling of motors it is necessary to switch off the faulty section of the circuit as quickly as possible.

Limiting of short-circuit currents :

In installations of large capacity, short-circuit currents can attain such high values that unless these are limited by some means, the selection of electrical equipment capacity of withstanding them is very difficult. This can be achieved by *interposing auxiliary inductive reactances called reactors* in each phase of the given installation.

Functions of a reactor :

1. Troubles may be localized or isolated at the point where they originate without communicating their disturbing effects to the other parts of the network.

2. They limit the flow of current into a short-circuit with the view of protecting the equipment from overheating as well as from failure due to destructive mechanical forces, and also protecting the system as a whole against shutdown by maintaining the voltage on most of the system while the short circuit is being cleared.

3. They permit the installation of lower capacity circuit breakers.

Location of reactors :

Reactors may be placed in the generator leads, between bus sections, in the low-tension transformer leads, between bus sections, in the low-tension transformer leads, or in outgoing low-tension feeders. No definite statement can be given as to which one of the above locations is preferable, each installation has its own particular demands which must be carefully considered before a choice of reactor location can be made. A brief description of the most important applications is given below :

1. **Generator reactors.** In Fig. 12.105 is shown the application of reactors in the generator leads. In this case the reactor may be considered as a part of the transient reactance of the generator, hence its effects is to protect the generator in case of any short circuit beyond the reactors. In the case of slow speed alternators, as for example in some of the hydroelectric units, it is possible to incorporate as much reactance as necessary in the generator itself, hence no reactors are needed. For this reason reactors are *rarely used in the generator leads of hydraulic plants. In the case of high-speed alternators it may often be desirable to use reactors in the generator circuit*.

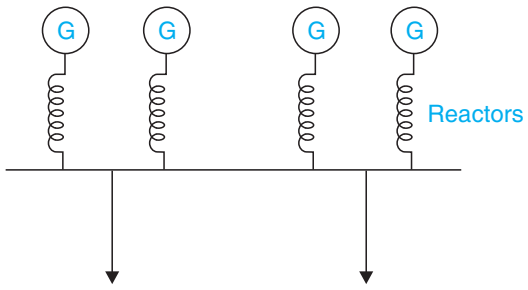


Fig. 12.105. Generator reactors.

2. **Transformer reactors.** In a few cases reactors have been installed in the low-tension side of power transformers as shown in Fig. 12.106, but as a general rule transformers can be designed with enough inherent reactance so that reactors are seldom necessary in the transformer circuits.

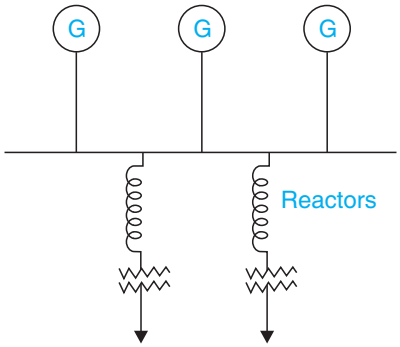


Fig. 12.106. Transformer reactors.

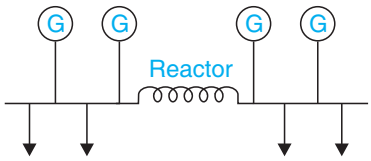


Fig. 12.107. Bus reactors.

3. **Bus reactors.** In power plant containing a large number of units it is often desirable to break up the low-tension bus into sections so that troubles can be confined to the section in which they started. These sections can be permanently connected through reactors, thereby obtaining a high degree of flexibility and also obtaining the protection under short circuit conditions due to localizing effect of the reactor (Fig. 12.107).

4. **Feeder reactors.** Most of the disturbances and short circuits occur in the low-tension distribution feeders either feeding from a power plant or distributing substation, hence it is not surprising that a large number of reactors are used for such circuits. In the case of a short circuit in a particular feeder, the *reactor prevents the communication of the trouble to the remainder of the system* (Fig. 12.108).

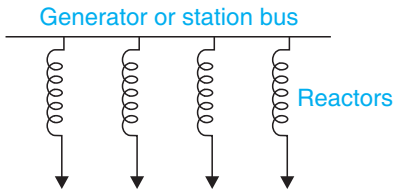


Fig. 12.108. Feeder reactors.

12.7. CONTROL ROOM

In a power station the control room (or the operating room) acts as the nerve centre. The following controls are located in a control room.

(*i*) Circuit breakers
(*ii*) Load and voltage adjustment
(*iii*) Transformer tap changing
(*iv*) Emergency tripping of the turbines etc.
(*v*) The instruments for indicating the load, voltage, frequency, power factor, winding temperatures and water levels in the case of hydrostations and so on.
(*vi*) Synchronising equipment
(*vii*) Voltage regulators
(*viii*) Relays
(*ix*) Integrating meters and other appliances
(*x*) A mimic diagram and suitable indicating equipment to show the open or closed position of circuit breakers, isolators etc.

The control room location in relation to other sections of the station, important and suitable position should be obtained. It should be located in the following manner :

(*i*) Should be located *near the switch house* so that lengths of the multicore cables are shortened.
(*ii*) Should be located *away from noise sources*.
(*iii*) From the control room there should be an access to the turbine house.
(*iv*) The location of the control room should be such that is should not be affected if any fire errupts in the switch house.

Fig. 12.109 shows the location of control room.

The control room should be well arranged as follows :

(*i*) Control room should be clean and comfortable.
(*ii*) Should be ventilated and well lighted.

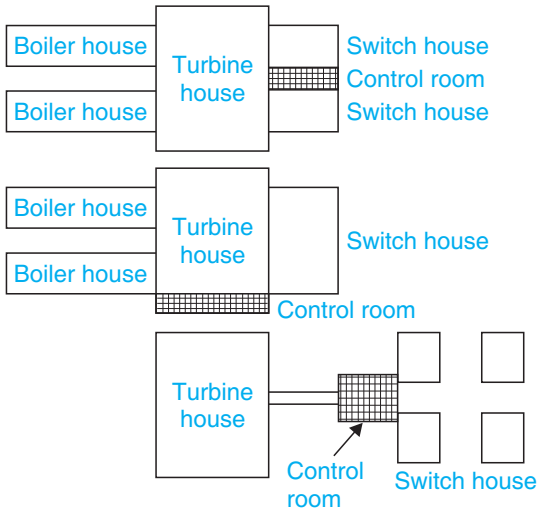


Fig. 12.109. Location of control room.

(*iii*) Should be free from draughts.

(*iv*) There should be no glare.

(*v*) The colour schemes should be soothing to eyes.

(*vi*) The instruments should have clear scales properly calibrated.

(*vii*) All the apparatus and circuits should be labelled so that they are clearly visible.

Control boards. These are of the following three forms :

(*i*) *Linear* (*ii*) *Horse shoe shaped*

(*iii*) *Semi-circular*.

The house shoe shaped and semicircular control boards occupy more floor space but they enable all the instruments to be seen from one point.

In some cases, the control boards are of *desk type* in which the control and indicating equipment are located on the front, and the relays and integrating instruments are placed behind.

Fig. 12.110 shows the layout of a control room.

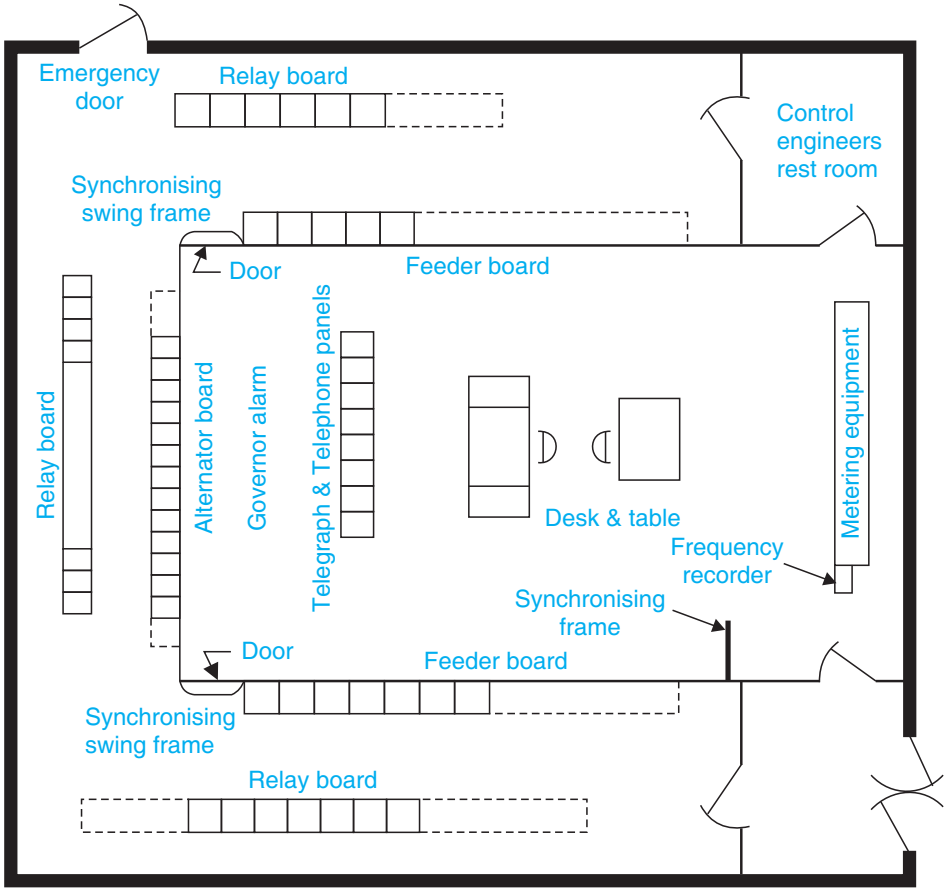


Fig. 12.110. Layout of a control room.

12.8. EARTHING OF A POWER SYSTEM

Earthing of neutrals of all industrial power systems is always preferable. Earthing is necessary as it offers many *advantages* given below :

1. Persistent arcing grounds is eliminated.
2. Over-voltage due to restriking is minimized.
3. The ground faults can be located and isolated fastly.
4. Steady state voltage stress to earth is reduced.
5. Sensitive protective apparatus can be used.
6. The maintenance expenditure is reduced.
7. Better safety is ensured.
8. Service reliability is improved.
9. Earthing provides improved lighting protection.

The earthing of systems should be done at the neutral of the supply transformers and generators. If the supply transformers and generators are delta connected, separate earthing transformers may be used.

In case the sources of power are two or more in number then the neutrals of these sources should be earthed to ensure having a neutral earthed in the event one of the sources is out of service.

The earthing of high voltage neutral is mainly done to protect the system while the low voltage neutral is earthed chiefly in order to reduce the possible danger to human life.

Where energy is transformed suitable provision should be made to protect the lower voltage system from becoming charged above its normal voltage by leakage or electrostatic induction from the higher voltage.

Methods of Earthing System Neutral

1. Solid earthing
2. Resistance earthing
3. Reactance earthing
4. Resonant earthing.

Solid earthing :

When the neutral of a generator or power transformer or earthing transformer is connected direct to the earth, as shown in Fig. 12.111 (*a*) (*b*) the system is solidly earthed. Solid earthing is generally used on low voltage circuits, 600 volts or less, and on most circuits above 15 kV. In the range of 2.2 to 15 kV any of the remaining three types may be used.

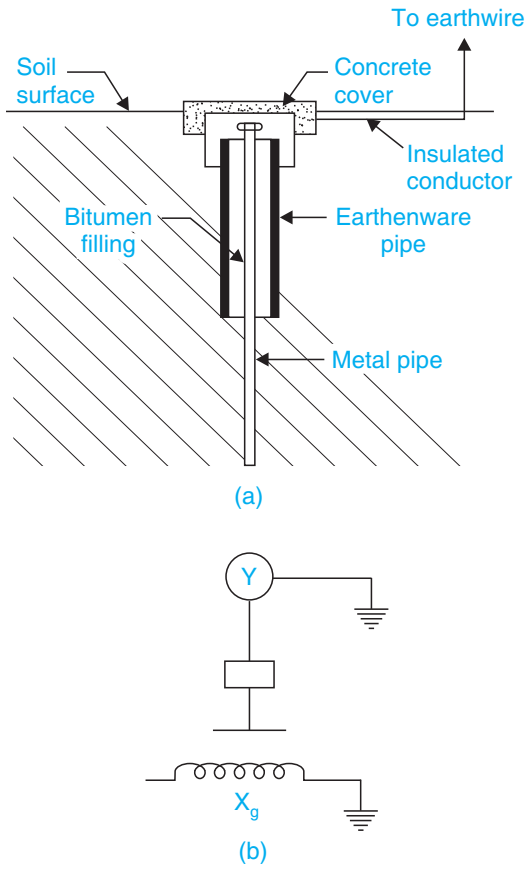


Fig. 12.111. Solid earthing.

In solid earthing, a direct metallic connection is made from the system neutral to one or more earth electrodes consisting of plates, rods or pipes buried in or driven into the ground, generally in a bed of coke below the permanent water level. Where permanently moist ground cannot be ensured a supply of water should be made available so that the periodic watering cannot be done. The value of contact resistance or resistance of the earthing system should be as small as possible and this should be checked from time to time. Now-a-days the term 'solidly earthed' has been replaced by the term '*Effectively earthed*'.

A transformer neutral may be 'solidly earthed' in that there may be no impedance between the neutral and earth. However, the transformer capacity thus solidly earthed may be too small in comparison with the sizes of the system to be effective in stabilizing the voltage from phases to ground when the fault takes place.

Resistance earthing :

The neutral of the generator is connected to the earth through a resistor as shown in Fig. 12.112. The resistance introduced in this case acts as a current limiting device. The resistors used in this case may be metallic carbon powder or liquid type. The magnitude of the resistance to be used should be such that it should limit the earth fault current to a value which will reduce minimum damage at the point of faults.

The *advantages* of resistance earthing are listed below :

1. The ground faults are readily relayed.
2. The hazards of arcing grounds are minimized.
3. The mechanical stresses in the circuit carrying fault currents are reduced.
4. Least inductive influence on neighbouring communication.
5. Electric shock hazards to the persons, caused by stay-earth fault currents in the earth return path, are reduced.
6. Line voltage drop, caused by the occurrence of earth fault, is reduced.

The main *disadvantage* of resistance earthing is that is *costlier* than the solidly earthed system.

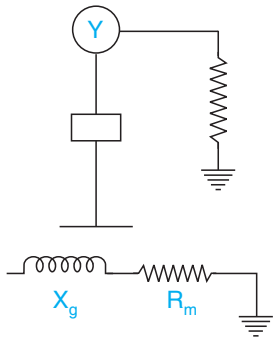


Fig. 12.112. Resistance earthing.

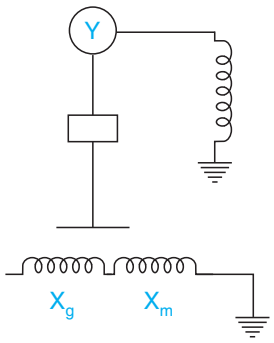


Fig. 12.113. Reactance earthing.

Reactance earthing :

In this case a reactor is connected between the neutral of the machine and earth as shown in the Fig. 12.113. Sometimes a low reactance is connected in series with the neutral of the machine to limit the earth fault current through the generator. This current should not be greater than the 3-phase fault current of the generator. The earth-fault-current of this system should not be less than 25% of the 3-phase fault current in order to minimize the transient voltages.

12.9. ELECTRICAL EQUIPMENT-LAYOUT

In a power station the layout of electrical equipment consists of the following :

(*i*) Busbars' arrangement (at generator voltage)

(*ii*) Circuit breakers and switches' arrangement

(*iii*) Transformers' location

(*iv*) Controlling switch board arrangement.

The following systems are used for layout of electrical equipment :

1. Single busbar system
2. Double busbar system
3. Ring busbar system.

1. Single busbar system :

Refer to Fig. 12.114. In case of a power plant which has a number of generators and a single busbar arrangement, the busbar is sectionalised by circuit breakers. The main *advantage* of this system is *that fault on one part of the busbar or system does not completely shutdown the whole station*. However, the use of such a large number of circuit breakers is out of date and presently there is a tendency to use fewer.

G = generator, CB = circuit breaker, S = Isolator or switch, LVB = Low voltage bus bar, HVB = high voltage bus bar, T = step up transformer.

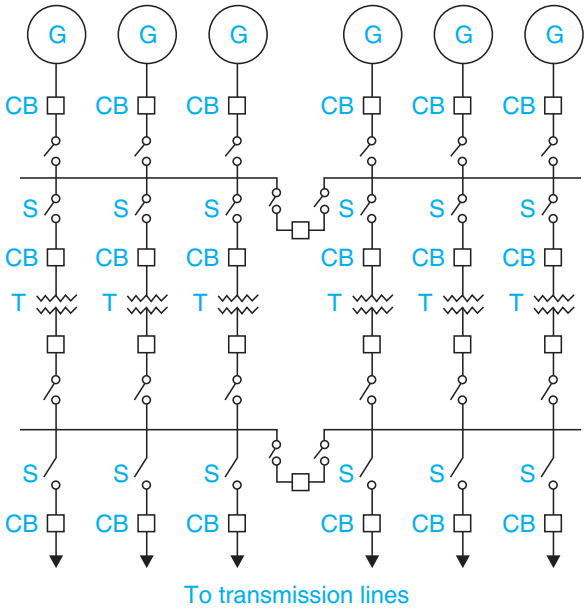


Fig. 12.114. Single busbar system.

2. Double busbar system :

In the Fig. 12.115 illustrated a double busbar system. In this system both low voltage and high busbars are duplicated, any one of the busbar sections can be used as desired. There is a provision of a *busbar coupling switch* for transferring operation from one busbar to another.

The *advantage* of this system is that it is possible to have one bus bar *"live"* and to carry out *repairs* on the other when required.

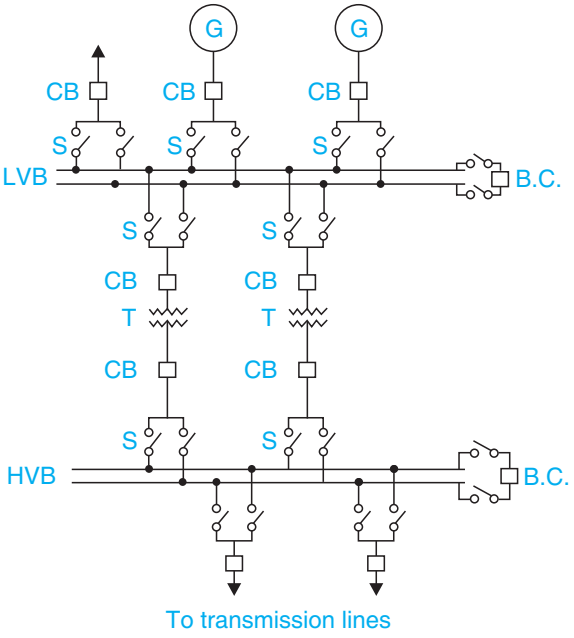


Fig. 12.115. Double busbar system.

3. Ring busbar system :

Refer to Fig. 12.116. In this arrangement two circuit breakers serve one line. This system has the *advantage* that there are always two parallel paths to the circuit and failure of one section does not interrupt the service completely.

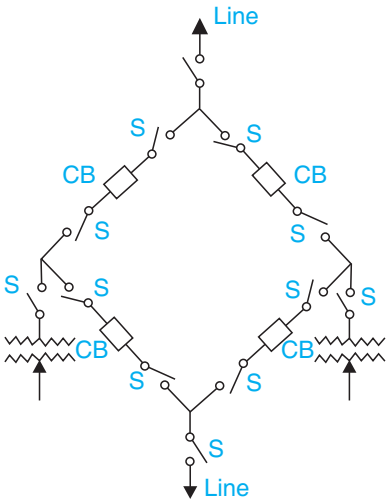


Fig. 12.116. Ring busbar system.

12.10. VOLTAGE REGULATION

For the satisfactory operation of a power system it is essential to *maintain the supply voltage within narrow limits*. In this connection there are some legal requirements. To achieve this purpose following methods are adopted :

1. Voltage control by generator excitation
2. Tap changing transformers
3. Booster transformer.

1. Voltage control by generator excitation. In several cases, especially in short lines, the voltage at the receiving end is kept within very narrow limits *by automatic or hand operated voltage regulators*, which act in the field circuit of the alternator excited. This method is, however, unsuitable for long lines.

The effect of *varying the excitation* depends upon the system into which the generator is feeding but in all cases the power output in unaffected as this depends on the fuel supply to the prime mover. In an interconnected system, in which there are two or more alternators, the distribution of load is unchanged by varying the voltage by excitation ; but the reactive kVA can be changed. The sharing of the load, off course, is determined by the regulation of the governor of the prime movers.

2. Tap changing transformers. In this case the variation of voltage is achieved by having a number of tappings on the secondary winding so that *turn-ratio can be changed as per requirement*. It can be done either manually or automatically depending upon the specific application and requirements.

3. Booster transformer. Booster transformers are installed immediately before the load where regulation is required. This booster system has the following *advantages*:

(*i*) It is independent of the main transformer so that a failure in the former will not throw the later out of service for any length of time.

(*ii*) It is much cheaper method when there is no main transformer at the point where regulation is desired.

Some other methods of regulation are :

(*i*) Phase angle control

(*ii*) Use of induction regulator, and

(*iii*) Voltage control by power factor.

12.11. TRANSMISSION OF ELECTRIC POWER

12.11.1. Systems of Transmission

For transmission of electrical power three-phase circuits are generally used because of economical reasons. Transmission lines may be classified as follows :

1. Single line
2. Parallel lines
3. Radial lines
4. Ring system
5. Network.

1. Single line. The simplest form is the single line, such as obtained from a power plant supplying its entire output to one load centre over a single-circuit line. Such a system has the *disadvantage* that in case of damage to the line the service is *interrupted*. Its use is more or less confined to small power systems and is therefore becoming more and more uncommon.

2. Parallel lines. Where continuity of service is necessary, it is best to use at least two circuits in parallel, placed either on the same supports or on separate supports.

Separate supports afford greater safety against both lines being damaged at the same time, but the cost is much higher than when two circuits are placed on one support. In some cases, where very large quantities of power must be handled, more than two circuits may be run in parallel.

3. **Radial lines.** Invariably a power plant or substation supplies power to the neighbouring territory by means of radial lines. These radial lines may be either single circuit for the less important loads or double circuit for the more important loads.

4. **Ring system.** For *systems covering a large territory* the ring system of transmission is very important. With this system the main high-voltage power line makes a closed ring, taps being taken off at any advantageous point of the ring, thus supplying a large territory. In case of damage to any section of the ring, that section may be disconnected for repairs, and power will be supplied from both ends of the rings, thereby maintaining continuity of service.

5. **Network.** A network often constitutes several ring systems with sections of single, parallel, or radial lines.

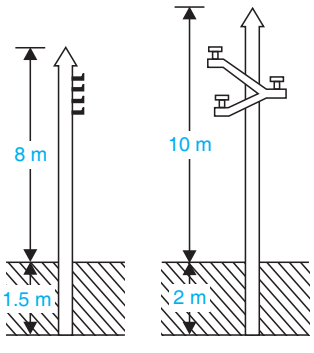
12.11.2. Line Supports

Electrical power may be transmitted by overhead or underground conductors. Underground transmission, with the exception of a few notable cases, is limited to voltage less than 45,000 volts.

The supports for the overhead transmission lines may be of any one of the following classes :

1. Poles 2. Towers

1. **Poles.** Poles may be made of materials like *wood*, steel, cement concrete etc. Usually R.C.C. poles are used. Figs. 12.117 and 12.118 show the wooden poles and R.C.C. poles respectively.



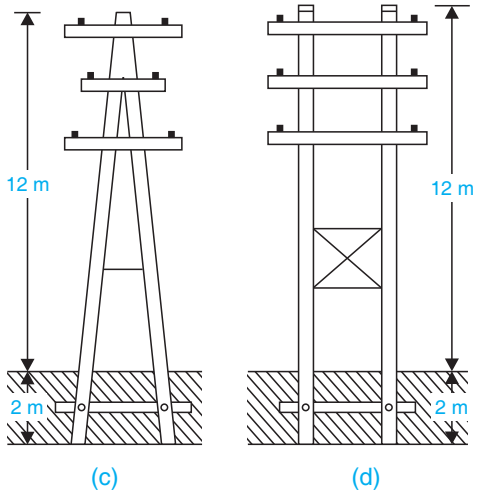


Fig. 12.117. Wooden poles : (*a*) 400 V, 4-phase, 4-wire distributor, (*b*) 11 kV, 3-phase feeder, (*c*) 'A' pole, double circuit, 33 kV feeder, (*d*) 'H' pole double circuit 33 kV feeder.

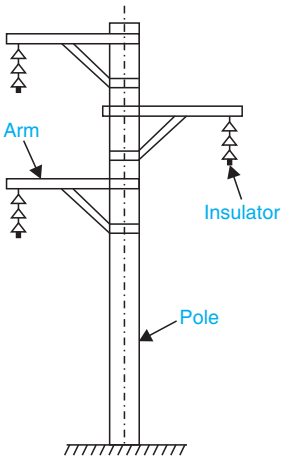


Fig. 12.118. R.C.C. pole.

2. **Towers.** Towers made of steel are mechanically sturdy and durable and are commonly used. These towers (steel) have been shown in Fig. 12.119 and Fig. 12.120. These towers are generally four legged, each leg anchored properly.

The line supports discussed above should have the following *characteristics* :

(*i*) High mechanical strength
(*ii*) Cheap in cost
(*iii*) Light in weight
(*iv*) Longer life
(*v*) Good looking
(*vi*) Easy accessible for painting and erection of line conductors
(*vii*) Low maintenance cost.

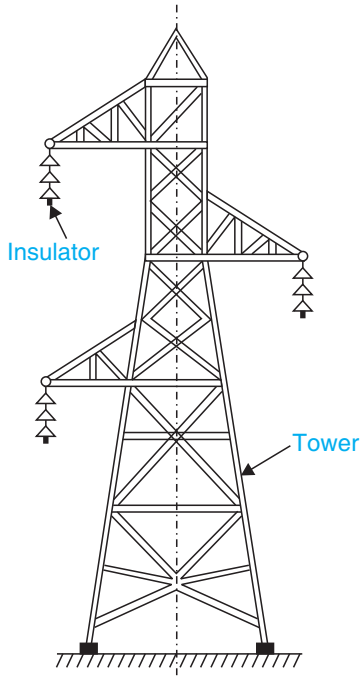


Fig. 12.119

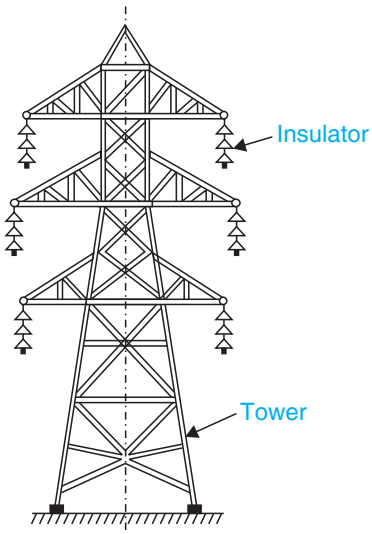


Fig. 12.120

12.11.3. Conductor Material

Electric power conductors are generally of the following materials: copper, aluminium and steel or some combination of these three metals. In some cases special alloys have been used. From a conductivity point of view, copper is the best conductor material, aluminium being second, and steel last. *Commercial conductors* are made in several forms, namely :

(*i*) Solid hard-drawn copper
(*ii*) Stranded copper
(*iii*) Hollow copper conductor, stranded
(*iv*) Hollow copper conductor, segmental
(*v*) Copperweld copper
(*vi*) Aluminium stranded, steel cored.

12.11.4. Line Insulators

The insulators of a transmission line are its most important item, since the operation of a line cannot be any better than the insulators that support the conductors. Transmission line insulators must possess *good mechanical strength and good insulating qualities under all conditions of weather and temperature and must not deteriorate fast*. Insulators are made of *glass, porcelain,* and *patented compounds*. Glass is the cheapest material and when properly made will produce satisfactory insulators for low-voltage work, such as telephone and telegraph, and under favourable conditions may be used upto 25,000 volts. Though there are a number of patented compounds on the market, these do not seem to offer much competition with porcelain, since *porcelain has very good electrical characteristics as well as high mechanical strength*.

Transmission line insulators may be classified as follows :

1. Pin type
2. Suspension type
3. Strain type.

— For *low voltages, pin-type insulators* made of glass are generally used. Pin-type insulators made of porcelain are designed for voltages upto about 90,000 volts but are seldom used on lines above 66,000 volts.

— For voltages above 66,000 volts it is generally desirable to use *suspension insulators*.

— *Strain insulators* may be of pin or suspension type. Upto about 30,000 volts pin-type insulators are satisfactory, but for higher voltages the suspension type is generally used. *Strain insulators are used on dead-end towers at bends or corners of transmission lines, or when making very long spans*. Extra heavy suspension units are made for such service, but often standard units may be used. On ordinary straight line dead-end towers a single strings is often sufficient but for severe service two more strings may be connected in parallel.

12.11.5. Distribution Systems

Oftenly it is impossible to draw a line between the distribution and transmission systems of a large power network. In general, *distribution systems comprise that part*

of the network of a power system which distributes power for local use.

Distribution systems may be classified as follows :

1. **Nature of current**

(*i*) Direct current

(*a*) Two wire (*b*) Three wire

(*ii*) Alternating current.

2. **Method of connections**

(*i*) Series

(*a*) Open loop (*b*) Parallel loop

(*c*) Combination of open and parallel loops

(*ii*) Multiple

(*a*) Three system (*b*) Feeder and main

(*c*) Network (*d*) Loop system

(*e*) Ring system.

3. **Number of phases**

(*i*) Single

(*a*) Two wire (*b*) Three wire

(*ii*) Two

(*a*) Three wire (*b*) Four wire

(*c*) Five wire

(*iii*) Three

(*a*) Three wire (*b*) Four wire

4. **Mounting**

(*i*) Overhead (*ii*) Underground

5. **Voltage** : 115/230, 550, 1100, 2200, 6600, 11000, 12000, 13200, 32000 V.

12.11.6. Underground Cables

Underground cables consist of one or more conductors properly insulated, all surrounded by a lead sheath, which excludes air and moisture and also acts as a protecting cover.

Cables for underground service may be classified as follows :

1. **Number of conductors**

(*i*) Single conductor (*ii*) Multiconductor

2. **Arrangement of conductors**

(*i*) Single (*ii*) Sector

(*iii*) Concentric

3. **Number of phases**

(*i*) Single phase (*ii*) Polyphase

4. **Type of insulation**

(*i*) Rubber (*ii*) Varnished cambric

(*iii*) Oiled paper (*iv*) Graded

(*v*) Oil filled

5. **Special features, split conductor**

(*i*) Concentric (*ii*) D-shaped

Fig. 12.121 shows the different types of underground cables.

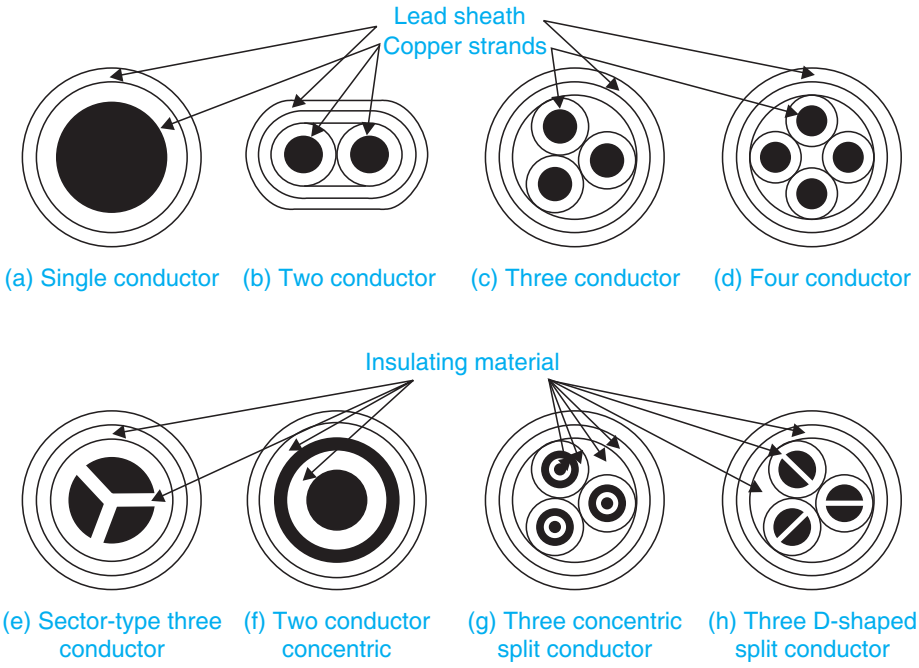


Fig. 12.121. Diagram illustrating different types of underground cables.

Advantages of underground power transmission systems :

1. Low maintenance cost.
2. Susceptible to less number of faults.
3. It is easier to transmit power in densely populated areas.

Advantages of over-head power transmission systems :

1. Over-head lines can be easily repaired.
2. It is cheaper to transmit power by over-head lines than underground cables.
3. Insulation of over-head lines is easier.

12.12. SUBSTATIONS

The substations *serve as sources of energy supply* for local areas of distribution in which these are located. Their main *functions* are *:*

(*i*) To *receive energy transmitted at high voltage* from the generating stations,

(*ii*) To *reduce the voltage* to a value appropriate for local distribution, and

(*iii*) To provide facilities for *switching*.

Substations have some *additional functions. They provide points where safety devices may be installed to disconnect equipment or circuit in the event of fault*. A substation is convenient place for installing synchronous condensers at the end of transmission line for the purpose of improving power factor and make measurements to check the operations of various parts of the power system. Street lighting equipment as well as switch control for street lights can be installed in a substation.

Some substations are simply *switching stations* where different connections between various transmission lines are made, others are *converting substations* which convert either A.C. to D.C. or *vice versa* or convert frequency from higher to lower or *vice versa*.

12.12.1. Classification of Substations

The substations may be classified as follows :

A. According to service

1. Transformer substations
   (*i*) Transmission and primary substations
   (*ii*) Sub-transmission or secondary substations
   (*iii*) Distribution substations.
2. Industrial substations
3. Switching substations
4. Power factor correction or synchronous substations
5. Frequency charger substation
6. Converting substations

B. According to design

1. Indoor type substations
2. Outdoor substations
   (*i*) Pole mounted substations
   (*ii*) Foundation mounted substations.

12.12.1.1. Indoor substations

According to construction indoor distribution transformer substations and high voltage switch boards are further subdivided as follows :

1. Substations of the integrally built type

In such substations the apparatus is installed on site. The all structures are constructed of concrete or brick.

2. Substations of the composite built up type

Here the assemblies and parts are factory or workshop fabricated, but are assembled on site within a substation switchgear room. The components of such substations take form of metal cabinets or enclosures, each of which contains the equipment of one main connection cell. Within such cabinets or enclosures an oil circuit breaker, a load interrupter switch, one or more voltage transformers may be mounted.

3. Unit type factory fabricated sub-stations and metal clay switch boards

These are built in electrical engineering workshops and are shipped to the rite of installation fully pre-assembled. After installation of sub-stations switch board only connection to the incoming and outgoing power circuits are required to be made.

12.12.1.2. Outdoor substations

These are of the following two types :

1. Pole-mounted substations

These substations are erected for mounting distribution transformers of capacity upto 300 kVA. Such substations are *cheapest, simple* and *smallest of substations*. All the equipment is of outdoor type and mounted on the supporting structure of high tension distribution line. Triple Pole Mechanically Operated (T.P.M.O.) switch is used for switching "*on*" and "*off*" of high tension transmission line. Lightning arrestors are installed over the high tension line to protect the high tension line to protect the transformer from the surges.

Substation is earthed at two or more places. Generally transformers upto 125 kVA are mounted on double pole structure and for transformers of capacity above 125 kVA but not exceeding 300 kVA, 4-pole structure with suitable plateform is used.

The pole-mounted substation is erected in very thickly populated location. The *maintenance cost* of such substations is *low* and by using a large number of

substations in a town it is possible to lay the distributors, at a lower cost.

2. Foundation mounted substations

Such substations are built entirely in the open and all the equipment is assembled into one unit usually enclosed by a fence from the point of view of safety.

Substations for primary and secondary transmission and for secondary distribution (above 300 kVA) are foundation mounted outdoor type. Since equipment required for such substations is heavy, therefore, site selected for these substations must have a good access for heavy transport.

The switch gear consists of circuit breakers of suitable type on both the sides but with the increased reliability of the modern transformers, the practice is to dispense with the circuit breaker on the incoming side from the economic consideration. The isolating switches thus serve the purpose.

While selecting the sites for such substations the following factors should be given due considerations :

1. Nearness to the load centres of distribution areas.
2. Availability of land.
3. Cost of land.
4. Local zoning laws.
5. Future load growth.

Advantages of outdoor substations over indoor substations :

1. Fault location is easier since all the equipment is within view.
2. The time required to erect such substations is less.
3. The extension of the installation is easier.
4. The smaller amount of building material is required.
5. Switch gear installation cost is low.

Disadvantages :

1. More space required.
2. The various switching operations with the isolators, as well as supervision and maintenance of the apparatus is to be performed in the open air during all kinds of weather.
3. The influence of rapid fluctuation in ambient temperature and dust and dirt deposits upon the outdoor substation equipment makes it necessary to install apparatus specially designed for outdoor service and, therefore, more costly.

Note. Not-withstanding the disadvantages, outdoor substations are very widely used in power system.

12.13. INDIAN ELECTRICITY ACT

Some extracts of the Indian Electricity Act, 1910, are given below :

Definitions. (*i*) *Area of supply*. Area of supply means the area within which alone licensee is for the time being authorised by his licence to supply energy.

(*ii*) *Consumer*. Consumer means any person who is supplied with energy by a licensee or the Government or by any other person engaged in the business of supplying energy to the public under this Act or any other law for the time being in force, and includes any person whose premises are for the time being connected for the purpose of receiving energy with the works of a licensee, the Government or such other person, as the case may be.

(*iii*) *Distributing main*. Distributing main means the portion of any main with which a service line is, or is intended to be, immediately connected.

(*iv*) *Electric supply line*. Electric supply line means a wire, conductor or other means used for conveying, transmitting or distributing energy, whether by overhead line or underground cable, together with any casing, coating, covering, tube, pipe or insulator enclosing, surrounding or support the same or any part thereof, or any apparatus connected therewith for the purpose of so conveying, transmitting or distributing such energy and includes any support, cross-arm, stay, strut or safety device erected or set up for that purpose.

(*v*) *Energy*. Energy means electrical energy—

(*a*) generated, transmitted or supplied for any purpose, or

(*b*) used for any purpose except the transmission of a message.

(*vi*) *Mains*. Mains means any electric supply line through which energy is, or is intended to be, supplied to the public.

(*vii*) *Service line*. Service line means any electric supply line through which energy is, or is intended to be, supplied :

(*a*) to a single consumer either from a distributing main or immediately from the supplier's premises, or

(*b*) from a distributing main to a group of consumers on the same premises or on adjoining premises, supplied from the same point of distributing main.

(*viii*) *Works*. Works includes electric supply line and any building, plant, machinery, apparatus and any other thing of whatever description required to supply energy to the public and to carry into effect the objects of a licence or sanction granted under this Act or any other law for the time being in force.

Criminal Offences and Procedure

1. **Theft of energy.** Whoever dishonestly abstracts, consumes or uses any energy shall be deemed to have committed theft within the meaning of theft under I.P.C. 45 and the existence of artificial means for such abstractions shall be *prime facie* evidence of such dishonest abstraction.

2. **Penalty for unauthorised supply of energy by non-licensees.** Whoever, in contravention of the provisions of the Act engages in the business of supplying energy, shall be punishable with fine which may extend to ₹ 30000 and in the case of a continuing contravention, with a daily fine which may extend to ₹ 300.

3. **Penalty for illegal or defective supply or for non-compliance with order.** Whoever: (*a*) being a licensee or a person who has obtained the sanction of the State Govt. to engage in the business of supplying energy to the public, save as permitted under relevant sections or by his licence or as the case may be by the conditions of sanction, supplies energy or lays down or places any electric supply line or works outside the area of supply ; or

(*b*) being a licensee or a person who has obtained the sanction of the State Govt. as aforesaid in contravention of the provisions of this Act or if the rules thereunder, or in breach of the conditions of licence or the sanction, as the case may be, and without reasonable excuse, the burden of proving which shall lie on him, discontinues the supply of energy or fails to supply energy ;

(*c*) makes default in complying with any of the provisions of an order or of any notice or requisition issued ;

(*d*) makes default in complying with any directions issued to him shall be punishable with fine which may extend to ₹ 1000, and, in the case of continuing offence or default, with a daily fine which may extend to ₹ 100.

4. **Penalty for illegals transmission or use of energy.** Whoever, in contravention of the provisions, transmits or used energy without giving the notice required thereby, shall be punishable with fine which may extend to ₹ 500 and, in the case of a continuing offence, with a daily fine which may extend to ₹ 50.

5. **Penalty for interference with meters or licensees works and for improper use of energy.** Whoever:

(*a*) connects any meter or indicator or apparatus with any electric supply line through which energy is supplied by a licensee, or disconnects the same from any such electric supply line ;

(*b*) lays, or causes to be laid, or connects up any works for the purpose of communicating with any other works belonging to a licensee ; or

(*c*) maliciously injures any meter or any indicator or apparatus or wilfully, or fraudulently alters the index of any such meter, indicator or apparatus or prevents any such meter, indicator or apparatus, from duly registering ; or

(*d*) improperly uses the energy of a licensee, shall be punishable with fine which may extend to ₹ 500 and in the case of continuing offence, with a daily fine which may extend to ₹ 50 ; and if it is proved that any artificial means exists for making such connection as is referred to in clause (*a*) or for causing alteration or prevention as is referred to in clause (*c*) or for facilitating such improper use as referred to in clause (*d*), and that the meter, indicator or apparatus under the custody or the control of the consumer, whether it is his property or not, it shall be presumed, until the contrary is proved, that such connection, communication, alteration, prevention or improper use, as the case may be, has been knowingly or wilfully caused by such consumer.

6. **Penalty for negligently wasting energy or injuring works.** Whoever negligently causes energy to be wasted or diverted, or negligently breaks, throws down or damages any electric supply line, post, pole or lamp or other apparatus connected with the supply of energy connected shall be punishable with fine which may extend to ₹ 200.

7. **Penalties for offences not otherwise provided for.** Whoever, in any case, not provided for by above sections makes default in complying with any of the above provisions of the Act, or with any order issued under it, or, in the case of a licensee, with any of the conditions of the licence, shall be punishable with fine which may extend to ₹ 100 and, in the case of a continuing default, with a daily fine which may extend to ₹ 20.

8. **Offences by companies.** (*i*) If any person committing an offence under this Act is a company, every person who at the time the offence was committed was in charge of, and was responsible to the company for the conduct of the business of the company, as well as the company, shall be deemed to the guilty of the offence and shall be liable to be proceeded against and punished accordingly ;

Provided that nothing contained in this sub-section shall render any such person liable to any punishment, if he proves that the offence was committed without his knowledge or that he exercised all due deligence to prevent the commission of such offence.

(*ii*) Notwithstanding anything contained in sub-section (1), where an offence under this Act has been committed with the consent or connivance of, or is attributable to, any neglect on the part of any director or manager, secretary or other officer of the company, such directors, manager, secretary or officer of the company shall also be deemed to be guilty of that offence and shall be liable to be proceeded against and punished accordingly.

Explanation. For the section :

(*a*) company means anybody corporate and includes a firm or other association of individuals ; and

(*b*) "director" in relation to a firm, means a partner in the firm.

9. **Institution of prosecutions.** No prosecution shall be instituted against any person for any offence against this Act, or any rule, licence order, thereunder, except at the instance of the Government, or an electrical Inspector or a person aggrieved by the same.

HIGHLIGHTS

1. Some of the important equipments available in a power plant are :
(*i*) Generators (*ii*) Exciters
(*iii*) Transformers (*iv*) Reactors
(*v*) Circuit breakers
(*vi*) Switchgear and protective equipment
(*vii*) Control board and equipment
(*viii*) Busbars
(*ix*) Stand by generators.

2. An electrical generator is a machine which converts mechanical energy (or power) in electrical energy (or power). The basic essential parts of an electrical generator are :
(*i*) Magnetic field
(*ii*) A conductor/conductors which can so move to cut the flux.

3. The three important characteristics of D.C. generators are :
1. No load saturation characteristics (E_0/I_f)
2. Internal or total characteristics (E/I_a)
3. External characteristics (V/I).

4. A machine for generating alternating currents is referred to an *alternator*. Alternators, according to their construction, are divided into the following two classifications :
1. Revolving armature type
2. Revolving field type.

5. The following methods are used to cool the alternators :
1. Open system using air
2. Closed system using air
3. Hydrogen cooling.

6. The function of a *transformer* is to transform alternating current energy from one voltage into another voltage. The transformer has no rotating parts, hence it is often called a static transformer.

7. Kinds of transformers :
(*i*) Power transformers
(*ii*) Auto-transformers
(*iii*) Transformer for feed installations with static converters.
(*iv*) Testing transformers
(*v*) Power transformers for special applications
(*vi*) Radio-transformers.

8. Three phase transformer connections :
(*i*) Primary *Y*—secondary *Y*
(*ii*) Primary Δ—secondary Δ
(*iii*) Primary Δ—secondary *Y*, or vice versa
(*iv*) Primary and secondary open Δ
(*v*) Primary *T*—secondary *T* (Scott connection).

9. The *switch gear* constitutes all parts or equipments of the power plant whose function is to receive and distribute electric power. It comprises of the following :
(*i*) Assemblies of switching apparatus
(*ii*) Protective and indicating metering devices
(*iii*) Interconnecting busbar systems and relevant accessories.

10. Types of Switches :
(*i*) Knife switches (*ii*) Disconnecting switches
(*iii*) Air-break switches (*iv*) Control switches
(*v*) Auxiliary switches (*vi*) Oil switches
(*vii*) Magnet impulse switches.

11. *Fuses* are used to protect circuits of small capacity against abnormal currents such as overloads or short-circuits.
The most important types of fuses that are used for power purposes are :
(*i*) Cartridge fuses (*ii*) Transformer fuse blocks
(*iii*) Expulsion fuses.

12. The function of a *circuit breaker* is to break a circuit when various abnormal conditions arise and create a danger for the electrical equipment in any installation. The circuit breakers are classified as follows :
1. Low voltage circuit breakers
2. High voltage circuit breakers
(*a*) Oil circuit breakers
(*i*) Bulk oil circuit breakers
(*ii*) Low oil contact circuit breakers.
(*b*) Oil-less circuit breakers
(*i*) Air blast circuit breakers
(*ii*) Water circuit breakers
(*iii*) Hard gas circuit breakers.

13. Types of switch gears :
(*i*) Cellular (*ii*) Cubicle
(*iii*) Truck (*iv*) Metal clad
(*v*) Outdoor switch gear.

14. The function of the *relay system* is to recognize the fault and to initiate the operation of devices or circuit breakers to isolate the defective element with the minimum disturbance to the service.
Relays may be classified as follows :
1. **According to their time action**
(*i*) Instantaneous (*ii*) Definite time limit
(*iii*) Inverse time.
2. **According to their mechanical details or principle of action**
(*i*) Plunger type (*ii*) Induction type.

3. **According to their application**
   (*i*) Current relays (*ii*) Directional relays
   (*iii*) Voltage relays (*iv*) Auxiliary relays
   (*v*) Differential relays
   (*vi*) Distance or impedance relays.

15. Methods of earthing system neutral :
   (*i*) Solid earthing (*ii*) Resistance earthing
   (*iii*) Reactance earthing (*iv*) Resonant earthing.

16. In a power station the layout of electrical equipment consists of the following :
   (*i*) Busbars' arrangement (at generator voltage).
   (*ii*) Circuit breakers and switches' arrangement
   (*iii*) Transformers' location
   (*iv*) Controlling switch board arrangement.

The following systems are used for layout of electrical equipment :
1. Single busbar system.
2. Double busbar system.
3. Ring busbar system.

17. *Transmission lines* may be classified as follows :
   (*i*) Single line (*ii*) Parallel lines
   (*iii*) Radial lines (*iv*) Ring system
   (*v*) Network.

18. The *substations* serve as sources of energy supply for local areas of distribution in which these are located.
Outdoor substations are very widely used in power system.

THEORETICAL QUESTIONS

1. Give the classification of generating equipment.
2. Explain the working principle of a '*generator*'.
3. Enumerate and explain briefly the characteristics of D.C. generators.
4. State the application of D.C. generators.
5. Explain the working principle of an 'alternator'.
6. What is an exciter ?
7. Write short note on A.C. exciters.
8. Explain the alternator synchronising procedure.
9. Enumerate and explain briefly different methods of cooling of alternators.
10. What is a transformer ? How are transformers classified ?
11. What are the advantages and disadvantages of the following three-phase transformer connections :
   (*i*) The *Y*—*Y* connection
   (*ii*) The *Y*—Δ connection
   (*iii*) The *V*—*V* connection.
12. How are three-phase transformers classified ?
13. What do you mean by a 'switch gear' ?
14. What are the functions of a switch gear ?
15. Enumerate important types of switches.
16. What is a fuse ? How are fuses classified ?
17. Explain with the help of a neat sketch the construction and working of a high rupturing capacity cartridge (H.R.C.) fuse.
18. What is a circuit breaker ?
19. How are circuit breakers classified ?
20. Explain briefly any one of the circuit breakers :
   (*i*) Oil circuit breaker
   (*ii*) Air circuit breaker
   (*iii*) Water circuit breaker.
21. State the function of a relay system.
22. How are relays classified ?
23. Explain briefly any two of the following relays :
   (*i*) Plunger type relay
   (*ii*) Over-current relay
   (*iii*) Differential relay.
24. Explain briefly the methods of protecting alternators against damage due to excess current due to short-circuit.
25. Explain briefly how the following is materialised.
   (*i*) Transformer protection
   (*ii*) Bus protection
   (*iii*) Protection of transmission lines.
26. What is a short-circuit ? What are the effects of short-circuits ?
27. What are the functions of a reactor ?
28. Give the layout of a control room.
29. Enumerate the methods of earthing system neutral. Explain with a neat sketch the '*solid earthing*' system.
30. Write a short note on transmission and distribution of electric power.
31. Explain briefly the following in regard to overhead transmission lines :
   (*i*) Line supports
   (*ii*) Conductor material
   (*iii*) Insulators.
32. How are cables (for underground service) classified ?
33. What are the advantages of underground power transmission systems ?
34. What are the advantages of over-head power transmission systems ?

COMPETITIVE EXAMINATION QUESTIONS

1. (*a*) What is the function of circuit breaker ? Name the different types of circuit breakers. Explain in detail with the help of neat diagrams oil circuit breakers.

(*b*) Explain the various methods of controlling the voltage at the consumer terminal used in power supply system.

2. (*a*) What is the necessity of generator cooling ? What methods are used for generator cooling ?

(*b*) What is the function of circuit breakers in a power supply system ? Explain the different types of circuit breakers.

3. (*a*) Write criteria for optimum loading of a power plant and economic loading of combined thermal and hydro-plants.

(*b*) Write the factors which affect economies of generation and distribution of power.

4. Write briefly on the following :

(*a*) Earthing of a power station ;

(*b*) Protective equipments ;

(*c*) Control board equipments.

5. (*a*) What are the different methods of earthing a power system ? Explain in detail.

(*b*) What are the different methods used for generator cooling ? Explain in detail.

6. (*a*) What type of dust collector is used in super thermal power plant ? Why is it preferred to other types ?

(*b*) How would you justify the combined working of power plants ?

(*c*) Define 'Hydrograph' and explain its importance in the design of storage of hydroelectric power project.

(*d*) Draw a neat sketch showing essential parts of a power transformer.

7. (*a*) Define rating of a transformer.

(*b*) Show the most commonly used connections for three-phase voltage transformation with schematic diagrams. State the merits and demerits of each.

(*c*) Explain parallel operation of transformers.

13 Pollution and Its Control

13.1. Introduction. 13.2. Pollution from thermal power plants—Gaseous emission and its control—Particulate emission and its control—Solid waste disposal—Thermal pollution. **13.3. Pollution from nuclear power plants. 13.4. Pollution from hydro-electric power plants and solar power generating stations**—*Highlights—Theoretical Questions.*

13.1. INTRODUCTION

All power production plants, invariably, pollute the atmosphere and the resulting imbalance on Ecology has a bad effect. The pollution is inevitable in some cases and has to be minimised to the extent possible. This is being achieved by effective legislations all over the world.

The power plant pollutants of major concern are:

A. **From fossil power plants**

(*i*) Sulphur oxide (*ii*) Nitrogen oxides

(*iii*) Carbon oxide (*iv*) Thermal pollution

(*v*) Particulate matter.

B. **From nuclear power plants**

(*i*) Radioactivity release

(*ii*) Radioactive wastes

(*iii*) Thermal pollution.

Besides this, pollutants such as lead and hydrocarbons are contributed by automobiles.

In this chapter, we shall look at the type of pollutions various power plants cause and the method of minimising these bad effects.

13.2. POLLUTION FROM THERMAL POWER PLANTS

The environment is polluted to a great extent by thermal power plants. The emission from the chimney throws unwanted gases and particles into the atmosphere while the heat is thrown into the atmosphere and rivers. Both these aspects pollute the environment beyond tolerable limits and now are being controlled by appropriate regulations. The types of emissions, effects and methods of minimising these pollutions are discussed below.

The *air pollution* in a large measure is caused by the thermal power plants burning conventional fuels (coal, oil or gas). The combustible elements of the fuel are converted to gaseous products and non-combustible elements to ash. Thus the emission can be classified as follow:

1. Gaseous emission
2. Particulate emission
3. Solid waste emission
4. Thermal pollution (or waste heat).

13.2.1. Gaseous Emission and Its Control

The various gaseous pollutants are:

(*i*) Sulphur dioxide

(*ii*) Hydrogen sulphide

(*iii*) Oxides of nitrogen

(*iv*) Carbon monoxide etc.

The effects of pollutants on environment are as follows :

S. No.	Pollutant	Effects		
		On man	On vegetation	On materials/animals
1.	SO_2	Suffocation, irritation of throat and eyes, respiration system	Destruction of sensitive crops and reduced yield	Corrosion
2.	NO_2	Irritation, bronchitis, oedema of lungs	–	–
3.	H_2S	Bare disease, respiratory diseases	Destruction of crops	Flourosis in cattle grazing
4.	CO	Poisoning, increased accident-liability	–	–

Removal of sulphur dioxide (SO_2)

SO_2 is removed by wet scrubbers as shown in Fig. 13.1.

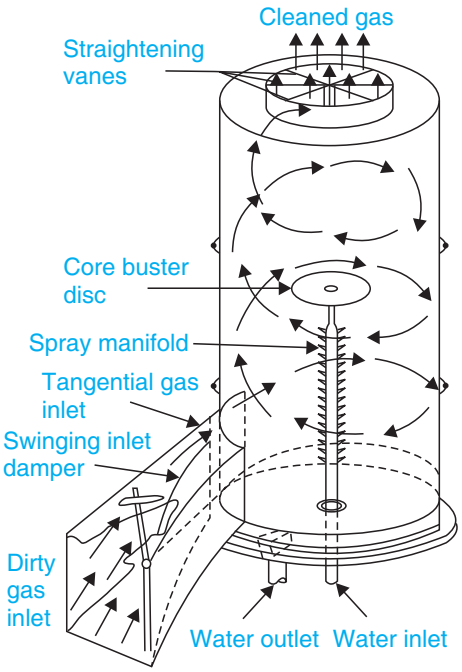


Fig. 13.1. Wet scrubber.

— The gases to be cleaned are admitted tangentially into the *scrubber* which will also help in separating the particulate matters. Water spray absorbs these gases and particulate matters which collect on the surface of the scrubber are washed down by the water and this water is further treated, filtered and reused.

— The wet scrubbers also find application in chemical and grain milling industries.

— The *collection efficiency of scrubber is about 90 per cent*.

The following are *disadvantages* of using wet scrubbers :

1. The gases are cooled to such an extent that they must be reheated before being sent to the stack.

2. The pressure drops are very high.

3. Water used, after dissolving sulphur oxides will contain sulphuric and sulphurous acids which may corrode the pipelines and the scrubber itself. This water cannot be let out into the rivers for obvious reasons.

In power plants where high sulphur content coal is the only source available, it is preferable to remove the sulphur from the coal before it is burnt. This is done by coal washing which reduces the fly-ash as well as some sulphur oxides in the flue gases. But the power plants employ "**Flue-gas desulphurization**" (FGD) system similar to wet scrubber system. FGD can be of the following types :

1. *The recovery or regenerative system*

2. *Throw away or non-regenerative system.* In this system the reactants are not recovered and the final products are *sulphur salts of calcium and magnesium*.

Regenerative System

Some of the regenerative systems are :

1. FW-Bergbau process
2. Wellman-Lord process
3. Wet magnesium oxide process.

— In the Fig. 13.2 is shown the *FW-Bergbau process*. In this process, SO_2 is removed by absorption and sulphur is collected as molten sulphur.

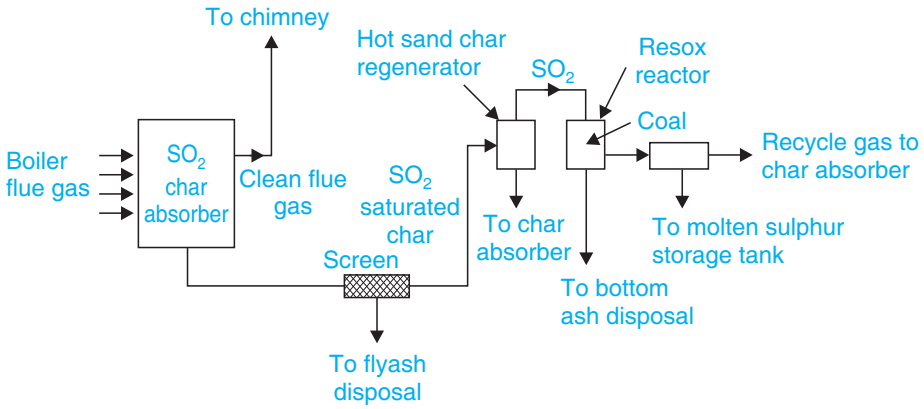


Fig. 13.2. F.W. Bergbau Forshung absorption FGD regenerative system.

— Fig. 13.3 shows the Wellman-Lord FGD system. This system removes SO_2 by absorption in sodium carbonate and SO_2 is recovered as sulphur or sulphuric acid products.

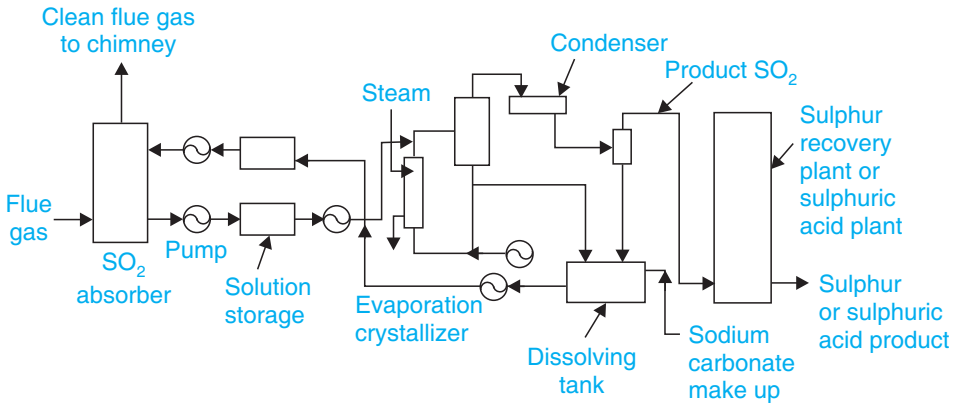


Fig. 13.3. Wellman-Load absorption FGD regenerative system.

In non-regenerative systems the principal reactant is either lime or limestone. The slurry is made into sludge by adding fly-ash and other properietory sludge additives and the sludge is disposed. This method could prove a bit more expensive since no sulphur or sulphur product is recovered and the reactant is not generated as in the case of FW Bergbau process.

Emission of NO_x

Nitrogen oxides are compounds of the elements nitrogen and oxygen, both of which are present in air. The combustion of *fossil fuels* in air is accompanied by the formation of nitric oxide (NO) which is subsequently partly oxidised to nitrogen dioxide (NO_2). The resulting mixture of variable combustion is represented by the symbol NO_x, where x has a value between 1 and 2. Nitrogen oxides are present in stack gases from coal, oil and gas furnaces (and also in the exhaust gases from internal combustion engines and gas turbines).

The following methods are commonly used to reduce the emission of NO_x from thermal (and gas turbine) power plants:

1. Reduction of temperature in combustion zone.
2. Reduction of residence period in combustion zone.
3. Increase in equivalence ratio in the combustion zone.

13.2.2. Particulate Emission and Its Control

The particulate emission, in power plants using fossil fuels, is easiest to control. Particulate matter can be either *dust* (particles having a diameter of 1 micron) which do not settle down or *particles* with a diameter of more than 10 microns which settle down to the ground. The particulate emission can be classified as follows:

Smoke. It composes of stable suspension of particles that have a diameter of *less than 10 microns* and are visible only in the aggregate.

Fumes. These are very small particles resulting from chemical reactions and are normally composed of metals and metallic oxides.

Fly-ash. These are ash particles of diameters of *100 microns or less*.

Cinders. These are ash particles of diameters of *100 microns or more*.

The above particulates, in any system of controlling the particulate emission, are to be effectively collected from the flue gases. The performance parameters for any particulate remover is called the *collection efficiency* defined as:

$$\textit{Collector efficiency} = \frac{\text{Mass of dust removed}}{\text{Mass of dust present}} \times 100$$

For different systems the collector efficiency varies from 50 to 99%; for an *electrostatic precipitator it is move than 90%*.

Some collector systems, their efficiencies and their adaptability, are discussed in the following paragraphs.

13.2.2.1. Cinder catchers

The cinder catchers are shown in Figs. 13.4 to 13.7.

— *Refer to Fig. 13.4.* Sudden decreases in gas velocity makes the particulates separate and fall.

— *Refer to Fig. 13.5.* A sudden change in the direction of flow of flue gas throws the particulates away and can be collected.

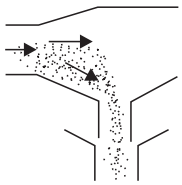


Fig. 13.4. Sudden decrease in gas velocity.

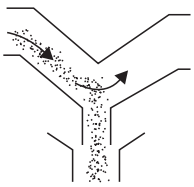


Fig. 13.5. Sudden change in the direction of the flow of flue gas.

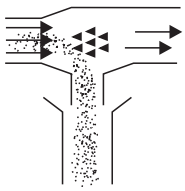


Fig. 13.6. Impingement of flues gases on a series of baffle stops.

— *Refer to Fig. 13.6.* Impingement of flue gases on a series of baffle stops the particulate matter as shown. These are commonly used in stoker and small cyclone furnaces where crushed coal is burned rather than the very fine pulverised coal. The collection efficiencies of cinder catchers are from 50 to 75%.

— *Refer to Fig. 13.7.* **Cinder-vane fan.** The cinder vane fan uses the fan which imparts centrifugal force to the particulates and they are collected as shown. The efficiency is from 50 to 75%.

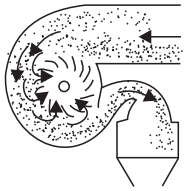


Fig. 13.7. Cinder-vane fan.

13.2.2.2. Wet scrubbers

— Wet scrubbers as described for removal of gases can also be used for removal of particulate matters ; but the gases will have to be reheated before they are sent to the stack.

— The wet scrubbers are *not commonly used to remove particulate matters*.

13.2.2.3. Electrostatic precipitator

— An electrostatic precipitator is shown in Fig. 13.8. In this device a very high voltage of 30 kV to 60 kV is applied to the wires suspended in a gas-flow passage between two grounded plates.

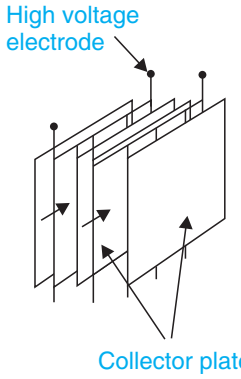


Fig. 13.8. Electrostatic precipitator.

The particles in the gas stream acquire a charge from the negatively charged wires and arc then attracted to the ground plates. The grounded plates are periodically rapped by a steel plug which is raised and dropped by an electromagnet and dust is collected in the hoppers below.

— In this type of collector, *care* must be taken to see that *large quantity of unburnt gases do not enter the precipitator*. If such a mixture enters, power should be turned off, otherwise there could be *explosion because of constant sparking between wires and plates*.

— The collection efficiency is about 99 per cent.

— Electrostatic precipitators are suitable for power plants where *fly-ash content is high*. Fly-ash having high electrical resistivity *does not* separate in the electrostatic precipitator. This problem can be solved by injecting *sulphur trioxide* into the exhaust gas which *improves the conductivity of fly-ash*. This again poses a problem of discharging objectionable sulphur trioxide into the atmosphere ; this needs a wet scrubber after the electrostatic precipitator.

13.2.2.4. Baghouse filters

Fig. 13.9 shows a baghouse filter. Baghouse filters are found useful in removing the particulate matters where *low sulphur coal is used*.

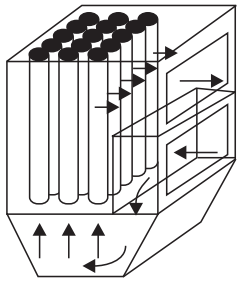


Fig. 13.9. Baghouse filter.

— The cloth filters cost about 20 per cent of installation cost and last for $1\frac{1}{2}$ to 3 years.

— The baghouse filter is usually cleaned by forcing air in the reversed direction. They need large filter areas of about 6.5 m^2/MW of power generation. Hence the installation cost could be high.

— Although baghouse filters are expensive, yet they are being widely used in *coal-fired systems*.

13.2.3. Solid Waste Disposal

From the fossil fuel fired power plants considerable amount of solids in the form of ash is discharged. This ash is removed as bottom ash or slug from the furnace. The fossil fuel fired system also discharges solid wastes such as calcium and magnesium salts generated by absorption of SO_2 and SO_3 by reactant like lime stone.

13.2.4. Thermal Pollution

Discharge of thermal energy into waters is commonly called '*Thermal pollution*'.

Thermal power stations invariably will have to discharge enormous amounts of energy into water since water is one medium largely used to condense steam. If this heated water from condensers is discharged into lakes or rivers, the water temperature goes up. The ability of water to hold dissolved gases goes down when the temperature increases. *At about 35°C, the dissolved oxygen will be so low that the acquatic life will die*. But in very cold regions, letting out hot water into the lakes or rivers helps in increasing the fish growth. But, in our country, such places are not many and hence, it is necessary that we minimise this thermal pollution of water. One of the regulation stipulates that a maximum temperature of water let out can be 1°C above the atmospheric temperature. Thus the thermal power plants or any other industry has to resort to various methods of adhering to this regulation.

13.2.4.1. Thermal discharge index (TDI)

Thermal discharge index (TDI) is the term usually used in connection with the estimation of the *amount of thermal energy released to environment from a thermal power plant*. TDI of any power plant is the *number of thermal energy units discharged to the environment for every unit of electrical energy generated*.

$$\text{TDI} = \frac{\text{Thermal power discharged to environment in } MW_{\text{thermal}}}{\text{Electrical power output in } MW_{\text{electrical}}}$$

This index cannot be zero or else the plant violates the Second law of thermodynamics ; but this index *should be as low as possible to improve the efficiency of the plant as well as to keep the pollution level low*.

The thermal discharge index (TDI) is *strongly dependent on the thermal efficiency of the plant*.

13.2.4.2. How to reduce thermal pollution ?

While considering the efficiency of the thermal plant, it is desirable that the water from a river or lake is pumped through the condenser and fed back to the source. The rise of temperature will be about 10°C which is highly objectionable from the pollution point of view. Hence, this waste heat which is removed from the condenser will have to be thrown into the atmosphere and not into the water source, in this direction following methods can be adopted :

1. Construction of a separate lake
2. Cooling pond
3. Cooling towers.

1. **Construction of a separate lake.** A sufficiently large water storage in the form of a lake can be built and once-through cooling the condenser can be adopted. If the natural cooling of water from the lake is not sufficient, floating spray pumps can be employed.

This method *improves the thermal efficiency* of the plant but can prove *expensive*. Also, it may not always be possible to have a large enough lake artificially built.

2. **Cooling pond.** A cooling pond with continuously operating fountains can be adopted for smaller power plants. This will also serve as a beautifying feature of the power plant site.

3. **Cooling towers.** In order to throw heat into the atmosphere most power stations adopt the cooling towers. The hyperbolic shape given to the tower automatically induces air from the bottom to flow upwards and the water is cooled by coming in direct contact with the air. This is a natural convection cooling and is also called '*wet-cooling tower*'. The overall efficiency of such plants will be lower than those of the plants adopting once-through cooling system. There will be considerable vapour flumes escaping from the cooling towers. Sometime, make-up cooling water may be scarce. In such cases, *dry cooling tower* can be adopted. Dry cooling towers are much more expensive than wet cooling towers.

All cooling towers, whether dry or wet, are *expensive and add to the initial investment of the plant*. Small plants can adopt mechanical-draft systems using induced or forced draft systems. This helps in avoiding height to the cooling towers. Thus, the initial cost is reduced but the maintenance cost of mechanical-draft systems are high.

13.3. POLLUTION FROM NUCLEAR POWER PLANTS

The various types of pollution from nuclear power plants are :

(*i*) Radioactive pollution

(*ii*) Waste from reactor (solid, liquid, gases)

(*iii*) Thermal pollution.

(*i*) **Radioactive pollution.** This is the most dangerous and serious type of pollution. This is due to radioactive elements and fissionable products in reactor. The best way to abate is the *radioactive shield around the reactor*.

(*ii*) **Waste from reactor.** Due to nuclear reactor reaction nuclear wastes (mixtures of various Beta and Gamma emitting radioactive isotopes with various half lives) are produced which cannot be neutralised by any chemical method. If the waste is discharged in the atmosphere, air and water will be contaminated beyond the tolerable limits. Some methods of storage or disposal of radioactive waste materials are discussed below :

1. **Storage tanks.** The radioactive wastes can be buried underground (very deep below the surface) in corrosion resistance tanks located in isolated areas. With the passage of time these will become stable isotopes.

2. **Dilution.** After storing for a short time, low energy wastes are diluted either in liquid or gaseous materials. After dilution, they are disposed off in sewer without causing hazard.

3. **Sea disposal.** This dilution can be used by adequately diluting the wastes and this method is being used by the British.

4. **Atmospheric dilution.** This method can be used for gaseous radioactive wastes. But solid particles from the gaseous wastes must be filtered out thoroughly since they are the most dangerous with higher half lives.

5. **Absorption by the soil.** Fission products are disposed off by this method. The radioactive particles are absorbed by the soil particles. But this is *expensive*.

6. **Burying is sea.** Solid nuclear wastes can be stored is concrete blocks which are burried in the sea. This method is *expensive but no further care is needed*.

13.4. POLLUTION FROM HYDRO-ELECTRIC POWER PLANTS AND SOLAR POWER GENERATING STATIONS

Hydro-electric and Solar Power Generation plants have no polluting effect on the environment. The hydro-electric project does not pollute the atmosphere at all, but it can be argued that the solar power stations in the long run may upset the balance in nature. To extend the argument to the logical end, imagine a very vast area of land is covered by solar collectors of different forms. Then the minimum required sun's rays may not reach the earth's surface. This will certainly kill the vegetation on the earth and also the bacteria which are destroyed by sun's rays may survive giving rise to new types of health problems. Further, the evaporation of water and consequent rains may change their cycles. Added to these, the average temperatures of the earth and ocean may change. This may result in new balances among the living creatures which cannot be easily predicted. Since we do not envisage such a large scale coverage of earth's surface in the near future, we can safely state that the solar energy power plants do not pollute the atmosphere.

HIGHLIGHTS

1. The power plant pollutants of major concern are :
   (*a*) From fossil power plants :
      (*i*) Sulphur oxide
      (*ii*) Nitrogen oxide
      (*iii*) Carbon oxide
      (*iv*) Thermal pollution
      (*v*) Particulate matter.
   (*b*) From nuclear power plants :
      (*i*) Radioactivity release
      (*ii*) Radioactive wastes
      (*iii*) Thermal pollution.
2. The emission may be classified as follows :
   (*i*) Gaseous emission
   (*ii*) Particulate emission
   (*iii*) Solid waste emission
   (*iv*) Thermal pollution (or waste heat).
3. Thermal discharge index (TDI) of any power plant is the number of thermal energy units discharged to the environment for every unit of electrical energy generated.
4. Thermal pollution can be reduced by :
   (*i*) Constructing a separate lake
   (*ii*) Cooling pond
   (*iii*) Cooling towers.
5. Some methods of storage or disposal of radioactive waste materials are :
   (*i*) Storage tanks (*ii*) Dilution
   (*iii*) Burial (*iv*) Sea disposal
   (*v*) Atmospheric dilution (*vi*) Absorption by soil
   (*vii*) Burying in sea (*viii*) Projecting into space.

THEORETICAL QUESTIONS

1. Name some power plant pollutants of major concern.
2. How are emissions from thermal power plants classified ?
3. Name important gaseous pollutants discharged by thermal power plants. How are they controlled ?
4. Describe briefly, with the help of a neat diagram, 'wet-scrubber' used for removing SO_2.
5. What is 'Particulate emission' ? How is it controlled ?
6. Define the following :
   Smoke, Fumes, Fly-ash, Cinders.
7. What is an electrostatic precipitator ?
8. Where are 'Baghouse filters' used ?
9. What do you mean by 'Thermal Pollution' ?
10. What is 'Thermal Discharge Index' (TDI) ?
11. Enumerate and explain briefly various methods of reducing the thermal pollution.
12. Write a short note on 'Pollution from Nuclear power plants'.
13. What are the various methods of storage or disposal of radioactive waste materials ?

'GATE' and 'UPSC' Examinations' Questions (Latest-Selected) with Answers/Solutions

14

(A) Conventional Questions with Answers/Solutions
(B) Multiple-choice Questions with Answers and "*Explanations*"

A. CONVENTIONAL QUESTIONS WITH ANSWERS/SOLUTIONS

Q.14.1. (Nuclear power plant): *The overall thermal efficiency of a 5 MW nuclear power plant for a submarine is 30%. Calculate the amount of natural uranium, U^{235}, needed to generate the power if the average energy release per fission for U^{235} is 190 MeV. Take 1 W = 6.241×10^{12} MeV/s. Avogadro's Number is 6.02×10^{23}.*

(IES)

Solution. *Given*: Power output = 5 MW; Efficiency, $\eta = 30\%$; Energy released by each atom of U^{235} = 190 MeV; 1 W = 6.241×10^{12} MeV/s; Avogadro's number = 6.02×10^{23}.

Mass of U^{235} needed, *m*:

$$\text{Power produced} = \frac{\text{Power output}}{\eta}$$

$$= \frac{5 \times 10^6}{0.3} = 16.67 \times 10^6 \text{ W}$$

$$= 16.67 \times 10^6 \times (6.241 \times 10^{12})$$

$$= 1.04 \times 10^{20} \text{ MeV}$$

Number of U^{235} atoms required to this amount of energy,

$$N = \frac{1.04 \times 10^{20}}{190} = 5.47 \times 10^{17}$$

Hence, the mass which contains 5.47×10^7 atoms

$$= \frac{235 \times 5.47 \times 10^{17}}{6.02 \times 10^{23}}$$

$$= \mathbf{2.135 \times 10^{-4} \text{ gm}} \quad \textbf{(Ans.)}$$

Q. 14.2. (Steam power plant): *A steam power plant generating 500 MW of electrical power employs a natural circulation boiler which supplies steam at a pressure of 150 bars and temperature of 550°C. The condenser pressure is 0.05 bar. The turbine, mechanical and generator efficiencies are 87%, 98% and 99% respectively. The boiler uses pulverized coal having a calorific value of 26 MJ/kg and yields 92% efficiency. The feedwater passing through the feed heaters enters the boiler at 160°C. The risers of the furnace are 55 m high while the downcomers are placed outside the furnace for producing natural circulation. The quality of steam at the top of the riser is 12% and a minimum exit velocity of mixture leaving the risers and entering the drum is 1.4 m/s. The dimensions of the riser tubes are 60 mm OD and 3 mm wall thickness while the dimensions of downcomers are 185 mm OD and 8 mm thick. Assume no pressure drop and heat loss to the risers. Work out the following:*

(i) Show the process on T-s diagram.

(ii) The generation of rate of steam ignoring the amount of steam bled off to feed heaters in kg/s.

(iii) The rate of fuel flow required in kg/s.

(iv) The evaporation factor.

(v) The circulation ratio.

(vi) The number of riser tubes.

(vii) The number of downcomers.

Take the following properties:

$h_1 = 3448.6$ kJ/kg

$h_2 = 1987$ kJ/kg

$h_{f3} = 137.8$ kJ/kg

$h_{f5} = 675.5$ kJ/kg

$\rho_{riser,\ top} = 396$ kg/m^3

$\rho_{downcomer,\ inlet} = 603$ kg/m^3

where suffixes 1, 2, 3 and 5 denote boiler exit (or turbine inlet), condenser exit, pump inlet and boiler inlet respectively. **(IES)**

Solution. *Given*: Power generated by the plant = 500 MW; p_1 = 150 bars; t_p = 550°C; $p_{cond.}$ = 0.05 bar; η_t = 87%; η_m = 98%; η_g = 99%; C.V. = 26 MJ/kg; η_{boiler} = 92%.

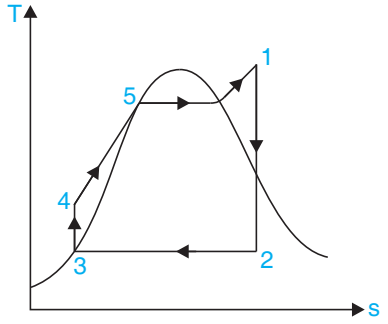


Fig. 14.1. T-s diagram.

(*i*) Fig. 14.1 shows the process on T-s diagram.

(*ii*) **Rate of steam generation, $\dot{m}_s$:**

Assuming isentropic expansion in that turbine and neglecting other losses, we have:

$$\dot{m}_s (h_1 - h_2)\, \eta_t\, \eta_m\, \eta_g = 500 \times 10^3$$

or, $$\dot{m}_s = \frac{500 \times 10^3}{(3448.6 - 1987) \times 0.87 \times 0.98 \times 0.99}$$

$$= \mathbf{405.28\ kg/s} \quad \textbf{(Ans.)}$$

(*iii*) **Rate of fuel flow, $\dot{m}_{fuel}$:**

$$\dot{m}_{fuel}\, (\text{C.V.})_{fuel} \cdot \eta_{boiler} = \dot{m}_s (h_1 - h_{f5})$$

$$\dot{m}_{fuel} \times (26 \times 10^3) \times 0.92 = 405.28\ (3448.6 - 675.5)$$

or, $$\dot{m}_{fuel} = \mathbf{46.98\ kg/s} \quad \textbf{(Ans.)}$$

(*iv*) **Evaporation factor:**

$$\text{Evaporation factor} = \frac{\dot{m}_s}{\dot{m}_{fuel}} = \frac{405.28}{46.98}$$

$$= \mathbf{8.627} \quad \textbf{(Ans.)}$$

(*v*) **Circulation ratio, CR:**

$$\text{CR} = \frac{1}{\text{Quantity of steam at the top of the riser } (x_{top})}$$

$$= \frac{1}{x_{top}} = \frac{1}{0.12} = \mathbf{8.333} \quad \textbf{(Ans.)}$$

(*vi*) **Number of riser tubes:**

Let us first calculate rate of steam formation in one riser, $\dot{m}_{rs}$.

$$\dot{m}_{rs} = A_i \rho_{top}\, C_i x_{top}$$

$$= \frac{\pi}{4}\ [(0.06 - 0.006)^2] \times 396 \times 1.4 \times 0.12$$

$$= 0.1524\ \text{kg/s}$$

$\therefore$ Number of riser tubes

$$= \frac{\dot{m}_s}{\dot{m}_{rs}} = \frac{405.28}{0.1524} = \mathbf{2660\ tubes} \quad \textbf{(Ans.)}$$

(*vii*) **Number of downcomers:**

Let us first calculate the mass flow rate of feed water through one downcomer, $\dot{m}_{dc}$.

$$\dot{m}_{dc} = A_i \rho_i\, C_i = \frac{\pi}{4}\ [(0.185 - 0.016)^2] \times 603 \times 1.4$$

$$= 18.94\ \text{kg/s}$$

$\therefore$ Number of downcomers

$$= \frac{\dot{m}_s}{\dot{m}_{dc}} = \frac{405.28}{18.94} = \mathbf{21.4\ say\ 22} \quad \textbf{(Ans.)}$$

Q.14.3. (Gas turbine plant): *In an open-cycle gas turbine plant, the air enters at 15°C and 1 bar, and is compressed in a compressor to a pressure ratio of 15. The air from the exit of compressor is first heated in a heat exchanger which is 75% efficient by turbine exhaust gas and then in a combustor to a temperature of 1600 K. The same gas expands in a two stage turbine such that the expansion work is maximum. The exhaust gas from H.P. turbine is reheated to 1500 K and then expands to L.P. turbine. The isentropic efficiencies of compressor and turbine may be taken as 86% and 88% respectively. The mechanical efficiencies for compressor and turbine are 97% each. The alternator efficiency is 98%. The output of turbo-alternator is 250 MW. Work out the following:*

(*i*) *Show the process on T-s diagram.*

(*ii*) *The cycle thermal efficiency.*

(*iii*) *The work ratio.*

(*iv*) *The specific power output.*

(*v*) *The mass flow rate of air.* **(IES)**

Solution. *Given*: T_1 = 15 + 273 = 288 K; p_1 = 1 bar; $\frac{p_2}{p_1}$ = 15; Effectiveness of heat exchange, ε = 0.75; T_3 = 1600 K; T_5 = 1500 K; $(\eta_{isen})_C$ = 86%; $(\eta_{isen})_T$ = 88%; $(\eta_{mech})_C$ = $(\eta_{mech})_T$ = 97%; $\eta_{alternator}$ = 98%; Output of alternator = 250 W.

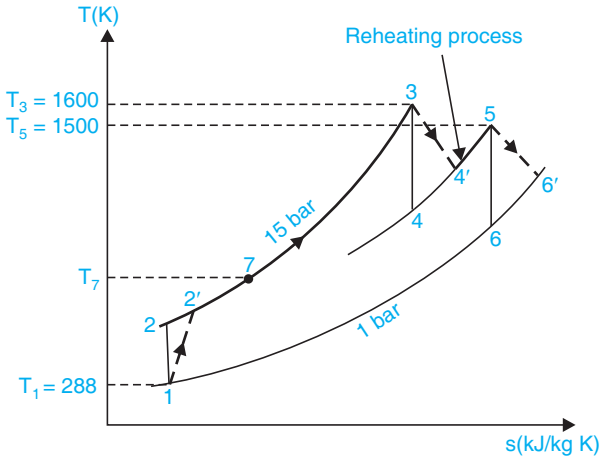


Fig. 14.2. T-s diagram.

(*i*) Fig. 14.2 shows the process on T-s diagram.

(*ii*) **Cycle thermal efficiency, $\eta_{thermal}$:**

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = (15)^{\frac{1.4-1}{1.4}} = 2.1678$$

or, $$T_2 = 288 \times 2.1678 = 624.33 \text{ K}$$

$$(\eta_{isen})_C = 0.86 = \frac{T_2 - T_1}{T_2' - T_1} = \frac{624.33 - 288}{T_2' - 288}$$

or, $$T_2' = \left(\frac{624.33 - 288}{0.86}\right) + 288 = 679.1 \text{ K}$$

Now, $$p_4 = p_5 = \sqrt{p_1 p_2} = \sqrt{1 \times 15} = 3.87 \text{ bar}$$

Again, $$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} \text{ or } \frac{T_4}{1600} = \left(\frac{3.87}{15}\right)^{\frac{1.4-1}{1.4}}$$

or, $$T_4 = 1086.5 \text{ K}$$

Similarly, $$\frac{T_6}{T_5} = \left(\frac{p_6}{p_5}\right)^{\frac{\gamma-1}{\gamma}} = \frac{T_6}{1500} = \left(\frac{1}{3.87}\right)^{\frac{1.4-1}{1.4}}$$

or, $$T_6 = 1018.9 \text{ K}$$

At $(\eta_{isen})_T = 88\%$, we have:

$$0.88 = \frac{T_3 - T_4'}{T_3 - T_4} = \frac{1600 - T_4'}{1600 - 1086.5}$$

or, $$T_4' = 1600 - 0.88\,(1600 - 1086.5)$$
$$= 1148.1 \text{ K}$$

Again, $$0.88 = \frac{T_5 - T_6'}{T_5 - T_6} = \frac{1500 - T_6'}{1500 - 1018.9}$$

or, $$T_6' = 1500 - 0.88\,(1500 - 1018.9)$$
$$= 1076.6 \text{ K}$$

Effective, $$\varepsilon = 0.75 = \frac{T_7 - T_2'}{T_6' - T_2'} = \frac{T_7 - 679.1}{1076.6 - 679.1}$$

or, $$T_7 = 0.75\,(1076.6 - 679.1) + 679.1$$
$$= 977.2 \text{ K}$$

$$W_{turbine} = [c_p(T_3 - T_4') + c_p(T_5 - T_6')] \times \eta_{mech}$$
$$= [1.005\,(1600 - 1148.1) + 1.005\,(1500 - 1076.6)] \times 0.97$$
$$= 853.29 \text{ kJ/kg}$$

$$W_{compressor} = \frac{c_p(T_2' - T_1)}{\eta_{mech}} = \frac{1.005\,(679.1 - 288)}{0.97}$$
$$= 405.21 \text{ kJ/kg}$$

$$Q_{supplied},\ Q_s = c_p\,(T_3 - T_7)$$
$$= 1.005\,(1600 - 977.2)$$
$$= 625.9 \text{ kJ/kg}$$

Hence, $$\eta_{thermal} = \frac{W_{turbine} - W_{compressor}}{Q_s}$$
$$= \frac{853.29 - 405.21}{625.9}$$
$$= 0.7159 \text{ or } \mathbf{71.59\%} \quad \textbf{(Ans.)}$$

(*iii*) **Work ratio:**

$$\text{Work ratio} = \frac{W_{turbine} - W_{compressor}}{W_{turbine}}$$
$$= \frac{853.29 - 405.21}{853.29}$$
$$= 0.525 \text{ or } \mathbf{52.5\%} \quad \textbf{(Ans.)}$$

(*iv*) **Specific power output:**

Specific power output = Net work output
$$= W_{turbine} - W_{compressor}$$
$$= 853.29 - 405.21$$
$$= \mathbf{448.08 \text{ kJ/kg}} \quad \textbf{(Ans.)}$$

(*v*) **Mass flow rate of air, $\dot{m}_a$:**

$$\dot{m}_a \times \text{Net work output} = \frac{250 \times 10^3}{\eta_{alternator}} = \frac{250 \times 10^3}{0.98}$$

or, $$\dot{m}_a \times 448.08 = \frac{250 \times 10^3}{0.98}$$

or, $$\dot{m}_a = \frac{250 \times 10^3}{448.08 \times 0.98}$$
$$= \mathbf{569.32 \text{ kg/s}} \quad \textbf{(Ans.)}$$

Q.14.4. (Gas turbine plant): *A two stage compression with intercooling in between stages and a single stage turbine with regeneration is employed in an open cycle gas turbine plant. Air at 1 bar and 15°C enters the compressor and the maximum pressure ratio is 5 and the maximum temperature in the cycle is 800°C. The rate of air flow through the cycle is 250 kg/sec and the calorific value of the fuel used is 42 MJ/kg. The isentropic efficiencies of both the compressors is 0.8 and the effectiveness of the regenerator is 0.7, and the isentropic efficiency of the turbine is 0.9. The combustion efficiency is 0.95, the mechanical efficiency is 0.96 and the generator efficiency is 0.75. Take c_p of air = 1.005 kJ/kg K and γ = 1.4 and for gases c_p = 1.08 kJ/kg K and γ = 1.33.*

Assuming perfect intercooling and neglecting pressure and heat losses, determine:

(*i*) *The air fuel ratio.*

(*ii*) *The cycle efficiency.*

(*iii*) *The specific fuel consumption.* **(IES)**

Solution. *Given*: $p_1 = 1$ bar; $T_1 = 15 + 273 = 288$ K; Max. pressure ratio $= \dfrac{p_5}{p_6} = 5$; $T_5 = 273 + 800 = 1073$ K; $\dot{m}_a = 250$ kg/s; C.V. $= 42$ MJ/kg or 42×10^3 kJ/kg; Isentropic efficiency of each compressor, $\eta_{comp.} = 0.8$; Effectiveness, $\varepsilon = 0.7$; Isentropic efficiency of turbine, $\eta_{turbine} = 0.9$; $\eta_{combustion} = 0.95$; $\eta_{mech.} = 0.96$; $\eta_{gen.} = 0.75$; c_{pa} of air $= 1.005$ kJ/kg K; $\gamma_a = 1.4$ and for gases, $c_{pg} = 1.08$ kJ/kg K and $\gamma_g = 1.33$.

Refer to Fig. 14.3.

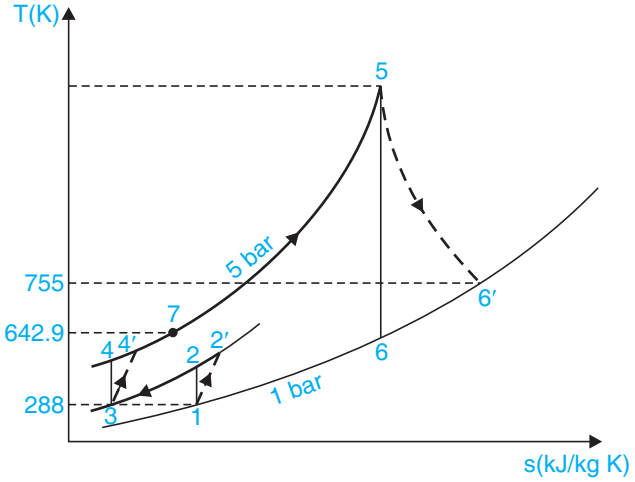


Fig. 14.3

(*i*) **Air fuel ratio, $\dfrac{\dot{m}_a}{\dot{m}_f}$:**

Due to perfect intercooling,

$$p_2 = p_3 = \sqrt{p_1 p_4} = \sqrt{1 \times 5} = 2.23 \text{ bar}$$

Since the pressure ratio and isentropic efficiency of each compressor is same then the *work input required for each compressor is the same* since both the compressors have the same inlet temperature *(perfect intercooling), i.e.,* $T_1 = T_3$ and $T_2' = T_4'$.

For compressors:

Now, $$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma_a - 1}{\gamma_a}}$$

or, $$\frac{T_2}{288} = (2.23)^{\frac{1.4-1}{1.4}} \quad \text{or} \quad T_2 = 362.2 \text{ K}$$

Also, $$(\eta_{isen})_{C(I)} = \frac{T_2 - T_1}{T_2' - T_1}$$

or, $$0.8 = \frac{362.2 - 288}{T_2' - 288} \quad \text{or } T_2' = 380.7 \text{ K}$$

Similarly, $$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma_a - 1}{\gamma_a}} \quad \text{or} \quad \frac{T_4}{288} = \left(\frac{5}{2.23}\right)^{\frac{1.4-1}{1.4}}$$

or, $$T_4 = 362.7 \text{ K}$$

Again, $$(\eta_{isen})_{C(II)} = \frac{T_4 - T_3}{T_4' - T_3} \text{ or } 0.8 = \frac{362.7 - 288}{T_4' - 288}$$

or, $$T_4' = 381.4 \text{ K}$$

For turbine:

$$\frac{T_5}{T_6} = \left(\frac{p_5}{p_6}\right)^{\frac{\gamma_g - 1}{\gamma_g}}$$

or, $$\frac{1073}{T_6} = \left(\frac{5}{1}\right)^{\frac{1.33-1}{1.33}} \quad T_6 = 719.7 \text{ K}$$

$$(\eta_{isen})_T = 0.9 = \frac{T_5 - T_6'}{T_5 - T_6} = \frac{1073 - T_6'}{1073 - 719.7}$$

or, $$T_6' = 755 \text{ K}$$

Effectiveness, $$\varepsilon = 0.7 = \frac{T_7 - T_4'}{T_6' - T_4'} = \frac{T_7 - 381.4}{755 - 381.4}$$

or, $$T_7 = 642.9 \text{ K}$$

Work done by compressors

$$= W_{C(I)} + W_{C(II)}$$
$$= \dot{m}_a c_{pa} (T'_2 - T_1) + \dot{m}_a c_{pa} (T_4' - T_3)$$
$$= 250 \times 1.005 \, [(380.7 - 288) + (381.4 - 288)]$$
$$= 46757.6 \text{ kJ/s}$$

Net work done by compressors

$$= \frac{46757.6}{\eta_{mech}} = \frac{46757.6}{0.96}$$
$$= 48705.8 \text{ kJ/s}$$

Heat supplied, $Q_s = \dot{m}_f \times \text{C.V.} \times \eta_{combustion}$

$$= \dot{m}_f \times (42 \times 10^3) \times 0.95 = 39.9 \times 10^3 \, \dot{m}_f$$

By energy balance equation, we have:

$$Q_s = (\dot{m}_a + \dot{m}_f) c_{pg} T_5 - \dot{m}_a c_{pa} T_7$$
$$= (250 + \dot{m}_f) \times 1.08 \times 1073 - 250 \times 1.005 \times 642.9$$

or, $$Q_s = (1158.8 \, \dot{m}_f + 128181.4)$$

$\therefore$ $$1158.8 \, \dot{m}_f + 128181.4 = 39.9 \times 10^3 \, \dot{m}_f$$

or, $$\dot{m}_f = \frac{128181.4}{[(39.9 \times 10^3) - 1158.8]}$$
$$= 3.31 \text{ kg/s}$$

Hence, $$\frac{\dot{m}_a}{\dot{m}_f} = \frac{250}{3.31} = \mathbf{75.53} \quad \textbf{(Ans.)}$$

(*ii*) **Cycle efficiency, η_{cycle}:**

$$W_{net} = W_{turbine} - W_{compressors}$$

$$W_{turbine} = (\dot{m}_a + \dot{m}_f)\, c_{pg}(T_5 - T'_6)$$
$$= (250 + 3.31) \times 1.08\ (1073 - 755)$$
$$= 86996.8 \text{ kW}$$

Net work done by turbine
$$= 86996.8 \times \eta_{gen}.$$
$$= 86996.8 \times 0.75 = 65247.6 \text{ kW}$$
$$\therefore \quad W_{net} = 65247.6 - 46757.6 = 18490 \text{ kW}$$

Hence, $$\eta_{cycle} = \frac{W_{net}}{Q_s} = \frac{18490}{\dot{m}_f \times \text{C.V.} \times \eta_{combustion}}$$
$$= \frac{18490}{3.31 \times (42 \times 10^3) \times 0.95}$$
$$= 0.14 \text{ or } \mathbf{14\%} \quad \textbf{(Ans.)}$$

(*iii*) **Specific fuel consumption:**

Specific fuel consumption
$$= \frac{\dot{m}_f \times 3600}{18490} = \frac{3.31 \times 3600}{18490}$$
$$= \mathbf{0.644\ kg/kWh} \quad \textbf{(Ans).}$$

Q.14.5. (Gas turbine plant): *Air is taken in a gas turbine plant at 1.1 bar, 20°C. The plant comprises of L.P. and H.P. compressors and L.P. and H.P. turbines. The compression in L.P. stage is upto 3.3 bar followed by intercooling to 27°C. The pressure of air after H.P. compressor is 9.45 bar. Loss in pressure during intercooling is 0.15 bar. Air from H.P. compressor is transferred to heat exchanger of effectiveness 0.65 where it is heated by the gases from L.P. turbine. After heat exchanger the air passes through combustion chamber. The temperature of gases supplied to H.P. turbine is 700°C. The gases expand in H.P. turbine to 3.62 bar and air then reheated to 670°C before expanding in L.P. turbine. The loss of pressure in reheater is 0.12 bar. Determine :*

(*i*) *The overall efficiency.*

(*ii*) *The work ratio.*

(*iii*) *Mass flow rate when the power generated is 6000 kW.*

Assume : Isentropic efficiency of compression in both stages = 0.82.

Isentropic efficiency of expansion in turbines = 0.85.

For air : $c_p = 1.005\ kJ/kg\ K$, $\gamma = 1.4$.

For gases : $c_p = 1.15\ kJ/kg\ K$, $\gamma = 1.33$.

Neglect the mass of fuel. **(IES)**

Solution. *Given :* $T_1 = 20 + 273 = 293$ K,

$p_1 = 1.1$ bar, $p_2 = 3.3$ bar,

$T_3 = 27 + 273 = 300$ K,

$p_3 = 3.3 - 0.15 = 3.15$ bar,

$p_4 = p_6 = 9.45$ bar, $T_6 = 973$ K,

$T_8 = 670 + 273 = 943$ K,

$p_8 = 3.5$ bar,

$\eta_{compressors} = 82\%$, $\eta_{turbines} = 85\%$,

Power generated = 6000 kW,

Effectiveness, $\varepsilon = 0.65$, $c_{pa} = 1.005$ kJ/kg K,

$\gamma_{air} = 1.44$,

$c_{pg} = 1.15$ kJ/kg K and $\gamma_{gases} = 1.33$.

Refer to Fig. 14.4.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.3}{1.1}\right)^{\frac{1.4-1}{1.4}} = 1.369$$

$$\therefore \quad T_2 = 293 \times 1.369 = 401 \text{ K}$$

$$\eta_{compressor\ (L.P.)} = 0.82 = \frac{T_2 - T_1}{T_2' - T_1} = \frac{401 - 293}{T_2' - 293}$$

$$\therefore \quad T_2' = \left(\frac{401 - 293}{0.82}\right) + 293 = 425 \text{ K}$$

Again, $$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{9.45}{3.15}\right)^{\frac{1.4-1}{1.4}} = 1.369$$

$$\therefore \quad T_4 = 300 \times 1.369 = 411 \text{ K}$$

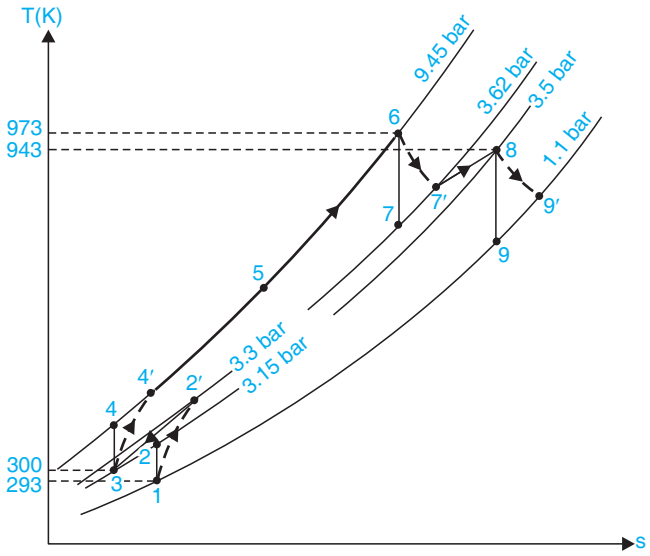


Fig. 14.4

Now, $$\eta_{compressor\ (H.P.)} = \frac{T_4 - T_3}{T_4' - T_3}$$

$$0.82 = \frac{411 - 300}{T_4' - 300}$$

$$\therefore \quad T_4' = \left(\frac{411 - 300}{0.82}\right) + 300 = 435 \text{ K}$$

Similarly, $\frac{T_6}{T_7} = \left(\frac{p_6}{p_7}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{9.45}{3.62}\right)^{\frac{1.33-1}{1.33}} = 1.268$

$\therefore \quad T_7 = \frac{T_6}{1.268} = \frac{973}{1.268} = 767 \text{ K}$

Also, $\eta_{\text{turbine (H.P.)}} = \frac{T_6 - T_7'}{T_6 - T_7}$

$0.85 = \frac{973 - T_7'}{973 - 767}$

or, $T_7' = 973 - 0.85(973 - 767) = 798 \text{ K}$

Again, $\frac{T_8}{T_9} = \left(\frac{p_8}{p_9}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.5}{1.1}\right)^{\frac{1.33-1}{1.33}} = 1.332$

$\therefore \quad T_9 = \frac{T_8}{1.332} = \frac{943}{1.332} = 708 \text{ K}$

$\eta_{\text{turbine (L.P.)}} = \frac{T_8 - T_9'}{T_8 - T_9}$

$0.85 = \frac{943 - T_9'}{943 - 708}$

$\therefore \quad T_9' = 943 - 0.85(943 - 708) = 743 \text{ K}.$

Effectiveness of heat exchanger,

$$\varepsilon = 0.65 = \frac{T_5 - T_4'}{T_9' - T_4'}$$

i.e., $0.65 = \frac{T_5 - 435}{743 - 435}$

$\therefore \quad T_5 = 0.65(743 - 435) + 435 = 635 \text{ K}$

$W_{\text{turbine (H.P.)}} = c_{pg}(T_6 - T_7')$
$= 1.15(973 - 798)$
$= 201.25 \text{ kJ/kg of gas}$

$W_{\text{turbine (L.P.)}} = c_{pg}(T_8 - T_9')$
$= 1.15(943 - 743)$
$= 230 \text{ kJ/kg of gas}$

$W_{\text{compressor (L.P.)}} = c_{pa}(T_2' - T_1)$
$= 1.005(425 - 293)$
$= 132.66 \text{ kJ/kg of air}$

$W_{\text{compressor (H.P.)}} = c_{pa}(T_4' - T_3)$
$= 1.005(435 - 300)$
$= 135.67 \text{ kJ/kg of air}$

Heat supplied $= c_{pg}(T_6 - T_5) + c_{pg}(T_8 - T_7')$
$= 1.15(973 - 635) + 1.15(943 - 798)$
$= 555.45 \text{ kJ/kg of gas}$

(*i*) **Overall efficiency η_{overall} :**

$$\eta_{\text{overall}} = \frac{\text{Net work done}}{\text{Heat supplied}}$$

$$= \frac{[W_{\text{turbine (H.P.)}} + W_{\text{turbine (L.P.)}}] - [W_{\text{comp. (L.P.)}} + W_{\text{comp. (H.P.)}}]}{\text{Heat supplied}}$$

$$= \frac{(201.25 + 230) - (132.66 + 135.67)}{555.45}$$

$$= \frac{162.92}{555.45} = 0.293 \text{ or } \mathbf{29.3\%}. \quad \textbf{(Ans.)}$$

(*ii*) **Work ratio:**

$$\textit{Work ratio} = \frac{\text{Net work done}}{\text{Turbine work}}$$

$$= \frac{[W_{\text{turbine (H.P.)}} + W_{\text{turbine (L.P.)}}] - [W_{\text{comp. (L.P.)}} + W_{\text{comp. (H.P.)}}]}{[W_{\text{turbine (H.P.)}} + W_{\text{turbine (L.P.)}}]}$$

$$= \frac{(201.25 + 230) - (132.66 + 135.67)}{(201.25 + 230)}$$

$$= \frac{162.92}{431.25} = 0.377$$

i.e., *Work ratio* = **0.377** **(Ans.)**

(*iii*) **Mass flow rate, $\dot{m}$:**

Net work done = 162.92 kJ/kg

Since mass of fuel is neglected, for 6000 kW, mass flow rate,

$$\dot{m} = \frac{6000}{162.92} = 36.83 \text{ kg/s}$$

i.e., *Mass flow rate* = **36.83 kg/s** **(Ans.)**

Q.14.6. (Gas turbine): *A gas turbine utilizes two-stages centrifugal compressor. The pressure ratios for the first and second stages are 2.5 and 2.1 respectively. The flow of air is 10 kg/s, this air being drawn at 1.013 bar and 20°C. If the temperature drop in the intercooler is 60°C and the isentropic efficiency is 90% for each stage, calculate:*

(*i*) *The actual temperature at the end of each stage.*

(*ii*) *The total compressor power.*

Assume $\gamma = 1.4$ *and* $c_p = 1.005$ *kJ/kg K for air.*

(IES)

Solution. *Given* : $\frac{p_2}{p_1} = 2.5$; $\frac{p_3}{p_2} = 2.1$; $\dot{m} = 10$ kg/s; $p_1 = 1.013$ bar; $T_1 = 20 + 273 = 293$ K; Temperature drop in intercooler; $T_2 - T_3 = 60°\text{C}$; $\eta_{\text{isen}} = 90\%$, $\gamma = 1.4$; $c_p = 1.005$ kJ/kg K for air.

(*i*) **Actual temperature at the end of each stage, T_2, T_3:**

For isentropic compression:

$$\frac{T_2'}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \text{ or } \frac{T_2'}{293} = (2.5)^{\frac{1.4-1}{1.4}}$$

or, $T_2' = 380.68$ K

Also, $\eta_{isen} = \dfrac{T_2' - T_1}{T_2 - T_1}$ or $0.9 = \dfrac{380.68 - 293}{T_2 - 293}$

or, $0.9\,(T_2 - 293) = 380.68 - 293 = 87.68$

or, $T_2 = \dfrac{87.68}{0.9} + 293 = \mathbf{390.42\ K}$ **(Ans.)**

and, $T_3 = 390.42 - 60 = \mathbf{330.42\ K}$ **(Ans.)**

(*ii*) **Total compressor power:**

Compressor power

$$= \dot{m} c_p\,[(T_2 - T_1) \times (T_4 - T_3)] \quad ...(i)$$

Now, $\dfrac{T_4'}{T_3} = \left(\dfrac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}}$ or $\dfrac{T_4'}{330.42} = (2.1)^{\frac{1.4-1}{1.4}}$

or, $T_4' = 330.42\ (2.1)^{\frac{0.4}{1.4}} = 408.44$ K

Also, $0.9 = \dfrac{T_4' - T_3}{T_4 - T_3} = \dfrac{408.44 - 330.42}{T_4 - 330.42}$

$$= \frac{78.02}{T_4 - 330.42}$$

or, $0.9\,(T_4 - 330.42) = 78.02$ or $T_4 = 417.11$ K

Inserting the values in eqn. (*i*), we get:

Compressor power

$$= 10 \times 1.005\,[(390.42 - 293) + (417.11 - 330.42)]$$

$$= \mathbf{1850.3\ kW} \quad \textbf{(Ans.)}$$

Q.14.7. (Centrifugal compressor): *A centrifugal compressor running at 16000 rpm takes in air at 17°C and compresses it through a pressure ratio of 4 with an isentropic efficiency of 82 per cent. The blades are radially inclined and the slip factor is 0.85. Guide vanes at inlet give the air an angle of prewhirl of 20° to the axial direction. The mean diameter of the impeller eye is 200 mm and the absolute air velocity at inlet is 120 m/s. Calculate the impeller tip diameter.* **(IES)**

Solution. *Given* : $N = 16000$ rpm; $T_1 = 17 + 273 = 290$ K; Pressure ratio, $r_p = 4$; $\eta_{isen} = 82\%$; Slip factor, $\phi_s = 0.85$, inlet prewhirl angle = 20° (to axis direction); Mean impeller diameter, $D_1 = 280$ mm = 0.2 m; Absolute air velocity at inlet, $C_1 = 120$ m/s.

Refer to Fig. 14.5.

Impeller tip diameter, D_1:

Velocity of flow at inlet,

$$C_{f_1} = 120 \cos 20° = 112.76 \text{ m/s}$$

Velocity of whirl at inlet,

$$C_{w_1} = 120 \sin 20° = 41.04 \text{ m/s}$$

Peripheral velocity at inlet,

$$C_{bl_1} = \frac{\pi D_1 N}{60} = \frac{\pi \times 0.2 \times 16000}{60} = 167.55 \text{ m/s}$$

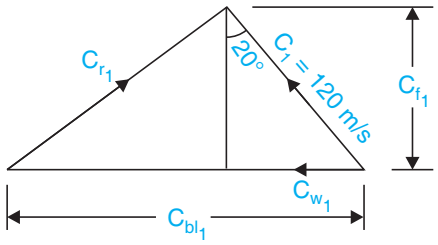


Fig. 14.5

Slip factor, $\phi_s = 0.85 = \dfrac{C_{w_2}}{C_{bl_2}}$ $\sigma, C_{w_2} = 0.85\ C_{bl_2}$

Now, $\dfrac{T_2'}{T_1} = \left(\dfrac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$

or, $\dfrac{T_2'}{290} = (4)^{\frac{1.4-1}{0.4}}$ or $T_2' = 430.9$ K

$$\eta_{isen} = 0.82 = \frac{T_2' - T_1}{T_2 - T_1} = \frac{430.9 - 290}{T_2 - 290}$$

or, $T_2 = 290 + \dfrac{430.9 - 290}{0.82} = 461.8$ K

Work done $= c_p(T_2 - T_1) = 1.005\,(461.8 - 290)$

$= 172.66$ kJ/kg ...(*i*)

Also, work done $= (C_{w_2}\ C_{bl_2} - C_{w_1}\ C_{bl_1})$

$= (0.85\ C_{bl_2} \times C_{bl_2} - 41.04 \times 167.55)$

$= 0.85\ C_{bl_2} - 6876.25$ ...(*ii*)

Equating eqns. (*i*) and (*ii*), we get:

$0.85\ C_{bl_2}^2 - 6876.25 = 172.66 \times 10^3$

$$C_{bl_2} = \left(\frac{6876.25 + 172.66 \times 10^3}{0.85}\right)^{1/2}$$

$= 459.6$ m/s

But, $C_{bl_2} = \dfrac{\pi D_2 N}{60}$ or

$$459.6 = \frac{\pi D_2 \times 16000}{60}$$

or, $$D_2 = \frac{459.6 \times 60}{\pi \times 16000}$$

$= 0.548$ m or **548 mm** **(Ans.)**

Q.14.8. (Reciprocating compressors): *A single-stage, double-acting compressor has a free air delivery (F.A.D.) of 14 m^3/min. measured at 1.013 bar and 15°C. The pressure and temperature in the cylinder during induction are 0.95 bar, 32°C. The delivery pressure is 7 bar and index of compression and expansion, n = 1.3. The clearance volume is 5% of the swept volume. Calculate :*

(i) Indicated power required ;

(ii) Volumetric efficiency. **(GATE)**

Solution.

Free air delivery,

F.A.D. = 14 m^3/min. (measured at 1.013 bar and 15°C)

Induction pressure, $p_1 = 0.95$ bar

Induction temperature, $T_1 = 32 + 273 = 305$ K

Delivery pressure, $p_2 = 7$ bar

Index of compression and expansion, $n = 1.3$

Clearance volume, $V_3 = V_c = 0.05\ V_s$

Refer to Fig. 14.6.

(*i*) **Indicated power :**

Mass delivered per minute,

$$m = \frac{pV}{RT} = \frac{1.013 \times 10^3 \times 14}{0.287 \times 288 \times 10^3}$$

$= 17.16$ kg/min.

where, F.A.D. per minute is V at p(= 1.013 bar)

and, T(= 15 + 273 = 288 K)

To find T_2, using the equation,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$, we have:

or, $$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

$$= 305 \times \left(\frac{7}{0.95}\right)^{\frac{1.3-1}{1.3}} = 483.5 \text{ K}$$

Indicated power

$$= \frac{n}{n-1} mR(T_2 - T_1)$$

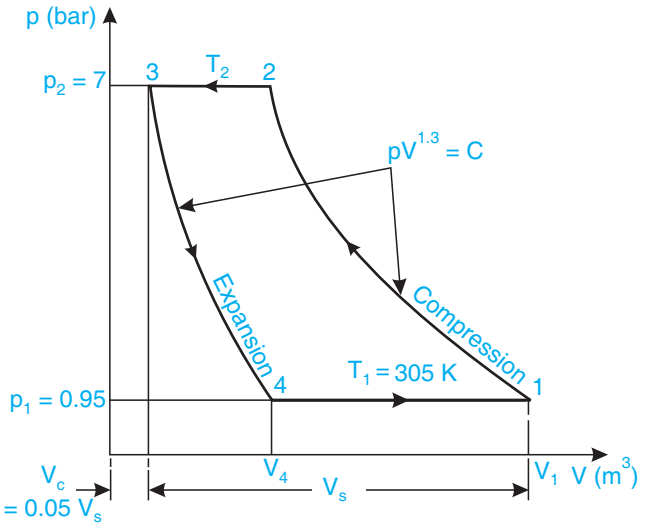


Fig. 14.6

$$= \frac{1.3}{1.3-1} \times 17.16 \times 0.287\,(483.5 - 305)$$

$= 3809.4$ kJ/min.

$\therefore$ **Indicated power**

$$= \frac{3809.4}{60} = \mathbf{63.49\ kW.}$$ **(Ans.)**

(*ii*) **Volumetric efficiency :**

Using the relation:

$$\frac{V_4}{V_3} = \left(\frac{p_3}{p_4}\right)^{1/n} = \left(\frac{p_2}{p_1}\right)^{1/1.3}$$

$$= \left(\frac{7}{0.95}\right)^{1/1.3} = 4.65$$

$\therefore$ $V_4 = 4.65 \times V_3 = 4.65 \times 0.05\ V_s = 0.233\ V_s$

$\therefore$ $V_1 - V_4 = V_1 - 0.233 V_s = 1.05\ V_s - 0.233\ V_s$

$= 0.817\ V_s$

Now, $$m = \frac{pV}{RT} = \frac{p_1 (V_1 - V_4)}{RT_1}$$

i.e., F.A.D./cycle, $V = (V_1 - V_4) \dfrac{T}{T_1} \cdot \dfrac{p_1}{p}$

(where p_1 and T_1 are the suction conditions)

$\therefore$ $$V = 0.817\ V_s \times \frac{288}{305} \times \frac{0.95}{1.013}$$

$= 0.723\ V_s$

$\therefore$ Volumetric efficiency,

$$\eta_{vol.} = \frac{V}{V_s} = \frac{0.723\ V_s}{V_s}$$

$= \mathbf{0.723}$ or **72.3%.** **(Ans.)**

Q.14.9. (Steam nozzle): *Steam nozzle is supplied steam at 15 bar 350°C and discharges steam at 1 bar. If the diverging portion of the nozzle is 80 mm long and the throat diameter is 6 mm, determine the cone angle of the divergent portion. Assume 12% of the total available enthalpy drop is lost in friction in the divergent portion. Also determine the velocity and temperature of the steam at throat.* **(IES)**

Solution. p_1 = 15 bar, 350°C, p_3 = 1 bar,

$k = 1 - 0.12 = 0.88$

When steam supplied to the nozzle is *superheated*, the pressure at throat,

$$p_2 = 0.546\, p_1 = 0.546 \times 15 = 8.19 \text{ bar}$$

Refer to Fig.14.7.

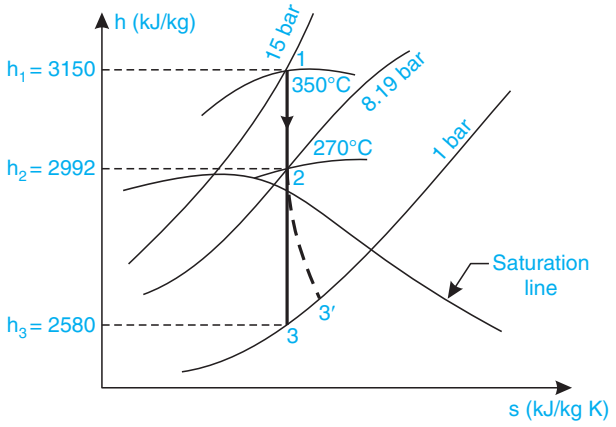


Fig. 14.7

From Mollier chart :

h_1 = 3150 kJ/kg, h_2 = 2992 kJ/kg

v_2 = 0.24 m³/kg, h_3 = 2580 kJ/kg

v_3' = 1.75 m³/kg, t_2 = 270°C

i.e., **Temperature of the steam at throat**

= **270°C. (Ans.)**

Velocity of steam at throat,

$$C_2 = 44.72\sqrt{h_d} = 44.72\sqrt{(h_1 - h_2)}$$

$$= 44.72\sqrt{(3150 - 2992)}$$

= **562.12 m/s. (Ans.)**

From the conditions at nozzle throat, mass flow rate,

$$\dot{m} = \frac{A_2 C_2}{v_2}$$

$$= \frac{\pi / 4\,(6/1000)^2 \times 562.12}{0.24} = 0.0662 \text{ kg/s}$$

At exit :

$$C_3' = 44.72\sqrt{kh_d'} = 44.72\sqrt{0.88 \times (h_1 - h_3)}$$

$$= 44.72\sqrt{0.88 \times (3150 - 2580)} = 1001.5 \text{ m/s}$$

Exit area of the nozzle,

$$A_3 = \frac{\dot{m} \times v_3'}{C_3'} = \frac{0.0662 \times 1.75}{1001.5} = 0.0001156 \text{ m}^2$$

i.e., $\frac{\pi}{4} D_3^2 = 0.0001156$

$$\therefore \quad D_3 = \left(\frac{4 \times 0.0001156}{\pi}\right)^{1/2} = 0.012 \text{ m or } 12.1 \text{ mm}$$

If θ be the cone angle of nozzle,

$$\tan\theta = \frac{(12.1 - 6)}{2 \times 80} = 0.03812 \text{ or } \theta = 2°\ 11'$$

Thus, **cone angle** = 2 × 2° 11′ = **4° 22′. (Ans.)**

Q.14.10. (Impulse turbine): *The first stage of a turbine is a two-row velocity compounded impulse wheel. The steam velocity at inlet is 600 m/s and the mean blade velocity is 120 m/s. The nozzle angle is 16° and the exit angles for the first-row of moving blades, the fixed blades, and the second row of moving blades are 18°, 21° and 35° respectively.*

(i) Calculate the blade inlet angles for each row.

(ii) Calculate also for each row of moving blades, the driving force and the axial thrust on the wheel for a mass flow of 1 kg/s.

(iii) Calculate the diagram efficiency for the wheel and the diagram power per kg/s steam flow.

(iv) What would be the maximum possible diagram efficiency for the given steam inlet velocity and nozzle angle?

Take the blade velocity co-efficient as 0.9 for all blades. **(IES)**

Solution. Refer to Fig. 14.8.

α = 16°, ϕ = 18°, C_1 = 600 m/s, C_{bl} = 120 m/s,

α′ = 21°, ϕ′ = 35°, $\dot{m}_s$ = 1 kg/s,

Blade velocity co-efficient, K = 0.9.

With the above data velocity triangles can be drawn.

From the diagram, by measurement:

$C_w = C_{w_1} + C_{w_0}$ = 875 m/s ;

$C_w' = C_{w_1}' + C_{w_0}'$ = 294 m/s ;

C_{f_1} = 168 m/s, C_{f_0} = 135 m/s ;

C_{f_1}' = 106 m/s, C_{f_0}' = 97 m/s.

(*i*) **Blade inlet angles :**

First row : θ = 20° (moving blade)

β = 24.5° (fixed blade)

Second row : θ′ = 34.5° (moving blade).

(*ii*) **Driving force :**

First row of moving blades

$$= \dot{m}_s(C_{w_1} + C_{w_0}) = \dot{m}_s C_w$$

= 1 × 875 = **875 N. (Ans.)**

Second row of moving blades

$$= \dot{m}_s(C_{w_1}' + C_{w_0}') = \dot{m}_s C_w'$$

$$= 1 \times 294 = \textbf{294 N.} \quad \textbf{(Ans.)}$$

Axial thrust :

First row of moving blades

$$= \dot{m}_s(C_{f_1}' + C_{f_0}') = 1 \times (168 - 135) = 33 \text{ N}$$

Second row of moving blades

$$= \dot{m}_s(C_{f_1}' - C_{f_0}') = 1 \times (106 - 97) = 9 \text{ N}$$

Total axial thrust

$$= 33 + 9 = \textbf{42 N per kg/s.} \quad \textbf{(Ans.)}$$

(*iii*) **Power developed**

$$= \frac{\dot{m}_s(C_w + C_w')\, C_{bl}}{1000}$$

$$= \frac{1 \times (875 + 294) \times 120}{1000}$$

$$= \textbf{140.28 kW per kg/s.} \quad \textbf{(Ans.)}$$

Diagram efficiency

$$= \frac{2C_{bl}(C_w + C_w')}{C_1^2} = \frac{2 \times 120\,(875 + 294)}{(600)^2}$$

$$= \textbf{0.7793 or 77.93\%.} \quad \textbf{(Ans.)}$$

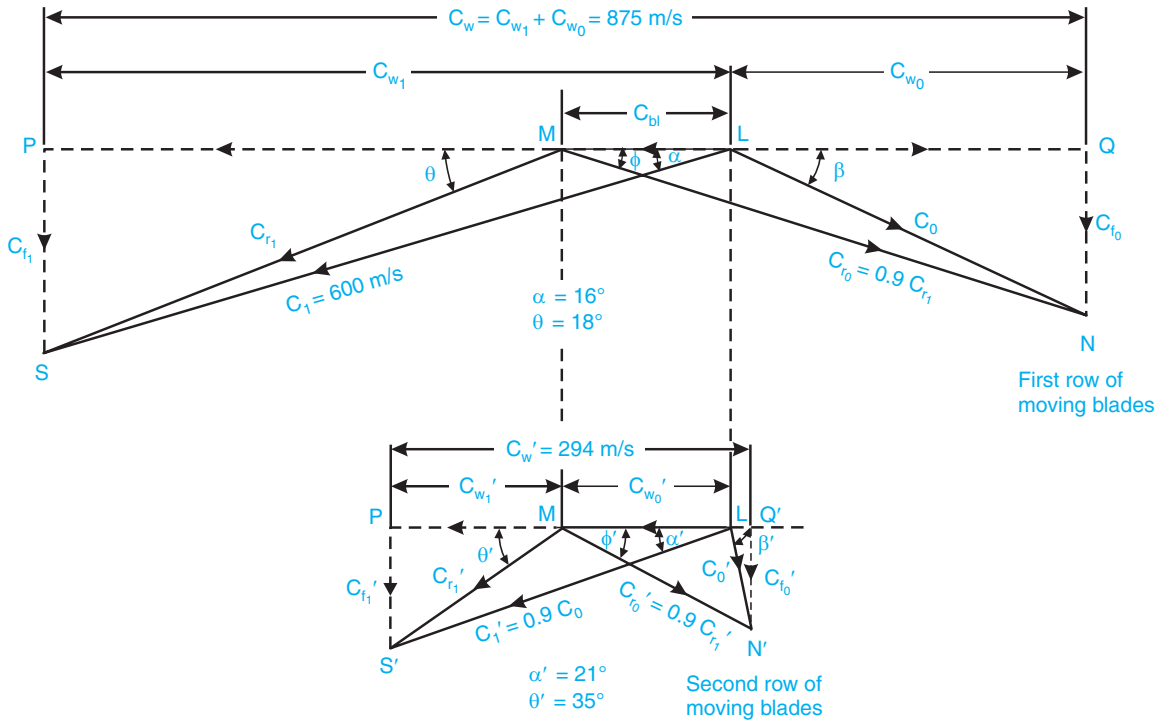


Fig. 14.8

(*iv*) **Maximum diagram efficiency**

$$= \cos^2 \alpha = \cos^2 16° = \textbf{0.924 or 92.4\%.} \quad \textbf{(Ans.)}$$

Q.14.11. (Parson's turbine): *A stage of a turbine with Parson's blading delivers dry saturated steam at 2.7 bar from the fixed blades at 90 m/s. The mean blade height is 40 mm, and the moving blade exit angle is 20°. The axial velocity of steam is 3/4 of the blade velocity at the mean radius. Steam is supplied to the stage at the rate of 9000 kg/h. The effect of the blade tip thickness on the annulus area can be neglected. Calculate :*

(*i*) *The wheel speed in r.p.m. ;*

(*ii*) *The diagram power ;*

(*iii*) *The diagram efficiency ;*

(*iv*) *The enthalpy drop of the steam in this stage.*

(IES)

Solution. The velocity diagram is shown in Fig. 14.9 (*a*) and the blade wheel annulus is represented in Fig. 14.9 (*b*).

Pressure = 2.7 bar, $x = 1$, $C_1 = 90$ m/s,

$h = 40$ mm $= 0.04$ m

$\alpha = \phi = 20°$, $C_{f_1} = C_{f_0} = 3/4\ C_{bl}$

Rate of steam supply = 9000 kg/h.

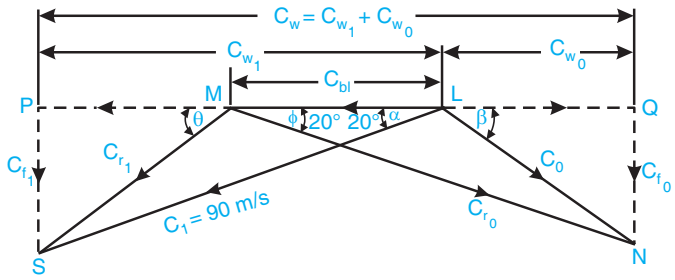
(*i*) **Wheel speed, N :**

$$C_f = 3/4\ C_{bl} = C_1 \sin 20° = 90 \sin 20°$$

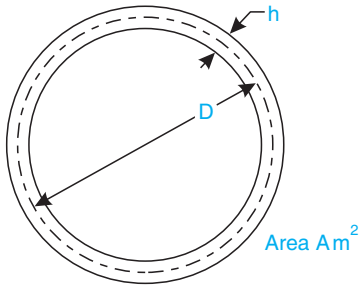
$$= 30.78 \text{ m/s}$$

$$\therefore \quad C_{bl} = 30.78 \times 4/3$$

$$= 41.04 \text{ m/s}$$



(a)



(b)

Fig. 14.9

The mass flow of steam is given by : $\dot{m}_s = \dfrac{C_f A}{v}$

where, A is the annulus area, and v is the specific volume of the steam.

In this case, $v = v_g$ at 2.7 bar = 0.6686 m³/kg

$$\therefore \quad \dot{m}_s = \frac{9000}{3600} = \frac{30.78}{0.6686}$$

or, $$A = \frac{9000 \times 0.6686}{3600 \times 30.78} = 0.054 \text{ m}^2$$

Now, annulus area, $A = \pi D h$

where, D is the mean diameter, and h is the mean blade height

$$\therefore \quad 0.054 = \pi D \times 0.04$$

or, $$D = \frac{0.054}{\pi \times 0.04} = 0.43 \text{ m}$$

Also, $$C_{bl} = \frac{\pi D N}{60}$$

or, $$41.04 = \frac{\pi \times 0.43 \times N}{60}$$

or, $$N = \frac{41.04 \times 60}{\pi \times 0.43} = \textbf{1823 r.p.m.} \quad \textbf{(Ans.)}$$

(*ii*) **The diagram power :**

Diagram power = $\dot{m}_s \; C_w \; C_{bl}$

Now, $C_w = 2C_1 \cos \alpha - C_{bl}$

$= 2 \times 90 \times \cos 20° - 41.04 = 128.1$ m/s

$$\therefore \quad \textit{Diagram power} = \frac{9000 \times 128.1 \times 41.04}{3600 \times 1000}$$

$$= \textbf{13.14 kW.} \quad \textbf{(Ans.)}$$

(*iii*) **The diagram efficiency :**

Rate of doing work per kg/s

$= C_w \; C_{bl} = 128.1 \times 41.04$ Nm/s

Also, energy input to the moving blades per stage

$$= \frac{C_1^2}{2} + \frac{C_{r_0}^2 - C_{r_1}^2}{2} = \frac{C_1^2}{2} + \frac{C_1^2 - C_{r_1}^2}{2}$$

$$= C_1^2 - \frac{C_{r_1}^2}{2} \qquad (\because \; C_{r_0} = C_1)$$

Referring to Fig. 14.9 (*a*), we have:

$$C_{r_1}^2 = C_1^2 + C_{bl}^2 - 2C_1 C_{bl} \cos \alpha$$

$$= 90^2 + 41.04^2 - 2 \times 90 \times 41.04 \times \cos 20°$$

$$= 8100 + 1684.28 - 6941.69$$

$$\therefore \quad C_{r_1} = 53.3 \text{ m/s}$$

$$\text{Energy input} = 90^2 - \frac{53.3^2}{2}$$

$= 6679.5$ Nm per kg/s

$$\therefore \quad \textit{Diagram efficiency} = \frac{128.1 \times 41.04}{6679.5}$$

$$= \textbf{0.787 or 78.7\%.} \quad \textbf{(Ans.)}$$

(*iv*) **Enthalpy drop in the stage :**

Enthalpy drop in the moving blades

$$= \frac{C_{r_0}^2 - C_{r_1}^2}{2} = \frac{90^2 - 53.3^2}{2 \times 1000}$$

$= 2.63$ kJ/kg $\qquad (\because \; C_{r_0} = C_{r_1})$

$\therefore$ *Total enthalpy drop per stage* $= 2 \times 2.63$

$$= \textbf{5.26 kJ/kg.} \quad \textbf{(Ans.)}$$

Q.14.12. *(a) How do 'fire-tube boilers' differ from 'water-tube boilers'?*

(b) How are the impurities in feed water removed from the boiler? **(GATE)**

Solution. (*a*) The comparison between the 'fire-tube boilers' and 'water-tube boiler' is given below:

S.No.	*Particulars*	*Fire-tube boilers*	*Water-tube boilers*
1.	*Position of water and hot gases*	Hot gases inside the tubes and water outside the tubes.	Water inside the tubes and hot gases outside the tubes.
2.	*Mode of firing*	Generally internally fired.	Externally fired.
3.	*Operating pressure*	Operating pressure limited to 16 bar.	Can work under as high pressure as 100 bar
4.	*Rate of steam production*	Lower	Higher
5.	*Suitability*	Not suitable for large power plants	Suitable for large power plants
6.	*Risk on bursting*	Involves lesser risk on explosion due to lower pressure	Involves more risk on bursting due to high pressure.
7.	*Floor area*	For a given power it occupies more floor area	For a given power it occupies less floor-area.
8.	*Construction*	Difficult	Simple
9.	*Transportation*	Difficult	Simple
10.	*Shell diameter*	Large for same power	Small for same power
11.	*Chances of explosion*	Less	More
12.	*Treatment of water*	Not so necessary	More necessary
13.	*Accessibility of various parts*	Various parts not so easily accessible for cleaning, repair and inspection.	Various parts are more accessible.
14.	*Requirement of skill*	Require less skill for efficient and economic working	Require more skill and careful attention.

(*b*) Before feeding the water (as make up water) to the boiler it is *adequately treated*. Still, it has some impurities in the form of total dissolved solids (TDS). These solids are expressed in ppm (parts per million). In order, to *maintain a certain ppm in the drum, 'blow down' is necessary*. *Trisodium phosphate* or *tanin* is injected in suitable doses periodically to help precipitate the salts at the bottom of the drum.

Q.14.13. *Defined air rate, specific power and the cycle work ratio in a gas turbine. What is the significance of these parameters?* **(IES)**

Solution. (*i*) **Air rate:** It is defined as *air supplied per second in a gas turbine cycle for combustion of fuel.*

(*ii*) **Specific power:** The *power output per unit mass of air supplied per second* is termed as "specific power".

(*iii*) **Cycle work ratio:** The 'work ratio' in a gas turbine cycle is defined as the *ratio of network output to the gross work output*.

In other words:

$$\text{Work ratio} = \frac{\text{Network output}}{\text{Gross work output}}$$

$$= \frac{\text{Work of expansion } (W_T) - \text{Work of compression } (W_C)}{\text{Work of expansion } (W_T)}$$

or, $$\text{Work ratio} = \frac{W_T - W_C}{W_T}$$

Significance of the parameters:

(*i*) "*Air rate*" is significant in deciding the *size of the compressor*.

(*ii*) "*Specific power*" decides the *efficiency of the combustion process* and also conveys whether complete combustion is taking place or not.

(*iii*) "*Work ratio*" is significant in deciding the ratio between $(W_T - W_C)$ and (W_T) and hence efficiency of the cycle.

Q.14.14. *Using a layout diagram describe a gas turbine plant for turbo-jet* **(IES)**

Solution. Fig. 14.10 shows a turbo-jet unit.

- It consists of *diffuser* at entrance which slows down the air (entering at velocity equal to the plane speed) and part of the kinetic energy of the air stream is converted into pressure ; this type of compression is called as *ram compression*.
- The air is further compressed to a pressure of 3 to 4 bar in a rotary compressor (usually of axial flow type).
- The compressed air then enters the combustion chamber (C.C.) where fuel is added. The combustion of fuel takes place at sensibly constant pressure and subsequently temperature rises rapidly.
- The hot gases then enter the gas turbine where *partial expansion* takes place. The *power*

produced is just sufficient to drive the compressor, fuel pump and other auxiliaries.

- The exhaust gases from the gas turbine which are at a higher pressure than atmosphere are expended in a nozzle and a very high velocity jet is produced which provides a forward motion to the aircraft by the jet reaction (Newton's third law of motion).

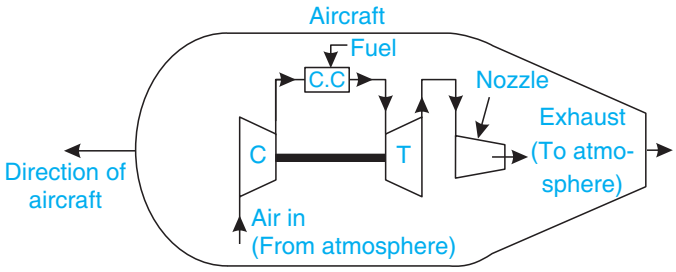


Fig. 14.10. Gas turbine plant for turbo-jet.

At higher speeds the turbo-jet gives higher propulsion efficiency. The turbo-jets are most suited to the aircrafts travelling *above 800 km/h*.

The overall efficiency of a turbo-jet is the product of the thermal efficiency of the gas turbine plant and the propulsive efficiency of the jet (nozzle).

Advantages of Turbo-jet engines

1. Construction much simpler (as compared to multi-cylinder piston engine of comparable power).
2. Engine vibrations absent.
3. Much higher speeds possible (more than 3000 km/h achieved).
4. Power supply is uninterrupted and smooth.
5. Weight to power ratios superior (as compared to that of reciprocating type of aero-engine).
6. Rate of climb higher.
7. Requirement of major overhauls less frequent.
8. Radio interference much less.
9. Maximum altitude ceiling as compared to turbo-prop and conventional piston type engines.
10. Frontal area smaller.
11. Fuel can be burnt over a large range of mixture strength.

Disadvantages of turbo-jet engines

1. Less efficient.
2. Life of the unit comparatively shorter.
3. The turbo-jet becomes rapidly inefficient below 550 km/h.
4. More noisy (than a reciprocating engine).
5. Materials required are quite expensive.
6. Require longer strip since length of take-off is too much.
7. At take-off the thrust is low, this effect is overcome by boosting.

Q.14.15. *(a) What is the objective of steam turbine governing? Enumerate the various methods of governing. Give the comparison of 'throttle and nozzle control governing'.*

(b) What is hydro-mechanical speed governing system (prime control). **(IES)**

Solution. (*a*) The *'objective of governing'* is to *keep the turbine speed fairly constant irrespective of load*. The *principal methods* of steam turbine governing are as follows:

1. Throttle governing
2. Nozzle governing
3. By-pass governing
4. Combination of 1 and 2 and 1 and 3.

Comparison of Throttle and Nozzle control governing

S.No.	*Aspects*	*Throttle control*	*Nozzle control*
1.	*Throttling losses*	Severe	No throttling losses (Actually there are a little throttling losses in nozzles valves which are partially open).
2.	*Partial admission losses*	Low	High
3.	*Heat drop available*	Lesser	Larger
4.	*Use*	Used in impulse and reaction turbines both.	Used in impulse and also in reaction (if initial stage impulse) turbines.
5.	*Suitability*	Small turbines	Medium and larger turbines.

(*b*) The hydro-mechanical speed governing system (prime control) uses a centrifugal governor (mechanical) to sense the speed of the turbine and the reference is set for rated sense of the turbine. The governor senses the speed through the accessory drive shaft and fly weights. Initially, the governor hydraulically amplifies the error signal and provides an actual output position that can be linked to a fuel valve. The fuel valve either throttles or bypasses the metered fuel from the main fuel control. The speed sensing device may be electrical or hydraulic.

Q.14.16. *What is the effect of impeller blade shape on performance of centrifugal compressors?* **(IES)**

Solution. The following shapes of blades are utilized in the impellers of centrifugal compressors :

1. *Backward-curved blades* ($\beta_2 < 90°$)

2. *Radial-curved blades* ($\beta_2 = 90°$)

3. *Forward-curved blades* ($\beta_2 > 90°$)

Fig. 14.11, shows the relative performance of these blades. Centrifugal effects on the curved blades *create a bending moment and produce increased stresses which reduce the maximum speed at which the impeller can run.*

- Normally backward blades/vanes with β_2 between 20–25° are employed except in cases where high head is the major consideration.
- Sometimes compromise is made between the low energy transfer (backward-curved vanes) and high outlet velocity (forward-curved vanes) by using *radial vanes.*

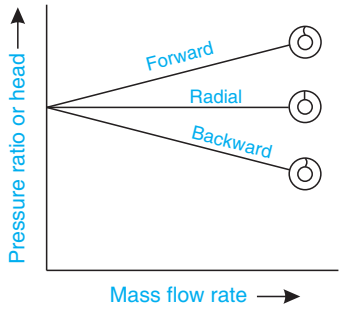


Fig. 14.11. Characteristics of backward-curved, radial curved, and forward-curved vanes.

Advantages of radial-blade impellers :

1. Can be manufactured *easily.*
2. Lowest unit blade stress for a given diameter and rotational speed, hence *highest weight.*
3. Free from complex bending stresses.
4. Equal energy conversion in impeller and diffuser, *giving high pressure ratios with good efficiency.*

In view of the above reasons, the *impeller with radial blades has been the logic choice of the designers of aircraft centrifugal compressors.*

Q.14.17. *Discuss the relative merits and demerits of axial flow compressors over centrifugal compressors.* **(IES)**

Solution. The relative merits and demerits of axial flow compressors over centrifugal compressors are given in a tabular form below:

S. No.	Aspects	Centrifugal compressors	Axial flow compressors
1.	*Type of flow*	Axial (Parallel to the direction of axis of the machine)	Radial
2.	*Pressure ratio per stage*	High, about 4.5 : 1. Thus unit is *compact* — In supersonic compressors, the pressure ratio is about 10 but at the cost of efficiency. Operation is *not* so difficult and risky.	Low, about 1.2 : 1. This is due to absence of centrifugal action. To achieve the pressure ratio equal to that per stage in centrifugal compressor 10 to 20 stages are required. Thus, the unit is *less compact* and *less rugged.*
3.	*Isothermal efficiency*	About 80 to 82%	About 86 to 88% (with modern aerofoil blades)
4.	*Frontal area*	Larger	Smaller (This makes the axial flow compressors *more suitable for jet engines due to less drag*).
5.	*Flexibility of operation*	More (due to adjustable prewhirl and diffuser vanes)	Less
6.	*Part load performance*	Better	Poor
7.	*Effect of deposit formation on the surface of impeller rotor*	*Performance not adversely affected*	*Performance adversely affected*

8.	*Starting torque required*	Low	High
9.	*Suitability for multi-staging*	Slightly difficult	More suitable for multi-staging
10.	*Delivery pressure possible*	Upto 400 bar	Upto 20 bar
11.	*Applications*	Used in blowing engines in steel mills, low pressure refrigeration, big central air conditioning plants, fertiliser and industry, supercharging I.C. engines, gas pumping in long distance pipe lines etc. — Previously it was used in jet engines	Mostly used in jet engines (due to higher efficiency and smaller frontal area). Also preferred in power plant gas turbines and steel mills.
12.	*Efficiency vs. speed curve*	More flat	Less flat comparatively

Q.14.18. *What are the constructional features of an axial flow compressor? How air is compressed and what is the method of getting higher compression ratio in such compressor?* **(IES)**

Solution. Axial flow compressor:

In an axial flow compressor, the *flow proceeds* throughout the compressor in a direction essentially *parallel to the axis of the machine.*

Construction: Refer to Fig. 14.12.

- An axial flow compressor consists of adjacent rows of rotor (moving) blades and stator (fixed) blades. The rotor blades are mounted on the rotating drum and stator blades are fixed to the casing stator. *One stage* of the machine comprises a row of rotor blades followed by a row of stator blades.
- For efficient operation the blades are of air foil section based on aerodynamic theory. The blades are so designed that wasteful losses due to shock and turbulence are prevented and the blades are free from *stalling troubles.* (The blades are said to *be stalled when the air stream fails to follow the blade contour*). Whereas the compressor blades have aerofoil section, the turbine blades have profiles formed by a number of circular arcs. This is so because the acceleration process being carried out in the converging blade passages of a reaction turbine is much more efficient and stable process as compared with the diffusing or decelerating process being carried out in the diverging passage between the blades of an axial flow compressor.
- The annular area is usually reduced from inlet to outlet of the compressor. This is to *keep the flow velocity constant throughout the compressor length.* In the diverging passages of the moving blades, there is rise in temperature due to diffusion. The absolute velocity is also increased due to work input.

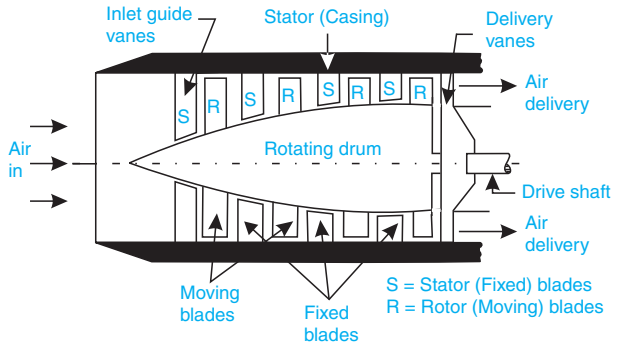


Fig. 14.12. Axial flow compressor.

The "*fixed blades*" serve the following two *purposes*:

(*i*) Convert a *part of the K.E. of the fluid into pressure energy. This conversion is achieved by diffusion process carried out in the diverge blade passages.*

(*ii*) *Guide and redirect the fluid flow so that entry to the next stage is without shock.*

Working

Basically, the compression is performed in a similar manner to that of the centrifugal type. The work input to the rotor shaft is transferred by the moving blades to the air, thus accelerating it. The blades are so arranged that the *spaces between the blades form diffuser passages, and hence the velocity of the air relative to the blades is decreased as the air passes through them, and there is a rise in pressure. The air is then further diffused in the stator blades, which are also arranged to form diffuser passages.* In the fixed stator blades the *air is turned through an angle so that its direction is such that it can be allowed to pass to a second row of moving rotor blades. It is usual to have a relativity large number of stages and to maintain a constant work input per stage* (*e.g.,* from 5 to 14 stages have been used).

—The necessary reduction in volume may be allowed by flaring the stator or by flaring rotor. It is more common to use a flared rotor, and this type is shown diagrammatically in Fig. 14.12.

—It is usually arranged to have an *equal temperature rise in the moving and the fixed blades, and to keep the axial velocity of air constant throughout the compressor.* Thus, *each stage of the compression is exactly similar with regard to air velocity and blade inlet and outlet angles.*

—A diffusing flow is less stable than a converging flow, and for this reason the blade shape and profile is much more important for a compressor than for a reaction turbine. The *design of compressor blades is based on aerodynamic theory and an aerofoil shape is used.*

Q.14.19. *What do you mean by supersaturated flow through steam nozzles? Discuss the causes of supersaturation phenomena.* **(GATE)**

Solution. Refer to *Art.* **3.18.5**.

Q.14.20. *Why are downcomers fewer in number and bigger in diameter, while risers are more in number and smaller in diameter in a steam generator?* **(IES)**

Solution. In a steam generator, $\Delta p = \dfrac{fLV^2}{2D}$, the downcomers are meant to move the water by *gravity*, '*bigger*' the diameter (D) '*less*' the pressure drop (Δp) due to *friction* since $\Delta p \propto \dfrac{1}{D}$. Hence, the downcomers are made biggers in diameter, which way vary from 150 mm to 200 mm or even higher?

Q.14.21. *Why are steam turbines compounded? What are methods of compounding?* **(GATE)**

Solution. Refer to *Art.* **3.19.5.**

B. MULTIPLE-CHOICE QUESTIONS WITH ANSWERS AND "*EXPLANATIONS*"

Q.14.1. Which of the following are boiler mountings?

1. Fusible plug 2. Blow-off cock
3. Steam trap 4. Feed check valve

Select the correct answer using the code given below:

(a) 1, 2 and 3 (b) 2, 3 and 4
(c) 1, 3 and 4 (d) 1, 2 and 4.

Ans. (d)

Explanation: "Boiler mountings" are different fittings and devices which are *necessary for the operation and safety of boilers*. Usually these devices are mounted over the shell.

In accordance with the Indian boiler regulation the following mountings should be fitted to the boiler:

Two safety valves, two water level indicators, a pressure gauge, a steam stop valve, a feed check valve, a blow-off cock, an attachment for inspector's test gauge, a man hole, Mud holes or sight holes.

Boilers of Lancashire and Cornish type should be fitted with a high pressure and low water safety valve.

All land boilers should have a 'fusible' plug in each furnace. Thus steam trap is *not* a mounting. Hence (d) is the correct answer.

Q.14.2. If the cross-section of a nozzle is increasing in the direction of flow in supersonic flow, then in the downstream direction

(a) Both pressure and velocity will increase
(b) Both pressure and velocity will decrease
(c) Pressure will increase but velocity will decrease
(d) Pressure will decrease but velocity will increase

Ans. (d)

Explanation: In case of a supersonic flow, Mach. number, $M > 1$

We know that: $\dfrac{dA}{A} = \dfrac{1}{\gamma} \cdot \dfrac{dp}{p}\left(\dfrac{1 - M^2}{M^2}\right)$

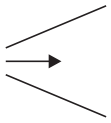


Fig. 14.13. Divergent nozzle.

Here, $\dfrac{dA}{A} = +\text{ve}$, $\dfrac{dp}{p} = -\text{ve}$

Hence, pressure will decrease and velocity will increase.

Q.14.3. What is the function of heavy water in a nuclear reactor?

(a) It serves as a coolant
(b) It serves as moderator
(c) It serves as a coolant as well as a moderator
(d) It serves as a neutron absorber.

Ans. (c)

Explanation: As a moderator heavy water (D_2O) in a nuclear reactor is the best material available [other commonly used moderators are H_2O, He (gas), Be and C (graphite)]. D_2O can be used as a *coolant* as well.

- In a nuclear reactor the functions of a '*moderator*' is *slow down* the neutrons *from the high velocities* but *not* absorb them.

- The function of 'coolant' is to remove the intense heat produced in the reactor and to bring out for being utilized.

Q.14.4. Consider the following statements:

1. The gases measured directly by Orsat apparatus from a flue gas sample are CO_2, O_2 and N_2.
2. Bomb calorimeter measures higher calorific value of fuel at constant pressure.
3. For burning 1 kg of fuel (carbon) to carbon monoxide, the stoichiometric quantity of air required is 8/3 kg.

Which of these statements is/are correct?

(*a*) Only 1 (*b*) Only 2

(*c*) Only 3 (*d*) 1, 2 and 3.

Ans. (*c*)

Explanation:

- The gases measured directly by 'Orsat apparatus' from a flue gas sample are CO_2, O_2 and CO (not N_2).
- A 'bomb calorimeter' measures the higher or gross calorific value because the fuel sample is burnt at a *constant volume* (*not* constant pressure).

Q. 14.5. The mass defect is

(*a*) a characteristic of certain elements

(*b*) a term used to prove the relationship between mass and energy

(*c*) a measure of fission energy

(*d*) the difference between mass of the nucleus and sum of the masses of the nucleons.

Ans. (*d*)

Explanation: The difference between mass of the nucleus and sum of the masses of nucleons is termed as "mass defect".

Q. 14.6. The ratio of the static enthalpy rise in the rotor to the static enthalpy rise in the stage of an axial flow compressor is defined as

(*a*) power input factor

(*b*) flow coefficient

(*c*) temperature coefficient

(*d*) degree of reaction.

Ans. (*d*)

Explanation: In an axial flow compressor degree of reaction (R_d) is defined as the ratio of pressure rise in the compressor stage. It is equal to the ratio of static enthalpy rise in the rotor to the static enthalpy rise in the stage of an axial flow compressor.

Q. 14.7. In a gas turbine cycle with regeneration

(*a*) pressure ratio increases

(*b*) work output decreases

(*c*) thermal efficiency increases

(*d*) heat input increases.

Ans. (*c*)

Explanation: In a gas turbine cycle with '*regeneration*' *thermal efficiency increases* (the exhaust gases from a gas turbine carry a large quantity of heat with them since their temperature is far above the ambient temperature, so they can be used to heat the air coming from the compressor thereby *reducing the mass of fuel* supplied in the combustion chamber).

Q. 14.8. In a normal shock wave in one dimensional flow

(*a*) the entropy remains constant

(*b*) the entropy increases across the shock

(*c*) the entropy decreases across the shock

(*d*) the velocity, pressure and density increase across the shock.

Ans. (*b*)

Explanation: In a normal shock wave in one dimensional flow there is always a change from supersonic to subsonic speed which involves pressure rise and never the reverse. As per second law of thermodynamics, entropy always increases during irreversible adiabatic change, thus *entropy increases* across the shock.

Q. 14.9. Uranium 238 is represented as $_{92}U^{238}$. What does it imply?

(*a*) It has 92 protons and 146 neutrons

(*b*) It has 146 protons and 92 electrons

(*c*) It has 92 protons and 238 neutrons

(*d*) It has 92 neutrons and 238 protons.

Ans. (*a*)

Explanation: Uranium 238 is represented as $_{92}U^{238}$ *i.e.,* number of proton atomic number = 92 and 10 number of neutron = 238 – 92 = 146.

Q. 14.10. Water-tube boilers are preferred for

(*a*) high pressure and high output

(*b*) high pressure and low output

(*c*) low pressure and high output

(*d*) low pressure and low output.

Ans. (*a*)

Explanation: Water-tube boilers are preferred for high pressure and high output.

- These boilers are used exclusively, when pressure above 10 bar and capacity in excess of 7000 kg of steam per hour, is required. 'Babcock and Wilcox water-tube boiler' is an example of horizontal straight tube boiler and may be designed for stationary or marine purposes.

Q. 14.11. Given:

η_s = stage efficiency

η_n = nozzle efficiency, and

η_b = blade efficiency.

Which one of the following is correct?

(*a*) $\eta_n = \eta_b\ \eta_s$ (*b*) $\eta_b = \eta_s\ \eta_n$

(*c*) $\eta_b \times \eta_n \times \eta_s = 1$ (*d*) $\eta_s = \eta_b\ \eta_n$.

Ans. (*d*)

Explanation: Stage efficiency = blade efficiency × nozzle efficiency

i.e., $\eta_s = \eta_b \times \eta_n$

Q. 14.12. The compounding of steam turbines is done

(*a*) to improve efficiency

(*b*) to reduce the speed of rotor

(*c*) to reduce exit losses

(*d*) to increase the turbine output.

Ans. (*b*)

Explanation: The *compounding* of steam turbine is done to *reduce* of speed of the rotor.

- If the steam is expanded from the boiler pressure to condenser pressure in one stage (as in simple impulse turbine) the speed of the rotor becomes *tremendously high* which crops up practical complicacies. There are several methods of reducing this speed to lower value, the different methods of compounding are:

(*i*) Velocity compounding

(*ii*) Pressure compounding

(*iii*) Pressure velocity compounding

(*iv*) Reaction turbine.

Q. 14.13. In a Brayton cycle, the value of optimum pressure ratio for maximum network done between temperatures T_1 and T_3, where T_3 is the maximum temperature and T_1 is the minimum temperature is

(*a*) $r_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$ (*b*) $r_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma-1}{2\gamma}}$

(*c*) $r_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}$ (*d*) $r_p = \left(\frac{T_3}{T_1}\right)^{\frac{2(\gamma-1)}{\gamma}}$.

Ans. (*c*)

Explanation: In case of a Brayton cycle pressure ratio (r_p) for maximum network done is given as: $r_p = \left(\frac{T_3}{T}\right)^{\frac{\gamma}{2(\gamma-1)}}$ (*i.e.,* r_p is a *function of the limiting temperature ratio*).

Q. 14.14. In a radial blade centrifugal compressor, the velocity of blade tip is 400 m/s and slip factor is 0.9. Assuming the absolute velocity at inlet to be axial, the work done per kg of flow is

(*a*) 36 kJ (*b*) 72 kJ

(*c*) 144 kJ (*d*) 360 kJ.

Ans. (*c*)

Explanation: *Given*: Velocity of blade tip, C_{bl} = 400 m/s; slip factor, $\phi_s = 0.9$, work done = $\phi_s\ C_{bl}^2$ = $0.9 \times 400^2 \times 10^{-3}$ kJ = 144 kJ

Q. 14.15. Which one of the following is used to bring down the speed of an impulse steam turbine to practical limits?

(*a*) A centrifugal governor

(*b*) Compounding of the turbine

(*c*) A large flywheel

(*d*) A gear box.

Ans. (*b*)

Explanation: If the steam is expanded from boiler pressure to condenser pressure in a simple impulse turbine, the rotor speed becomes tremendously high, which crops up practical complicacies. To control this high speed *"compounding"* of the turbine is required.

Q. 14.16. Consider the following features for a gas turbine plant:

1. Intercooling
2. Regeneration
3. Reheat

Which of the above features in a simple gas turbine cycle increase the work ratio?

(*a*) 1, 2 and 3 (*b*) Only 1 and 2

(*c*) Only 2 and 3 (*d*) Only 1 and 3.

Ans. (*d*)

Explanation: Work ratio

$$= \frac{\text{Network output}}{\text{Gross work output}}$$

$$= \frac{\text{Work of expansion} - \text{Work of compression}}{\text{Work of expansion}}$$

or, $\frac{W_T - W_C}{W_T}$

i.e., Intercooling and reheating increases the work ratio.

- An heat exchanger (Regeneration feature) is usually used in large gas turbine units for marine propulsion or industriate power. Hence (*d*) is the correct answer.

Q. 14.17. What is the ratio of the isentropic work to Euler's work known as?

(*a*) Pressure coefficient

(*b*) Slip factor

(*c*) Work factor

(*d*) Degree of reaction.

Ans. (*c*)

Explanation: The 'work factor' is the ratio of isentropic work to Euler's work.

i.e., $$\text{Work factor} = \frac{\text{Isentropic work}}{\text{Euler's work}}$$

The value of input factor is kept nearer to unity, the actual value is about 1.04.

- 'Work factor' is introduced to take care of losses due to friction between the casing and the air carried by the vanes, etc., thus actual work input is greater than the theoretical value.

Q. 14.18. Consider the following statements:

For a large aviation gas turbine, an axial flow compressor is usually preferred over centrifugal compressor because

1. the maximum efficiency is higher
2. the frontal area is lower
3. the pressure rise per stage is more
4. the cost is lower

Which of these statements are correct?

(*a*) 1 and 4 (*b*) 1 and 2

(*c*) 1, 2 and 3 (*d*) 2, 3 and 4.

Ans. (*b*)

Explanation: For a large aviation gas turbine, an axial flow compressor is usually preferred over centrifugal compressor due to the reasons it has *lower frontal area* and *higher maximum efficiency*.

- Axial flow compressors is also preferred in power plant gas turbines and steel mills.

Q. 14.19. In an axial flow compressors, when the degree of reaction is 50%, it implies that

(*a*) Work done in compression will be the least

(*b*) 50% stages of the compressor will be ineffective

(*c*) Pressure after compression will be optimum

(*d*) The compressor will have symmetrical blades

Ans. (*d*)

Explanation: In a reaction turbine if the degree of reaction is 50%, $\theta = \beta$ and $\phi = \alpha$ which means that moving blade and fixed blade have the *same shape* (*i.e.,* symmetrical). This condition gives *symmetrical* velocity diagrams. This type of turbine is known as '*Parson's reaction turbines*'.

Q. 14.20. The power required to drive a turbo-compressor for a given pressure ratio decreases when

(*a*) Air is heated at entry

(*b*) Air is cooled at entry

(*c*) Air is cooled at exit

(*d*) Air is heated at exit.

Ans. (*b*)

Explanation: The power required to drive a turbo-compressor for a given pressure ratio decreases when air is cooled at entry, this is so because *density of air at low temperature is high*.

Q. 14.21. Consider the following statements indicating a comparison between rocket and jet propulsion systems:

1. Both rocket and jet engines carry the fuel and oxidant.
2. Rockets do not employ compressor or propeller.
3. Rockets can operate in vacuum also.
4. Rockets can use solid fuels and oxidants.

Which of these statements are correct?

(*a*) 1, 2, 3 and 4 (*b*) Only 1 and 2

(*c*) Only 2, 3 and 4 (*d*) Only 1, 3 and 4.

Ans. (*c*)

Explanation: In case of *'jet propulsion'* the oxygen required for combustion is taken from the atmosphere and fuel is stored whereas for '*rocket engine*', the fuel and oxidiser '*both*' are contained in a propelling body and as such it can function in *vacuum*.

Q. 14.22. What does application of centrifugal air compressors lead to?

(*a*) Large frontal area of aircraft

(*b*) Higher flow rate through the engine

(*c*) Higher aircraft speed

(*d*) Lower frontal area of the aircraft.

Ans. (*a*)

Explanation: The application of centrifugal air compressor leads to large frontal area of aircraft and consequently drag increases. That is why axial flow compressors are used in aircraft.

Q. 14.23. Consider the following:

1. Injector
2. Economizer
3. Blow-off cock
4. Steam stop valve

Which of the above is/are not boiler mountings?

(*a*) Only 1 (*b*) Only 1 and 2

(*c*) 1, 2 and 3 (*d*) 2 and 4.

Ans. (*b*)

Explanation: Injector and economiser are some of the important boiler accessories.

Q. 14.24. Wilson line is associated with which one of the following?

(*a*) Total steam consumption with respect to power output

(*b*) Supersonic flow of steam through a nozzle

(*c*) Nozzle flow with friction
(*d*) Supersaturated flow of steam through a nozzle.

Ans. (*d*)

Explanation: Wilson line is associated with the supersaturated flow of steam through a nozzle. The limiting condition of under-cooling at which condensation commences and is assumed to restore conditions of normal thermal equilibrium is called the "*Wilson line*".

Q. 14.25. Which one of the following expresses the maximum blade efficiency of a Parsons' turbine?

(*a*) $\frac{2\cos^2\alpha}{1+\cos^2\alpha}$ (*b*) $\frac{\cos^2\alpha}{1+2\cos^2\alpha}$

(*c*) $\frac{\cos\alpha}{1+\cos^2\alpha}$ (*d*) $\frac{\cos\alpha}{2}$.

Ans. (*b*)

Explanation: The expression for maximum blade efficiency of Parson's turbine is given as:

$$(\eta_{bl})_{max} = \frac{2\cos^2\alpha}{1+\cos^2\alpha},$$

where, α is the angle of discharging

The condition for *maximum efficiency* of a reaction turbine is derived by the following assumptions:

(*i*) The degree of reaction is 50%.
(*ii*) The moving and fixed blades are symmetrical.
(*iii*) The velocity of steam at exit from the preceding stage is same as velocity of steam at the entrance to the succeeding stage.

Q. 14.26. In a reaction turbine the enthalpy drop in a stage is 60 units, the enthalpy drop in the moving blades is 32 units. The degree of reaction is

(*a*) 0.533 (*b*) 0.284
(*c*) 0.466 (*d*) 1.875

Ans. (*a*)

Explanation: The '*degree of reaction*' (R_d) of reaction turbine stage is defined as the ratio of heat drop over the moving blades (Δh_m) to the total heat drop ($\Delta h_f + \Delta h_m$) in the stage or,

$$h_d = \frac{\Delta h_m}{\Delta h_f + \Delta h_m} = \frac{32}{60} = 0.533$$

Q. 14.27. A converging diverging nozzle is connected to a gas pipeline. At the inlet of the nozzle (converging section) the Mach number is 2. It is observed that there is a shock in the diverging section. The value of the Mach number at the throat is

(*a*) < 1 (*b*) Equal to 1
(*c*) > 1 (*d*) ≥ 1.

Ans. (*b*)

Explanation: In a converging-diverging nozzle the value of Mach number at the throat is always unity *i.e.*, $M = 1$.

Q. 14.28. Blade erosion in steam turbines takes place

(*a*) Due to high temperature steam
(*b*) Due to droplets in steam
(*c*) Due to high rotational speed
(*d*) Due to high flow rate.

Ans. (*b*)

Explanation: In steam turbines the blade erosion takes place due to *droplets in steam*. When the speed is high and moisture *exceeds 10 per cent* the effect of moisture is *most prominant*. The most effected portion is the *back* of the inlet edge of the blade, where either grooves are formed or even some portion breaks away. Due to centrifugal force the water particles tend to concentrate in the outer annulus and their tip speed is greater than the root speed, hence corrosion effect is *most on tips*.

Q. 14.29. Consider the following statements in respect of axial flow air compressors.

1. An axial flow air compressor is often described as a reversed reaction turbine.
2. With 50% degree of reaction, the velocity diagrams are symmetrical.

Which of these statements is/are correct?

(*a*) 1 only (*b*) 2 only
(*c*) Both 1 and 2 (*d*) Neither 1 nor 2.

Ans. (*c*)

Explanation: (*c*) is the correct answer because the working principle of an axial flow compressor is opposite to that of a reaction turbine and the velocity diagrams of a reaction turbine are symmetrical when the degree of reaction is 50 per cent.

Q. 14.30. Which one of the following boiler accessories does not need 'flue-gas' for its operation?

(*a*) Economizer (*b*) Preheater
(*c*) Injector (*d*) Superheater.

Ans. (*c*)

Explanation: The function of an '*injector*' is to feed water into the boiler. It does *not* need fuel gas for its operation. It is commonly employed for vertical and locomotive boilers and does not find application in large capacity high pressure boilers. It is also used where the space is not available for the installation of a feed pump.

Q. 14.31. Which one of the following fittings is mounted on the boiler to put off the fire in the furnace, when water level falls to an unsafe limit?
(*a*) Feed check valve
(*b*) Safety valve
(*c*) Fusible plug
(*d*) Blow-off-cock.

Ans. (*c*)

Explanation: The function of a 'fusible plug' is to protect the boiler against damage due to over heating for low water level. It is mounted on the fire box crown plate to put off the fire in the furnace when the water level falls to an unsafe limit.

Q. 14.32. Which one of the following statements is correct about the Fanno flow?
(*a*) For an initially subsonic flow, the effect of friction is to decrease the Mach number towards unity
(*b*) For an initially supersonic flow, the effect of friction is to increase the Mach number towards unity
(*c*) At the point of maximum entropy, the Mach number is unity
(*d*) Stagnation pressure always increases along the Fanno line.

Ans. (*c*)

Explanation: In case of 'Fanno flow' the Mach number (M) is unity at the point of maximum entropy.

Q. 14.33. The turbine of the turbo-prop engine as compared to that of turbo-jet engine is
(*a*) similar (*b*) smaller
(*c*) bigger (*d*) unpredictable.

Ans. (*c*)

Explanation: The turbine of the turbo-prop engine as compared to that of a turbo-jet engine is *bigger* because in the former case turbine expansion process is *greater* than that of the latter one.

Q. 14.34. Consider the following statements in respect of gas turbines:
A gas turbine plant with reheater leads to a
1. Considerable improvement in the work output.
2. Considerable improvement in the thermal efficiency.

Which of these statements is/are correct?
(*a*) 1 only (*b*) 2 only
(*c*) Both 1 and 2 (*d*) Neither 1 nor 2.

Ans. (*a*)

Explanation: In a gas turbine 'reheating' increases the work output but the thermal efficiency may be increased or decreased depending upon the mean temperature of heat addition.

Q. 14.35. An open cycle constant pressure gas turbine uses a fuel of calorific value 40,000 kJ/kg, with air fuel ratio of 80 : 1 and develops a net output of 80 kJ/kg of air. The thermal efficiency of the cycle is
(*a*) 61% (*b*) 16%
(*c*) 18% (*d*) None of these.

Ans. (*b*)

Explanation: *Given*: Calorific value = 40000 kJ/kg

$$\dot{m}_a / \dot{m}_f = 80 : 1$$

$$W_{out} = 80 \text{ kJ/kg of air}$$

$$\eta_{thermal} = \frac{\text{Work output } (W_{out})}{\text{Heat supplied } (Q_{in})}$$

$$= \frac{\dot{m}_a \times 80}{\dot{m}_f \times 40000}$$

$$= \frac{80 \times 80}{40000} = 0.16 \text{ or } 16\%$$

Q. 14.36. A centrifugal compressor is suitable for which of the following?
(*a*) High pressure ratio, low mass flow
(*b*) Low pressure ratio, low mass flow
(*c*) High pressure ratio, high mass flow
(*d*) Low pressure ratio, high mass flow.

Ans. (*d*)

Explanation: A centrifugal pressure is suitable for low and medium pressures (pressure ratio about 3 to 4.5) and high mass flow (large gas volumes).

Q. 14.37. The suction pressure is 1 bar and delivery pressure is 125 bar. What is the ideal intermediate pressure at the end of first stage for a 3-stage air compressor?
(*a*) 25 bar (*b*) 5 bar
(*c*) 10 bar (*d*) 20 bar.

Ans. (*b*)

Explanation: Suction pressure = 1 bar
Ideal intermediate pressure at the end of 1st stage = $(5)^1$ = 5 bar.
(Pressure after 2nd stage = $(5)^2$ = 25 bar, pressure after 3rd stage = $(5)^3$ = 125 bar)

Q. 14.38. A nuclear reactor is said to be critical when the neutron population in the reactor core is
(*a*) rapidly increasing leading to the point of explosion
(*b*) decreasing from a specific value

(*c*) reduced to zero

(*d*) constant.

Ans. (*d*)

Explanation: A nuclear reactor is said to be critical when the neutron population in the reactor core is '*constant*'.

Q. 14.39. A gas turbine plant working on Joule cycle produces 4000 kW of power. If its work ratio is 40%, the power consumed by the compressor is

(*a*) 2000 kW (*b*) 4000 kW

(*c*) 6000 kW (*d*) 8000 kW.

Ans. (*c*)

Explanation: *Given*: $W_T - W_C = 4000$ kW, work ratio = 0.4

$$\text{Work ratio} = \frac{\text{Network output}}{\text{Gross work output}} = \frac{W_T - W_C}{W_T}$$

or, $$0.4 = \frac{4000}{W_T} \text{ or } W_T = 10000 \text{ kW}$$

$\therefore$ Power consumed by compressor

$W_C = 10000 - 4000 = 6000$ kW

Q. 14.40. Once-throught boiler is named as such because

(*a*) flue gas passes only in one direction

(*b*) there is no recirculation of water

(*c*) air is sent through the same direction

(*d*) steam is sent out only in one direction.

Ans. (*b*)

Explanation: The correct choice is (*b*) since once-through boiler is one in which there is no recirculation of water as in case of natural or forced circulation boilers.

Q. 14.41. In a steam condenser, the partial pressure of steam and air are 0.06 bar and 0.007 bar respectively. The condenser pressure is

(*a*) 0.067 bar (*b*) 0.06 bar

(*c*) 0.053 bar (*d*) 0.007 bar.

Ans. (*a*)

Explanation:

Condenser pressure = Partial pressure of steam (p_s) + partial pressure of air (p_{air})

= 0.06 + 0.007 = 0.067 bar

Q. 14.42. In a 50% reaction turbine stage, the tangential component of absolute velocity at rotor inlet is 537 m/s and blade velocity is 454 m/s. The power output in kW per kg of steam will be

(*a*) 302 (*b*) 282

(*c*) 260 (*d*) 284.

Ans. (*b*)

Explanation: In case of a 50% reaction turbine, the work done (W) is

$$= \frac{C_{bl}}{1000}(2C_1 \cos \alpha - C_{bl})$$

where, C_{bl} = blade velocity,

C_1 = absolute velocity of steam,

and, α = nozzle angle, $C_{bl} = 454$ m/s,

and, $C_1 \cos \alpha = 537$ m/s (Given)

$$= \frac{454}{1000}(2 \times 537 - 454)$$

$$= 282 \text{ kW/kg}$$

Thus (*b*) is correct choice.

Q. 14.43. A single-stage impulse turbine with a diameter of 120 cm runs at 3000 r.p.m. If the blade speed ratio is 0.42, then the inlet velocity of steam will be

(*a*) 79 m/s (*b*) 188 m/s

(*c*) 1450 m/s (*d*) 900 m/s.

Ans. (*c*)

Explanation:

$$\text{Blade speed, } C_{bl} = \frac{\pi DN}{60} = \frac{\pi \times 1.2 \times 3000}{60}$$

$$= 188.5 \text{ m/s}$$

Blade speed ratio

$$= \frac{\text{Blade speed } (C_{bl})}{\text{Velocity of steam of entry } (C_1)}$$

or, $$0.42 = \frac{188.5}{C_1}$$

or $$C_1 = \frac{188.5}{0.42} \approx 450 \text{ m/s}$$

Q. 14.44. Fig. 14.14 represents pressure and velocity variation for a

(*a*) reaction type turbine

(*b*) velocity compounded impulse turbine

(*c*) pressure-velocity compounded impulse turbine

(*d*) pressure compounded impulse turbine.

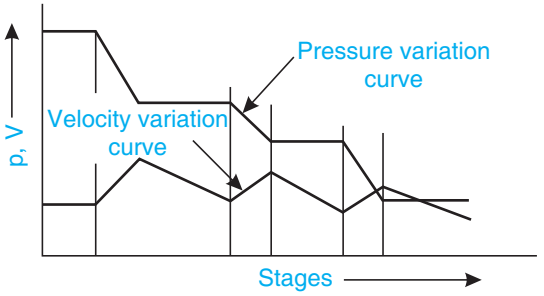


Fig. 14.14

Ans. (*d*)

Explanation: (*d*) is the correct choice because the total pressure gets dropped in three stages and in each stage the velocity increases in passing through the nozzle and then decreases in passing through blades (impulse stage).

Q. 14.45. In a reaction turbine, the enthalpy drop in the fixed blade ring is 50 kJ per kg and the enthalpy drop in the moving blade ring is 25 kJ per kg. The degree of reaction of the turbine is

(*a*) 66.7% (*b*) 50.0%

(*c*) 33.3% (*d*) 6.0%

Ans. (*c*)

Explanation:

Degree of reaction, R_d

$$= \frac{\Delta h \text{ (moving blades)}}{\Delta h \text{ (moving blades)} + \Delta h \text{ (fixed blades)}}$$

$$= \frac{25}{25+50} = \frac{25}{75} = 0.333 \quad \text{or} \quad 33.3\%$$

Q. 14.46. A single-stage reciprocating compressor takes 1 m^3 of air per minute at 1.013 bar and 15 bar and delivers it at 7 bar. Assuming that the law of compression is $pv^{1.35}$ = constant, and the clearance is negligible, the indicated power is

(*a*) 2.23 kW (*b*) 3.23 kW

(*c*) 4.23 kW (*d*) 5.23 kW.

Ans. (*c*)

Explanation:

Mass of air delivered per min,

$$m = \frac{p_1 V_1}{RT_1}$$

$$= \frac{1.013\times10^5\times1}{287\times288} = 1.226 \text{ kg/min}$$

Delivery temperature,

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

$$= \left(\frac{7}{1.013}\right)^{\frac{1.35-1}{1.35}} = 475.2 \text{ K}$$

$$\text{Indicated work} = \frac{n}{n-1} mR\,(T_2 - T_1) \text{ kJ/min}$$

$$= \frac{1.35}{1.35-1} \times 1.226 \times 0.287\,(475.2 - 288)$$

$$= 254 \text{ kJ/min}$$

i.e., Indicated power,

$$\text{I.P.} = \frac{254}{60} = 4.23 \text{ kW}$$

Q. 14.47. If the compressor of Q. 46 is driven at 300 r.p.m and is a single-acting, single-cylinder machine, calculate the cylinder bore required, assuming a stroke to bore ratio of 1.5 : 1. Calculate the power of the motor required to drive the compressor if the mechanical efficiency of the compressor is 85% and that of the motor transmission is 90%.

(*a*) 100 mm, 2.53 kW

(*b*) 110 mm, 3.53 kW

(*c*) 120 mm, 4.53 kW

(*d*) 141.4 mm, 5.53 kW

Ans. (*d*)

Explanation: Volume dealt with per minute at inlet = 1 m^3/min

Volume drawn in per cycle

$$= \frac{1}{300} = 0.00333 \text{ m}^3\text{/cycle},$$

i.e., Cylindrical volume = 0.00333 m^3

$$\therefore \quad \frac{\pi}{4} D^2 L = 0.00333$$

$$\text{or,} \quad \frac{\pi}{4} D^2(1.5 \times D) = 0.00333$$

$$\text{or,} \quad D = 0.1414 \text{ m or } 141.4 \text{ mm}$$

$$\text{Power input to compressor} = \frac{4.23}{0.85} = 4.98 \text{ kW}$$

$$\therefore \quad \text{Motor power} = \frac{4.98}{0.9}$$

$$= 5.53 \text{ kW}.$$

Q. 14.48. A multi-stage compressor is to be designed for a given flow rate and pressure ratio, if the compressor consists of axial flow stages followed by centrifugal instead of only axial flow stages, then the

(*a*) overall diameter would be decreased

(*b*) overall diameter would be increased

(*c*) axial length of the compressor would be increased

(*d*) axial length of the compressor would be decreased.

Ans. (*b*)

Explanation: The choice (*b*) is correct, because in case of axial flow stages, diameter is less and same, but in case of centrifugal compressor, the flow is radial at outlet and hence overall diameter will increase.

Q. 14.49. If the velocity of propagation of small disturbances in air at 27°C is 300 m/s, then at a temperature of 54°C, its speed would be

(*a*) 660 m/s (*b*) $300 \times \sqrt{2}$ m/s

(*c*) $300/\sqrt{2}$ m/s (*d*) $330 \times \sqrt{\frac{327}{300}}$ m/s.

Ans. (*d*)

Explanation: Velocity of propagation of small disturbance, $V \propto \sqrt{T}$

$$\frac{V_{54°C}}{V_{27°C}} = \frac{\sqrt{(54+273)}}{\sqrt{(27+273)}}$$

or, $$\frac{V_{54°C}}{V_{27°C}} = \frac{\sqrt{327}}{\sqrt{300}}$$

or, $$V_{54°C} = 300\sqrt{\frac{327}{300}} \text{ m/s.}$$

Q. 14.50. Fig. 14.15 represents a schematic view of the arrangement of a supersonic wind tunnel section. A normal shock can exist without affecting the test conditions

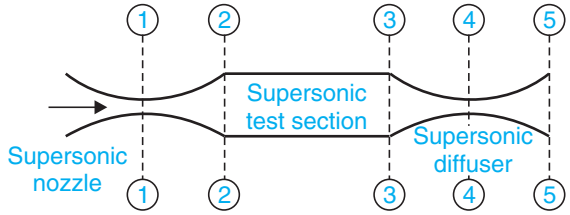


Fig. 14.15

(*a*) between sections 4 and 5

(*b*) at section 4

(*c*) between sections 4 and 3

(*d*) between sections 1 and 2.

Ans. (*d*)

Explanation: The correct choice is (*d*), because a normal shock can exist between 1 and 2 without affecting the test conditions, as it can be swallowed through the second throat by making it larger than first.

Q. 14.51. Intercooling in gas turbines

(*a*) decrease net output but increases thermal efficiency

(*b*) increases net output but decreases thermal efficiency

(*c*) decreases both net output and thermal efficiency

(*d*) increases both net output and thermal efficiency

Ans. (*b*)

Explanation: In a gas turbine, intercooling is employed to compressor air in two stages (with intercooling the work done on the compressor decreases and consequently *net output of turbine increases*). However more heat has to be added in the combustion chamber which results in *decrease in thermal efficiency*.

Q. 14.52. The inlet and exit velocity diagrams of a turbomachine rotor are shown in the Fig. 14.16. The turbo-machine is

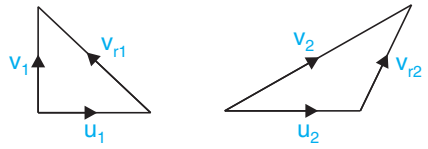


Fig. 14.16

(*a*) an axial compressor with backward curved blades

(*b*) a radial compressor with backward curved blades

(*c*) a radial compressor, with forward curved blades

(*d*) an axial compressor with forward curved blades

Ans. (*c*)

Explanation: From inlet and exist velocity diagrams of a turbomachine rotor it is evident that $u_2 > u_1$, which means that it is a *radial compressor* (for axial compressor $u_2 = u_1$). Further in outlet velocity triangle, V_{r2} is in the direction of u_2 which means blades are formed curved (in case of backward curved blades the direction of V_{r2} will be opposite to that of u_2, the angle between V_{r2} and u_2 will be acute). Thus (*c*) is the correct choice.

Q. 14.53. For a multi-stage compressor, the polytropic efficiency is

(a) the efficiency of all stages combined together

(b) the efficiency of one stage

(c) constant throughout for all the stages

(d) a direct consequence of the pressure ratio.

Ans. (c)

Explanation: The polytropic efficiency is defined as the isentropic efficiency of an element stage of compressor which is constant throughout the whole process.

Q. 14.54. In a Babcock-Wilcox boiler baffles are provided in between water tubes to

(a) have better contact of flue gases with water tubes

(b) prevent buckling of water tubes

(c) regulate steam flow

(d) regulate water flow

Ans. (a)

Explanation: In a Babcock-Wilcox boiler baffles are provided in between water tubes to *have better contact of flue gases with water tubes*.

Q. 14.55. Which of the following boilers can generate superheated steam without additional accessories?

(a) Cochran boiler

(b) Cornish boiler

(c) Lancashire boiler

(d) Locomotive boiler

Ans. (d)

Explanation: *Locomotive boiler* can generate superheated steam without additional accessories.

OBJECTIVE TYPE QUESTIONS BANK

Objective Type Questions Bank

A. Choose the Correct Answers :

1. The commercial sources of energy are
(*a*) solar, wind, biomass
(*b*) fossil fuels, hydropower and nuclear energy
(*c*) wood, animal wastes and agriculture wastes
(*d*) none of the above.

2. Non-commercial sources of energy are
(*a*) wood, animal wastes and agricultural wastes
(*b*) solar, wind, biomass
(*c*) fossil fuels, hydropower and nuclear power
(*d*) none of the above.

3. The primary sources of the energy are
(*a*) coal, oil and uranium
(*b*) hydrogen, oxygen and water
(*c*) wind, biomass and geothermal
(*d*) none of the above.

4. The secondary sources of energy are
(*a*) solar, wind and water
(*b*) coal, oil and uranium
(*c*) none of the above.

5. In India largest thermal power station is located at
(*a*) Kota (*b*) Sarni
(*c*) Chandrapur (*d*) Neyveli.

6. The percentage O_2 by weight in atmospheric air is
(*a*) 18% (*b*) 23%
(*c*) 77% (*d*) 79%.

7. The percentage O_2 by volume in atmospheric air is
(*a*) 21% (*b*) 23%
(*c*) 77% (*d*) 79%.

8. The proper indication of incomplete combustion is
(*a*) high CO content in flue gases at exit
(*b*) high CO_2 content in flue gases at exit
(*c*) high temperature of flue gases
(*d*) the smoking exhaust from chimney.

9. The main source of production of biogas is
(*a*) human waste (*b*) wet cow dung
(*c*) wet livestock waste (*d*) all above.

10. India first nuclear power plant was installed at
(*a*) Tarapore (*b*) Kota
(*c*) Kalpakkam.

11. In fuel cell, the ..... energy is converted into electrical energy
(*a*) Mechanical (*b*) Chemical
(*c*) Heat (*d*) Sound.

12. Solar thermal power generation can be achieved by
(*a*) using focusing collector or heliostates
(*b*) using flat plate collectors
(*c*) using a solar pond
(*d*) any of the above system.

13. The energy radiated by sun on a bright sunny day is approximately
(*a*) 700 W/m^2 (*b*) 800 W/m^2
(*c*) 1 kW/m^2 (*d*) 2 kW/m^2.

14. Thorium Breeder Reactors are most suitable for India because
(*a*) these develop more power
(*b*) its technology is simple
(*c*) abundance of thorium deposits are available in India
(*d*) they can be easily designed.

BASIC STEAM POWER CYCLES

15. Rankine cycle is a
(*a*) reversible cycle (*b*) irreversible cycle
(*c*) constant volume cycle (*d*) none of the above.

16. The overall efficiency of thermal power plant is equal to
(*a*) Rankine cycle efficiency
(*b*) Carnot cycle efficiency
(*c*) Regenerative cycle efficiency
(*d*) Boiler efficiency × turbine efficiency × generator efficiency.

17. Rankine cycle efficiency of a good steam power plant may be in the range of
(*a*) 15 to 20% (*b*) 35 to 45%
(*c*) 70 to 80% (*d*) 90 to 95%.

18. Rankine cycle operating on low pressure limit of p_1 and high pressure limit of p_2
(*a*) has higher thermal efficiency than the Carnot cycle operating between same pressure limits
(*b*) has lower thermal efficiency than Carnot cycle operating between same pressure limits
(*c*) has same thermal efficiency as Carnot cycle operating between same pressure limits
(*d*) may be more or less depending upon the magnitude of p_1 and p_2.

19. Rankine efficiency of a steam power plant
(*a*) improves in summer as compared to that in winter
(*b*) improves in winter as compared to that in summer
(*c*) is unaffected by climatic conditions
(*d*) none of the above.

20. Carnot cycle comprises of
(*a*) two isentropic processes and two constant volume processes
(*b*) two isentropic processes and two constant pressure processes
(*c*) two isothermal processes and two constant pressure processes
(*d*) none of the above.

21. In Rankine cycle the work output from the turbine is given by
(*a*) change of internal energy between inlet and outlet
(*b*) change of enthalpy between inlet and outlet
(*c*) change of entropy between inlet and outlet
(*d*) change of temperature between inlet and outlet.

22. Regenerative heating *i.e.*, bleeding steam to reheat feed water to boiler
(*a*) decreases thermal efficiency of the cycle
(*b*) increases thermal efficiency of the cycle
(*c*) does not affect thermal efficiency of the cycle
(*d*) may increase or decrease thermal efficiency of the cycle depending upon the point of extraction of steam.

23. Regenerative cycle thermal efficiency
(*a*) is always greater than simple Rankine thermal efficiency
(*b*) is greater than simple Rankine cycle thermal efficiency only when steam is bled at particular pressure
(*c*) is same as simple Rankine cycle thermal efficiency
(*d*) is always less than simple Rankine cycle thermal efficiency.

24. In a regenerative feed heating cycle, the optimum value of the fraction of steam extracted for feed heating
(*a*) decreases with increase in Rankine cycle efficiency
(*b*) increases with increase in Rankine cycle efficiency
(*c*) is unaffected by increase in Rankine cycle efficiency
(*d*) none of the above.

25. In a regenerative feed heating cycle, the greatest economy is affected
(*a*) when steam is extracted from only one suitable point of steam turbine
(*b*) when steam is extracted from several places in different stages of steam turbine
(*c*) when steam is extracted only from the last stage of steam turbine
(*d*) when steam is extracted only from the first stage of steam turbine.

26. The maximum percentage gain in regenerative feed heating cycle thermal efficiency
(*a*) increases with number of feed heaters increasing
(*b*) decreases with number of feed heaters increasing
(*c*) remains same unaffected by number of feed heaters
(*d*) none of the above.

27. In regenerative cycle feed water is heated by
(*a*) exhaust gases
(*b*) heaters
(*c*) draining steam from the turbine
(*d*) all above.

28. Reheat cycle in steam power plant is used to
(*a*) utilise heat of flue gases
(*b*) increase thermal efficiency
(*c*) improve condenser performance
(*d*) reduce loss of heat.

29. Mercury is a choice with steam in binary vapour cycle because it has
(*a*) higher critical temperature and pressure
(*b*) higher saturation temperature than other fluids
(*c*) relatively low vaporisation pressure
(*d*) all of the above.

30. Binary vapour cycles are used to
(*a*) increase the performance of the condenser
(*b*) increase the efficiency of the plant
(*c*) increase efficiency of the turbine.

STEAM POWER PLANT

31. A steam power station requires space
(*a*) equal to diesel power station
(*b*) more than diesel power station
(*c*) less than diesel power station.

32. Economiser is used to heat
(*a*) air (*b*) feed water
(*c*) flue gases (*d*) all above.

33. The modern steam turbines are
(*a*) impulse turbines
(*b*) reaction turbines
(*c*) impulse-reaction turbines
(*d*) none of the above.

34. The draught which a chimney produces is called
(*a*) induced draught (*b*) natural draught
(*c*) forced draught (*d*) balanced draught.

35. The draught produced by steel chimney as compared to that produced by brick chimney for the same height is
(*a*) less (*b*) more
(*c*) same (*d*) may be more or less.

36. In a boiler installation the natural draught is produced
(*a*) due to the fact that furnace gases being light go through the chimney giving place to cold air from outside to rush in
(*b*) due to the fact that pressure at the grate due to cold column is higher than the pressure at chimney base due to hot column
(*c*) due to the fact that at the chimney top the pressure is more than its environmental pressure
(*d*) all of the above.

37. The draught produced, for a given height of the chimney and given mean temperature of chimney gases
(*a*) decreases with increase in outside air temperature
(*b*) increases with increase in outside air temperature
(*c*) remains the same irrespective of outside air temperature
(*d*) may increase or decrease with increase in outside air temperature.

38. The draught produced by chimney of given height at given outside temperature
(*a*) decreases if the chimney gas temperature increases
(*b*) increases if the chimney gas temperature increases
(*c*) remains same irrespective of chimney gas temperature
(*d*) may increase or decrease.

39. For forced draught systems, the function of chimney is mainly
(*a*) to produce draught to accelerate the combustion of fuel
(*b*) to discharge gases high up in the atmosphere to avoid hazard
(*c*) to reduce the temperature of the hot gases discharged
(*d*) none of the above.

40. Artificial draught is produced by
(*a*) induced fan (*b*) forced fan
(*c*) induced and forced fan (*d*) all of the above.

41. The draught in locomotive boilers is produced by
(*a*) forced fan
(*b*) chimney
(*c*) steam jet
(*d*) only motion of locomotive.

42. For the same draught produced the power of induced draught fan as compared to forced draught fan is
(*a*) less (*b*) more
(*c*) same (*d*) not predictable.

43. Artificial draught is produced by
(*a*) air fans (*b*) steam jet
(*c*) fan or steam jet (*d*) all of the above.

44. The artificial draught normally is designed to produce
(*a*) less smoke
(*b*) more draught
(*c*) less chimney gas temperature
(*d*) all of the above.

45. For the induced draught the fan is located
(*a*) near bottom of chimney
(*b*) near bottom of furnace
(*c*) at the top of the chimney
(*d*) anywhere permissible.

46. The pressure at the furnace is minimum in case of
(*a*) forced draught system
(*b*) induced draught system
(*c*) balanced draught system
(*d*) natural draught system.

47. For maximum discharge of hot gases through the chimney, the height of hot-gas column producing draught is

(*a*) twice the height of chimney
(*b*) equal to the height of chimney
(*c*) half the height of chimney
(*d*) none of the above.

48. The efficiency of chimney is approximately
(*a*) 80% (*b*) 40%
(*c*) 20% (*d*) 0.25%.

49. In balanced draught system the pressure at force fan inlet
(*a*) is greater than pressure at chimney outlet
(*b*) is less than pressure at chimney outlet
(*c*) approximately same as that at chimney outlet.

50. For a steam nozzle, if p_1 = inlet pressure, p_2 = exit pressure and n is the index of isentropic expansion, the mass flow rate per unit area is maximum if
(*a*) $\frac{p_2}{p_1} \le \left(\frac{2}{n+1}\right)^{\frac{n-1}{n}}$ (*b*) $\frac{p_2}{p_1} \le \left(\frac{1}{n+1}\right)^{\frac{n}{n+1}}$
(*c*) $\frac{p_2}{p_1} \le \left(\frac{2}{n+1}\right)^{\frac{n}{n+1}}$ (*d*) $\frac{p_2}{p_1} \le \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$.

51. The isentropic expansion of steam through nozzle for the steam initially superheated at inlet is approximated by equation
(*a*) $pv^{1.3} = C$ (*b*) $pv^{1.125} = C$
(*c*) $pv^{1.4} = C$ (*d*) $pv = C$.

52. The ratio of exit pressure to inlet pressure for maximum mass flow rate per unit area of steam through a nozzle when steam is initially dry saturated is
(*a*) 0.6 (*b*) 0.578
(*c*) 0.555 (*d*) 0.5457.

53. The ratio of exit pressure to inlet pressure for maximum mass flow rate per unit area of steam through nozzle when steam is initially superheated is
(*a*) 0.555 (*b*) 0.578
(*c*) 0.5457 (*d*) 0.6.

54. The critical pressure ratio of a convergent nozzle is defined as
(*a*) the ratio of outlet pressure to inlet pressure of nozzle
(*b*) the ratio of inlet pressure to outlet pressure of nozzle
(*c*) the ratio of outlet pressure to inlet pressure only when mass flow rate per unit area is minimum
(*d*) the ratio of outlet pressure to inlet pressure only when mass flow rate per unit is maximum.

55. The isentropic expansion of steam through nozzle for the steam initially dry saturated at inlet is approximated by equation
(*a*) $pv = C$ (*b*) $pv^{1.4} = C$
(*c*) $pv^{1.3} = C$ (*d*) $pv^{1.135} = C$.

56. The effect of considering friction losses in steam nozzle for the same pressure ratio leads to
(*a*) increase in exit velocity from the nozzle
(*b*) decrease in exit velocity from nozzle
(*c*) no change in exit velocity from nozzle
(*d*) increase or decrease depending upon the exit quality of steam.

57. The effect of considering friction in steam nozzles for the same pressure ratio leads to
(*a*) increase in dryness fraction of exit steam
(*b*) decrease in dryness fraction of exit steam
(*c*) no change in the quality of exit steam
(*d*) may decrease or increase of dryness fraction of exit steam depending upon inlet quality.

58. In case of impulse steam turbine
(*a*) there is enthalpy drop in fixed and moving blades
(*b*) there is enthalpy drop only in moving blades
(*c*) there is enthalpy drop in nozzles
(*d*) none of the above.

59. De Laval turbine is
(*a*) pressure compounded impulse turbine
(*b*) velocity compounded impulse turbine
(*c*) simple single wheel impulse turbine
(*d*) simple single wheel reaction turbine.

60. The pressure on the two sides of the impulse wheel of a steam turbine
(*a*) is same (*b*) is different
(*c*) increases from one side to the other side
(*d*) decreases from one side to the other side.

61. In De Laval steam turbine
(*a*) the pressure in the turbine rotor is approximately same as in condenser
(*b*) the pressure in the turbine rotor is higher than pressure in the condenser
(*c*) the pressure in the turbine rotor gradually decreases from inlet to exit to condenser
(*d*) none of the above.

62. In case of reaction steam turbine
(*a*) there is enthalpy drop both in fixed and moving blades
(*b*) there is enthalpy drop only in fixed blades
(*c*) there is enthalpy drop only in moving blades
(*d*) none of the above.

63. Curtis turbine is
(*a*) reaction steam turbine
(*b*) pressure-velocity compounded steam turbine
(*c*) pressure compounded impulse steam turbine
(*d*) velocity compounded impulse steam turbine.

64. Rateau steam turbine is
(*a*) reaction steam turbine
(*b*) velocity compounded impulse steam turbine
(*c*) pressure compounded impulse steam turbine
(*d*) pressure-velocity compounded steam turbine.

65. Parson's turbine is
(*a*) pressure compounded steam turbine
(*b*) simple single wheel, impulse steam turbine
(*c*) simple single wheel reaction steam turbine
(*d*) multi-wheel reaction steam turbine.

66. Blade or diagram efficiency is given by
(*a*) $\frac{(C_{w_1} \pm C_{w_0})\, C_{bl}}{C_1}$ (*b*) $\frac{2C_{bl}\,(C_{w_1} \pm C_{w_0})}{C_1^2}$
(*c*) $\frac{C_{bl}^2}{C_1^2}$ (*d*) $\frac{C_1^2 - C_0^2}{C_1^2}$.

67. Axial thrust on rotor of steam turbine is
(*a*) $\dot{m}_s\,(C_{f_1} - C_{f_0})$ (*b*) $\dot{m}_s^2\,(C_{f_1} - 2C_{f_0})$
(*c*) $\dot{m}_s\,(C_{f_1} + C_{f_0})$ (*d*) $\dot{m}_s\,(2C_{f_1} - C_{f_0})$.

68. Stage efficiency of steam turbine is
(*a*) $\eta_{blade}/\eta_{nozzle}$ (*b*) $\eta_{nozzle}/\eta_{blade}$
(*c*) $\eta_{nozzle} \times \eta_{blade}$ (*d*) none of the above.

69. For maximum blade efficiency for single stage impulse turbine
(*a*) $\rho \left(= \frac{C_{bl}}{C_1}\right) = \cos^2 \alpha$ (*b*) $\rho = \cos \alpha$
(*c*) $\rho = \frac{\cos \alpha}{2}$ (*d*) $\rho = \frac{\cos^2 \alpha}{2}$.

70. Degree of reaction as referred to steam turbine is defined as
(*a*) $\frac{\Delta h_f}{\Delta h_m}$ (*b*) $\frac{\Delta h_m}{\Delta h_f}$
(*c*) $\frac{\Delta h_m}{\Delta h_m + \Delta h_f}$ (*d*) $\frac{\Delta h_f}{\Delta h_f + \Delta h_m}$.

71. For Parson's reaction steam turbine, degree of reaction is
(*a*) 75% (*b*) 100%
(*c*) 50% (*d*) 60%.

72. The maximum efficiency for Parson's reaction turbine is given by
(*a*) $\eta_{max} = \frac{\cos \alpha}{1 + \cos \alpha}$ (*b*) $\eta_{max} = \frac{2 \cos \alpha}{1 + \cos \alpha}$
(*c*) $\eta_{max} = \frac{2 \cos^2 \alpha}{1 + \cos^2 \alpha}$ (*d*) $\eta_{max} = \frac{1 + \cos^2 \alpha}{2 \cos^2 \alpha}$.

73. Reheat factor in steam turbines depends on
(*a*) exit pressure only
(*b*) stage efficiency only
(*c*) initial pressure and temperature only
(*d*) all of the above.

74. For multistage steam turbine, reheat factor is defined as
(*a*) stage efficiency × nozzle efficiency
(*b*) cumulative enthalpy drop × η_{nozzle}
(*c*) $\frac{\text{cumulative enthalpy drop}}{\text{isentropic enthalpy drop}}$
(*d*) $\frac{\text{isentropic enthalpy drop}}{\text{cumulative actual enthalpy drop}}$.

75. The value of reheat factor normally varies from
(*a*) 0.5 to 0.6 (*b*) 0.9 to 0.95
(*c*) 1.02 to 1.06 (*d*) 1.2 to 1.6.

76. Steam turbines are governed by which of the following methods ?
(*a*) Throttle governing
(*b*) Nozzle control governing
(*c*) By pass governing
(*d*) All of the above.

77. In steam turbines the reheat factor
(*a*) increases with the increase in number of stages
(*b*) decreases with the increase in number of stages
(*c*) remains same irrespective of number of stages
(*d*) none of the above.

78. The thermal efficiency of the engine with condenser as compared to without condenser, for a given pressure and temperature of steam, is
(*a*) higher
(*b*) lower
(*c*) same as long as initial pressure and temperature is unchanged
(*d*) none of the above.

79. In Jet type condensers
(*a*) cooling water passes through tubes and steam surrounds them
(*b*) steam passes through tubes and cooling water surrounds them
(*c*) steam and cooling water mix
(*d*) steam and cooling water do not mix.

80. In a shell and tube surface condenser
(*a*) steam and cooling water mix to give the condensate
(*b*) cooling water passes through the tubes and steam surrounds them
(*c*) steam passes through the cooling tubes and cooling water surrounds them
(*d*) all of the above varying with situation.

81. In a surface condenser if air is removed, there is
(*a*) fall in absolute pressure maintained in condenser
(*b*) rise in absolute pressure maintained in condenser

(*c*) no change in absolute pressure in the condenser
(*d*) rise in temperature of condensed steam.

82. The cooling section in the surface condenser
(*a*) increases the quantity of vapour extracted along with air
(*b*) reduces the quantity of vapour extracted along with air
(*c*) does not affect vapour quantity extracted but reduces pump capacity of air extraction pump
(*d*) none of the above.

83. Edward's air pump
(*a*) removes air and also vapour from condenser
(*b*) removes only air from condenser
(*c*) removes only un-condensed vapour from condenser
(*d*) removes air alongwith vapour and also the condensed water from condenser.

84. Vacuum efficiency of a condenser is ratio of
(*a*) $\frac{\text{actual vacuum in condenser with air present}}{\text{theoretical vacuum in condenser with no air present}}$
(*b*) $\frac{\text{theoretical vacuum in condenser with no air present}}{\text{actual vacuum in condenser with air present}}$
(*c*) $\frac{\text{partial pressure of vapour + partial pressure of air present}}{\text{partial pressure of vapour only}}$
(*d*) $\frac{\text{partial pressure of vapour only}}{\text{partial pressure of vapour + partial pressure of air pressure}}$.

85. In a steam power plant the function of a condenser is
(*a*) to maintain pressure below atmospheric to increase work output from the prime mover
(*b*) to receive large volumes of steam exhausted from steam prime mover
(*c*) to condense large volumes of steam to water which may be used again in boiler
(*d*) all of the above.

86. In a regenerative surface condenser
(*a*) there is one pump to remove air and condensate
(*b*) there are two pumps to remove air and condensate
(*c*) there are three pumps to remove air, vapour and condensate
(*d*) there is no pump, the condensate gets removed by gravity.

87. Evaporative type of condenser has
(*a*) steam in pipes surrounded by water
(*b*) water in pipes surrounded by steam
(*c*) either (*a*) or (*b*)
(*d*) none of the above.

88. Condenser efficiency is defined as
(*a*) $\frac{\text{saturation temperature at condenser pressure}}{\text{rise in cooling water temperature}}$
(*b*) $\frac{\text{temperature rise of cooling water}}{\text{saturation temperature corresponding to condenser pressure}}$
(*c*) $\frac{\text{temperature rise of cooling water}}{\text{saturation temperature corresponding to condenser pressure - cooling water inlet temperature}}$
(*d*) $\frac{\text{saturation temperature corresponding to condenser pressure}}{\text{saturation temperature of vapour at its partial pressure in condenser}}$.

89. Pipes carrying steam are generally made up of
(*a*) steel (*b*) cast iron
(*c*) copper (*d*) aluminium.

90. For the safety of a steam boiler the number of safety valves fitted are
(*a*) four (*b*) three
(*c*) two (*d*) one.

91. Steam turbines commonly used in steam power station are
(*a*) condensing type
(*b*) non-condensing type
(*c*) none of the above.

92. Belt conveyor can be used to transport coal at inclinations upto
(*a*) 30° (*b*) 60°
(*c*) 80° (*d*) 90°.

93. The maximum length of a screw conveyor is about
(*a*) 30 metres (*b*) 40 metres
(*c*) 60 metres (*d*) 100 metres.

94. The efficiency of a modern boiler using coal and heat recovery equipment is about
(*a*) 25 to 30% (*b*) 40 to 50%
(*c*) 65 to 70% (*d*) 85 to 90%.

95. The average ash content in Indian coals is about
(*a*) 5% (*b*) 10%
(*c*) 15% (*d*) 20%.

96. Load centre in a power station is
(*a*) centre of coal fields
(*b*) centre of maximum load of equipments
(*c*) centre of gravity of electrical system.

97. Steam pressure in a steam power station, which is usually kept now-a-days is of the order of
(a) 20 kgf/cm^2 (b) 50 kgf/cm^2
(c) 100 kgf/cm^2 (d) 150 kgf/cm^2.

98. Economisers improve boiler efficiency by
(a) 1 to 5% (b) 4 to 10%
(c) 10 to 12% (d) 15 to 20%.

99. In steam power station, the choice of high temperature steam is for
(a) increasing the efficiency of boiler alone
(b) increasing the efficiency of turbine alone
(c) increasing overall efficiency
(d) none of the above.

100. Location of centre of gravity ($c.g.$) of any electrical distribution system is determined as
(a) $c.g. = \dfrac{\text{total loading (electrical)}}{\text{sum of moments about two axes}}$
(b) $c.g. = \dfrac{\text{sum of moments about two axes}}{\text{total loading}}$
(c) $c.g.$ = sum of moments × total loading
(d) $c.g.$ = sum of moments × (total loading)^2.

101. Capacity of turbine and generator are related as
(a) Turbine kW = $\dfrac{\text{generator kW}}{\text{generator efficiency}}$
(b) Turbine kW = generator kW × generator efficiency
(c) Turbine kW = generator kW
(d) Turbine kW = (generator kW)^2.

102. The capacity of large turbo-generators varies from
(a) 20 to 100 MW (b) 50 to 300 MW
(c) 70 to 400 MW (d) 100 to 650 MW.

103. Caking coals are those which
(a) burn completely
(b) burn freely
(c) do not form ash
(d) form lumps or masses of coke.

104. Primary air is that air which is used to
(a) reduce the flame length
(b) increase the flame length
(c) transport and dry the coal
(d) provide air around burners for getting optimum combustion.

105. Secondary air is the air used to
(a) reduce the flame length
(b) increase the flame length
(c) transport and dry the coal
(d) provide air round the burners for getting optimum combustion.

106. Presence of sulphur in coal will result in
(a) corroding air heaters
(b) spontaneous combustion during coal storage
(c) causing clinkering and slagging
(d) facilitating ash precipitation
(e) all of the above.

107. Pulverised fuel is used for
(a) saving fuel
(b) better burning
(c) obtaining more heat.

108. Combustible elements in the fuel are
(a) carbon and hydrogen
(b) carbon, hydrogen and sulphur
(c) carbon, hydrogen and nitrogen
(d) carbon, hydrogen and ash.

109. Heating value of diesel oil is about
(a) 5000 kcal/kg (b) 7000 kcal/kg
(c) 9000 kcal/kg (d) 11000 kcal/kg.

110. Higher calorific value (H.C.V.) is the heating value of fuel
(a) without water vapour which are formed by combustion
(b) with water vapour which are formed by combustion
(c) none of the above.

111. Which one is essential for combustion of fuel ?
(a) oxygen to support combustion
(b) correct fuel air ratio
(c) proper ignition temperature
(d) all the three above.

112. Ultimate analysis of fuel is determination of percentage of
(a) total carbon by weight
(b) total carbon by weight unit weight of H_2, O_2, N_2, sulphur and ash
(c) ash, volatile matter and moisture.

113. Which of the following coals has the highest calorific value ?
(a) Peat (b) Lignite
(c) Bituminous (d) Anthracite coal.

114. The proximate analysis of coal gives
(a) various chemical constituents, carbon, hydrogen, oxygen and ash
(b) fuel constituents as percentage by weight, of moisture, volatile, fixed carbon and ash
(c) percentage by weight, of moisture, volatile matter, fixed carbon and ash.

115. In coal preparation plant, magnetic separators are used to remove
(*a*) dust (*b*) clinkers
(*c*) iron particles (*d*) sand.

116. Load carrying capacity of belt conveyor is about
(*a*) 20 to 40 tons/hr (*b*) 50 to 100 tons/hr
(*c*) 100 to 150 tons/hr (*d*) 150 to 200 tons/hr.

117. Method which is commonly applied for unloading the coal for small power plant is
(*a*) lift trucks (*b*) coal accelerators
(*c*) tower cranes (*d*) belt conveyor.

118. Bucket elevators are used for
(*a*) carrying coal in horizontal direction
(*b*) carrying coal in vertical direction
(*c*) carrying coal in any direction.

119. The amount of air which is supplied for complete combustion is called
(*a*) primary air (*b*) secondary air
(*c*) tertiary air.

120. In ..... system fuel from a central pulverizing unit is delivered to a burner and then to the various burners
(*a*) unit (*b*) central
(*c*) none of the above.

121. Underfeed stokers work best for ..... coals high in volatile matter and with caking tendency
(*a*) anthracite (*b*) lignite
(*c*) semi-bituminous and bituminous.

122. Example of overfeed type stoker is
(*a*) chain grate (*b*) spreader
(*c*) travelling grate (*d*) all of the above.

123. Where unpulverised coal has to be used and boiler capacity is large, the stoker which is used is
(*a*) underfeed stoker (*b*) overfeed stoker
(*c*) any.

124. Travelling grate stokers can burn coals at the rates of
(*a*) 50–75 kg/m^2 per hour
(*b*) 75–100 kg/m^2 per hour
(*c*) 100–150 kg/m^2 per hour
(*d*) 150–200 kg/m^2 per hour.

125. Capacity of the underfeed stoker is of the order of
(*a*) 100 to 200 kg of coal burned per hour
(*b*) 100 to 500 kg of coal burned per hour
(*c*) 100 to 2000 kg of coal burned per hour
(*d*) 100 to 4000 kg of coal burned per hour.

126. Economisers are usually used in boiler plant working above
(*a*) 30 kgf/cm^2 (*b*) 50 kgf/cm^2
(*c*) 70 kgf/cm^2 (*d*) 90 kgf/cm^2.

127. Superheating of steam is desirable for
(*a*) increasing the efficiency of Rankine cycle
(*b*) reducing initial condensation losses
(*c*) avoiding too high moisture in the last stage of turbine
(*d*) all of the above
(*e*) none of the above.

128. Thermal efficiency of the steam plant is of the order of
(*a*) 30% (*b*) 50%
(*c*) 60% (*d*) 80%.

129. In a regenerative air preheater, the heat is transferred
(*a*) by direct mixing
(*b*) by extracting some gas from the furnace
(*c*) from heating an intermediate material and then heating the air from this material.

130. The height of chimney in a steam power plant is governed by
(*a*) flue gases quantity
(*b*) the draught to be produced
(*c*) control of pollution.

131. In boilers, the feed water treatment is done mainly for removing ..... troubles.
(*a*) corrosion (*b*) scale formation
(*c*) carry over (*d*) embrittlement
(*e*) all of the above.

132. Blowing down of boiler water is the process to
(*a*) reduce the boiler pressure
(*b*) increase the steam temperature
(*c*) control the solid concentration in the boiler water by removing some of the concentrated saline water.

133. Deaerative heating is done to
(*a*) heat the water
(*b*) heat the air in the water
(*c*) remove dissolved gases in the water.

134. Reheat factor is the ratio of
(*a*) isentropic heat drop to useful heat drop
(*b*) adiabatic heat drop to isentropic heat drop
(*c*) cumulative actual enthalpy drop for all stages to total isentropic enthalpy heat drop.

135. The value of the reheat factor is of the order of
(*a*) 0.8 to 1.0 (*b*) 1.0 to 1.05
(*c*) 1.1 to 1.5 (*d*) above 1.5.

136. Compounding of steam turbine is done for
(*a*) reducing the work done
(*b*) increasing the rotor speed
(*c*) reducing the rotor speed
(*d*) balancing the turbine.

137. Topping turbines are
(*a*) low pressure condensing units
(*b*) high pressure non-condensing units
(*c*) low pressure non-condensing units
(*d*) high pressure condensing units.

138. In throttle governing
(*a*) larger heat drop is available
(*b*) lesser heat drop is available
(*c*) there no effect on heat drop.

139. The commonly used material of condenser tubes is
(*a*) aluminium (*b*) cast iron
(*c*) admiralty brass (*d*) mild steel.

140. The blades of impulse turbine are
(*a*) symmetrically shaped around the centre line
(*b*) asymmetrically shaped around the centre line
(*c*) none of the above.

141. For medium and large size turbines the ..... governing is used.
(*a*) throttle
(*b*) nozzle control
(*c*) by pass
(*d*) combination of (*a*), (*b*), (*c*).

142. Function of air pump in condenser is to
(*a*) remove water (*b*) maintain vacuum
(*c*) maintain atmospheric pressure.

143. Wet air pump removes
(*a*) air only (*b*) only condensate
(*c*) both air and condensate.

DIESEL POWER STATION

144. In diesel cycle
(*a*) compression ratio and expansion ratio are equal
(*b*) compression ratio is greater than expansion ratio
(*c*) compression ratio is less than expansion ratio
(*d*) compression ratio = (expansion ratio)^2.

145. Compression ratio of an I.C. engine is the ratio of
(*a*) $\frac{\text{total volume}}{\text{swept volume}}$ (*b*) $\frac{\text{total volume}}{\text{clearance volume}}$
(*c*) either of the above (*d*) none of the above.

146. In a diesel engine the heat lost to the cooling water is
(*a*) 10% (*b*) 20%
(*c*) 30% (*d*) 70%.

147. The mechanical efficiency of a diesel engine is defined as
(*a*) $\frac{\text{B.H.P.}}{\text{I.H.P.}}$ (*b*) $\frac{\text{I.H.P.}}{\text{B.H.P.}}$
(*c*) B.H.P. × I.H.P. (*d*) $\frac{(\text{B.H.P.})^2}{\text{I.H.P.}}$.

148. The temperature of cooling water leaving the diesel engine should not be more than
(*a*) 30°C (*b*) 40°C
(*c*) 60°C (*d*) 80°C.

149. Total cost of a diesel power plant per kW of installed capacity is less than that of steam power plant by
(*a*) 5 to 10% (*b*) 20 to 30%
(*c*) 40 to 50% (*d*) 70 to 80%.

150. The ratio of piston stroke to bore of cylinder for internal combustion engines varies between
(*a*) 0.9 to 1.9 (*b*) 0.5 to 0.8
(*c*) 0.3 to 0.6 (*d*) 0.1 to 0.2.

151. Air fuel rate required for the combustion in diesel engine is about
(*a*) 5 : 1 (*b*) 10 : 1
(*c*) 15 : 1 (*d*) none of the above.

152. In multicylinder engines a particular sequence in the firing order is necessary
(*a*) to provide the best engine performance
(*b*) to obtain uniform turning moment
(*c*) to operate the ignition system smoothly
(*d*) to obtain non-uniform turning moment.

153. Most high speed diesel engines work on
(*a*) Diesel cycle (*b*) Carnot cycle
(*c*) Dual combustion cycle (*d*) Otto cycle.

154. In case of diesel engine, the pressure at the end of compression is in the range of
(*a*) 7–8 kgf/cm^2 (*b*) 20–25 kgf/cm^2
(*c*) 35–40 kgf/cm^2 (*d*) 50–60 kgf/cm^2.

155. Reciprocating motion of the piston is converted into a rotary one by
(*a*) connecting rod (*b*) crank shaft
(*c*) crank web (*d*) gudgeon pin.

156. Maximum temperature which is developed in the cylinder of a diesel engine is of the order of
(*a*) 1000–1500°C (*b*) 1500–2000°C
(*c*) 2000–2500°C (*d*) 2500–3000°C.

157. In a four-stroke cycle engine, the four operations namely suction, compression, expansion and exhaust are completed in the number of revolutions of crank shaft equal to
(*a*) four (*b*) three
(*c*) two (*d*) one.

158. In a two-stroke cycle engine, the operations namely suction, compression, expansion and exhaust are completed in the number of revolutions of crank shaft equal to
(*a*) four (*b*) three
(*c*) two (*d*) one.

159. In a four stroke cycle S.I. engine the cam shaft runs
(*a*) at the same speed as crank shaft
(*b*) at half the speed of crank shaft
(*c*) at twice the speed of crank shaft
(*d*) at any speed irrespective of crank shaft speed.

160. The following is an S.I. engine.
(*a*) Diesel engine (*b*) Petrol engine
(*c*) Gas engine (*d*) None of the above.

161. The following is C.I. engine.
(*a*) Diesel engine (*b*) Petrol engine
(*c*) Gas engine (*d*) None of the above.

162. In a four stroke cycle petrol engine, during suction stroke
(*a*) only air is sucked in
(*b*) only petrol is sucked in
(*c*) mixture of petrol and air is sucked in
(*d*) none of the above.

163. In a four stroke cycle diesel engine, during suction stroke
(*a*) only air is sucked in
(*b*) only fuel is sucked in
(*c*) mixture of fuel and air is sucked in
(*d*) none of the above.

164. The two stroke cycle engine has
(*a*) one suction valve and one exhaust valve operated by one cam
(*b*) one suction valve and one exhaust valve operated by two cams
(*c*) only ports covered and uncovered by piston to effect charging and exhausting
(*d*) none of the above.

165. For same output, same speed and same compression ratio the thermal efficiency of a two stroke cycle petrol engine as compared to that for four stroke cycle petrol engine is
(*a*) more (*b*) less
(*c*) same as long as compression ratio is same
(*d*) same as long as output is same.

166. The ratio of brake power to indicated power of an I.C. engine is called
(*a*) mechanical efficiency (*b*) thermal efficiency
(*c*) volumetric efficiency (*d*) relative efficiency.

167. The specific fuel consumption of a diesel engine as compared to that for petrol engine is
(*a*) lower (*b*) higher
(*c*) same for same output (*d*) none of the above.

168. The thermal efficiency of petrol engine as compared to diesel engine is
(*a*) lower (*b*) higher
(*c*) same for same power output
(*d*) same for same speed.

169. Compression ratio of petrol engines is in the range of
(*a*) 2 to 3 (*b*) 7 to 10
(*c*) 16 to 20 (*d*) none of the above.

170. Compression ratio of diesel engines may have a range
(*a*) 8 to 10 (*b*) 10 to 15
(*c*) 16 to 20 (*d*) none of the above.

171. The thermal efficiency of good I.C. engine at the rated load is in the range of
(*a*) 80 to 90% (*b*) 60 to 70%
(*c*) 30 to 35% (*d*) 10 to 20%.

172. In case of S.I. engine, to have best thermal efficiency the fuel-air mixture ratio should be
(*a*) lean (*b*) rich
(*c*) may be lean or rich (*d*) chemically correct.

173. The fuel-air ratio, for maximum power of S.I. engines, should be
(*a*) lean (*b*) rich
(*c*) may be lean or rich (*d*) chemically correct.

174. In case of petrol engine, at starting
(*a*) rich fuel-air ratio is needed
(*b*) weak fuel-air ratio is needed
(*c*) chemically correct fuel-air ratio is needed
(*d*) any fuel-air ratio will do.

175. Carburettor is used for
(*a*) S.I. engines (*b*) gas engines
(*c*) C.I. engines (*d*) none of the above.

176. Fuel injector is used in
(*a*) S.I. engines (*b*) gas engines
(*c*) C.I. engines (*d*) none of the above.

177. Very high speed engines are generally
(*a*) gas engines (*b*) S.I. engines
(*c*) C.I. engines (*d*) steam engines.

178. In S.I. engine, to develop high voltage for spark plug
(*a*) battery is installed
(*b*) distributor is installed
(*c*) carburettor is installed
(*d*) ignition coil is installed.

179. In S.I. engine, to obtain required firing order
(*a*) battery is installed
(*b*) distributor is installed
(*c*) carburettor is installed
(*d*) ignition coil is installed.

180. For petrol engines the method of governing employed is
(*a*) quantity governing (*b*) quality governing
(*c*) hit and miss governing (*d*) none of the above.

181. For diesel engines the method of governing employed is
(*a*) quantity governing
(*b*) quality governing
(*c*) hit and miss governing
(*d*) none of the above.

182. Voltage developed to strike spark in the spark plug is in the range
(*a*) 6 to 12 volts (*b*) 1000 to 2000 volts
(*c*) 20000 to 25000 volts (*d*) none of the above.

183. In a 4-cylinder petrol engine the standard firing order is
(*a*) 1-2-3-4 (*b*) 1-4-3-2
(*c*) 1-3-2-4 (*d*) 1-3-4-2.

184. The torque developed by the engine is maximum
(*a*) at minimum speed of engine
(*b*) at maximum speed of engine
(*c*) at maximum volumetric efficiency speed of engine
(*d*) at maximum power speed of engine.

185. Iso-octane content in a fuel for S.I. engines
(*a*) retards auto-ignition
(*b*) accelerates auto-ignition
(*c*) does not affect auto-ignition
(*d*) none of the above.

186. Normal heptane content in fuel for S.I. engines
(*a*) retards auto-ignition
(*b*) accelerates auto-ignition
(*c*) does not affect auto-ignition
(*d*) none of the above.

187. The knocking in S.I. engines increases with
(*a*) increase in inlet air temperature
(*b*) increase in compression ratio
(*c*) increase in cooling water temperature
(*d*) all of the above.

188. The knocking in S.I. engines gets reduced
(*a*) by increasing the compression ratio
(*b*) by retarding the spark advance
(*c*) by increasing inlet air temperature
(*d*) by increasing the cooling water temperature.

189. Increasing the compression ratio in S.I. engines
(*a*) increases the tendency for knocking
(*b*) decreases tendency for knocking
(*c*) does not affect knocking
(*d*) none of the above.

190. The knocking tendency in petrol engines will increase when
(*a*) speed is decreased
(*b*) speed is increased
(*c*) fuel-air ratio is made rich
(*d*) fuel-air ratio is made lean.

191. The ignition quality of fuels for S.I. engines is determined by
(*a*) cetane number rating (*b*) octane number rating
(*c*) calorific value rating (*d*) volatility of the fuel.

192. Petrol commercially available in India for Indian passenger cars has octane number in the range
(*a*) 40 to 50 (*b*) 60 to 70
(*c*) 80 to 85 (*d*) 95 to 100.

193. Octane number of the fuel used commercially for diesel engine in India is in the range
(*a*) 80 to 90 (*b*) 60 to 80
(*c*) 60 to 70 (*d*) 40 to 45.

194. The knocking tendency in C.I. engines increases with
(*a*) decrease of compression ratio
(*b*) increase of compression ratio
(*c*) increasing the temperature of inlet air
(*d*) increasing cooling water temperature.

195. If petrol is used in a diesel engine, then
(*a*) low power will be produced
(*b*) efficiency will be low
(*c*) black smoke will be produced
(*d*) higher knocking will occur.

GAS TURBINE POWER PLANT

196. Thermal efficiency of a gas turbine plant as compared to diesel engine plant is
(*a*) higher (*b*) lower
(*c*) same
(*d*) may be higher or lower.

197. Mechanical efficiency of a gas turbine as compared to internal combustion reciprocating engine is
(*a*) higher (*b*) lower
(*c*) same (*d*) un-predictable.

198. For a gas turbine the pressure ratio may be in the range
(*a*) 2 to 3 (*b*) 3 to 5
(*c*) 16 to 18 (*d*) 18 to 22.

199. The air standard efficiency of closed gas turbine cycle is given by (r_p = pressure ratio for the compressor and turbine)
(*a*) $\eta = 1 - \dfrac{1}{(r_p)^{\gamma-1}}$ (*b*) $\eta = 1 - (r_p)^{\gamma-1}$
(*c*) $\eta = 1 - \left(\dfrac{1}{r_p}\right)^{\frac{\gamma-1}{\gamma}}$ (*d*) $\eta = (r_p)^{\frac{\gamma-1}{\gamma}} - 1$.

200. A closed cycle gas turbine works on
(*a*) Carnot cycle (*b*) Rankine cycle
(*c*) Joule cycle (*d*) Atkinson cycle.

201. Thermal efficiency of closed cycle gas turbine plant increases by
(*a*) reheating (*b*) intercooling
(*c*) regenerator (*d*) all of the above.

202. With the increase in pressure ratio thermal efficiency of a simple gas turbine plant with fixed turbine inlet temperature
(*a*) decreases
(*b*) increases
(*c*) first increases and then decreases
(*d*) first decreases and then increases.

203. The thermal efficiency of a gas turbine cycle with ideal regenerative heat exchanger is
(*a*) equal to work ratio (*b*) less than work ratio
(*c*) more than work ratio (*d*) unpredictable.

204. In a two stage gas turbine plant reheating after first stage
(*a*) decreases thermal efficiency
(*b*) increases thermal efficiency
(*c*) does not affect thermal efficiency
(*d*) none of the above.

205. In a two stage gas turbine plant reheating after first stage
(*a*) increases work ratio
(*b*) decreases work ratio
(*c*) does not affect work ratio
(*d*) none of the above.

206. In a two stage gas turbine plant, with intercooling and reheating
(*a*) both work ratio and thermal efficiency improve
(*b*) work ratio improves but thermal efficiency decreases
(*c*) thermal efficiency improves but work ratio decreases
(*d*) both work ratio and thermal efficiency decrease.

207. For a jet propulsion unit, ideally the compressor work and turbine work are
(*a*) equal
(*b*) unequal
(*c*) not related to each other
(*d*) unpredictable.

208. Greater the difference between jet velocity and aeroplane velocity
(*a*) greater the propulsive efficiency
(*b*) less the propulsive efficiency
(*c*) unaffected is the propulsive efficiency
(*d*) none of the above.

209. For starting gas turbine, the turbine rotor is usually motored upto 'coming in' speed which is equal to
(*a*) rated speed of the gas turbine
(*b*) half of the rated speed of the gas turbine
(*c*) no relation with speed of the turbine.

210. The blades of the gas turbine rotor are made of
(*a*) carbon steel
(*b*) stainless steel
(*c*) high alloy steel
(*d*) high nickel alloy (Nimic 80).

211. Maximum temperature in a gas turbine is of the order of
(*a*) 700°C (*b*) 900°C
(*c*) 1600°C (*d*) 2100°C.

212. In gas turbines, high thermal efficiency is obtained in
(*a*) closed cycle (*b*) open cycle
(*c*) in both the cycles.

213. In a gas turbine plant, a regenerator increases
(*a*) work output (*b*) pressure ratio
(*c*) thermal efficiency (*d*) none of the above.

214. Maximum combustion pressure in a gas turbine is ..... as compared to diesel engine.
(*a*) same (*b*) less
(*c*) more.

215. Capital cost of a gas turbine plant is ..... than that of a steam power plant of same capacity
(*a*) same (*b*) lower
(*c*) higher.

HYDRO-ELECTRIC POWER PLANTS

216. Pelton turbines are mostly
(*a*) horizontal (*b*) vertical
(*c*) inclined.

217. The annual depreciation of a hydropower plant is about
(*a*) 0.5 to 1.5% (*b*) 10 to 15%
(*c*) 15 to 20% (*d*) 20 to 25%.

218. The power output from a hydro-electric power plants depends on three parameters
(*a*) head, type of dam and discharge
(*b*) head, discharge and efficiency of the system
(*c*) efficiency of the system, type of draft tube and type of turbine used
(*d*) type of dam, discharge and type of catchment area.

219. Water hammer is developed in
(*a*) penstock (*b*) draft tube
(*c*) turbine (*d*) surge tank.

220. The function of a surge tank is
(*a*) to supply water at constant pressure
(*b*) to produce surges in the pipe line
(*c*) to relieve water hammer pressures in the penstock pipe.

221. Gross head of a hydropower station is
(*a*) the difference of water level between the level in the storage and tail race
(*b*) the height of the water level in the river where the storage is provided
(*c*) the height of the water level in the river where tail race is provided.

222. Operating charges are minimum in the case of ..... for same power output.
(*a*) gas turbine plant (*b*) hydel plant
(*c*) thermal plant (*d*) nuclear plant.

223. Location of the surge tank in a hydro-electric station is near to the
(*a*) tailrace (*b*) turbine
(*c*) reservoir.

224. Pelton wheel turbine is used for minimum of the following heads
(*a*) 40 m (*b*) 120 m
(*c*) 180 m or above.

225. Running cost of a hydro-electric power plant is
(*a*) equal to running cost of a steam power plant
(*b*) less than running cost of a steam power plant
(*c*) more than running cost of a steam power plant.

226. The empirical relation for determination of number of buckets (Z) for Pelton turbine in terms of jet ratio (m) is given by
(*a*) $Z = 15\text{ m} + 0.5$ (*b*) $Z = 0.5\text{ m} + 15$
(*c*) $Z = \dfrac{m}{0.5} + 15$.

227. Francis turbine is usually used for
(*a*) high heads (*b*) medium heads
(*c*) low heads.

228. In high head hydro-power plant the velocity of water is pen stock is about
(*a*) 1 m/s (*b*) 4 m/s
(*c*) 7 m/s (*d*) 12 m/s.

229. Pelton turbine is suitable for high head and
(*a*) high discharge (*b*) low discharge
(*c*) both low and high discharge.

230. In reaction turbine, function of the draft tube is
(*a*) to increase the flow rate
(*b*) to reduce water hammer effect
(*c*) to convert kinetic energy of water to potential energy by a gradual expansion in divergent part.

231. Francis turbine is usually used for
(*a*) low head installation upto 30 m
(*b*) medium head installation from 30 to 180 m
(*c*) high head installation above 180 m
(*d*) for all heads.

232. In Francis turbine runner, the number of blades is generally of the order of
(*a*) 1–2 (*b*) 4–6
(*c*) 6–8 (*d*) 12–16.

233. Francis, Kaplan and propeller turbines fall under the category of
(*a*) impulse turbine
(*b*) reaction turbine
(*c*) impulse reaction combined
(*d*) axial flow.

234. The specific speed (N_S) of the turbine is given by
(*a*) $N_S = \dfrac{N\sqrt{P}}{H^{5/4}}$ (*b*) $N_S = \dfrac{N\sqrt{P}}{H^{3/4}}$
(*c*) $N_S = \dfrac{N\sqrt{P}}{H^{3/2}}$ (*d*) $N_S = \dfrac{N\sqrt{P}}{H^{2/3}}$.

235. The expression for power output (P) in kW, of a hydro-electric station is
(*a*) $\dfrac{QwH\,\eta_0}{0.736 \times 75}$ (*b*) $\dfrac{0.736\,QwH}{75 \times \eta_0}$
(*c*) $\dfrac{75\,QwH\,\eta_0}{0.736}$ (*d*) $\dfrac{0.736\,QwH\,\eta_0}{75}$.

NUCLEAR POWER STATIONS

236. The average thermal efficiency of a modern nuclear power plant is about
(*a*) 30% (*b*) 40%
(*c*) 60% (*d*) 80%.

237. Reflectors of a nuclear reactor are made up of
(*a*) boron (*b*) cast iron
(*c*) beryllium (*d*) steel.

238. The function of a moderator in a nuclear reactor is
(*a*) to slow down the fast moving electrons
(*b*) to speed up the slow moving electrons
(*c*) to start the chain reaction
(*d*) to transfer heat produced inside the reactor to a heat exchanger.

239. When a nuclear reactor is operating at constant power the multiplication factor is
(*a*) less than unity (*b*) greater than unity
(*c*) equal to unity (*d*) none of the above.

240. The conversion ratio of a breeder reactor is
(*a*) equal to unity (*b*) more than unity
(*c*) less than unity (*d*) none of the above.

241. In the nuclear fission reactions ..... isotope of uranium is used.
(*a*) U^{233} (*b*) U^{234}
(*c*) U^{238}.

242. Tarapur nuclear power plant has
(*a*) pressurised water reactors
(*b*) boiling water reactors
(*c*) CANDU type reactors.

243. Critical mass of fuel is the amount required to make the multiplication factor ..... unity.
(*a*) equal to (*b*) less than
(*c*) more than.

244. The nuclear energy is measured as
(*a*) MeV (*b*) MW
(*c*) Curie.

245. Fission chain reaction is possible when
(*a*) fission produces the same number of neutrons which are absorbed
(*b*) fission produces more neutrons than are absorbed
(*c*) fission produces less neutrons than are absorbed
(*d*) none of the above.

246. In nuclear chain fission reaction, each neutron which causes fission produces
(*a*) no new neutron (*b*) one new neutron
(*c*) more than one new neutron.

247. ..... is the most commonly used moderator.
(*a*) Graphite (*b*) Sodium
(*c*) Deuterium (*d*) Any of the above.

248. Which of the following are fertile materials
(*a*) U^{238} and Th^{239} (*b*) U^{238} and Th^{232}
(*c*) U^{233} and Pu^{239} (*d*) U^{238} and Pu^{239}.

249. In a nuclear reactor the function of a reflector is to
(*a*) reduce the speed of the neutrons
(*b*) stop the chain reaction
(*c*) reflect the escaping neutrons back into the core.

250. In gas cooled reactor (GCR) ..... are used as moderator and coolant respectively.
(*a*) heavy water and CO_2 (*b*) graphite and air
(*c*) graphite and CO_2 (*d*) none of the above.

251. In a pressurised water reactor (PWR)
(*a*) the coolant water is pressurised to work as moderator
(*b*) the coolant water boils in the core of the reactor
(*c*) the coolant water is pressurised to prevent boiling of water in the core
(*d*) no moderator is used.

252. The function of the moderator in a nuclear reactor is to
(*a*) stop chain reaction
(*b*) absorb neutrons
(*c*) reduce the speed of neutrons
(*d*) reduce temperature.

253. Thermal shielding is provided to
(*a*) protect the walls of the reactor from radiation damage
(*b*) absorb the fast neutrons
(*c*) protect the operating personnel from exposure to radiation
(*d*) (*a*), (*b*) and (*c*) above
(*e*) (*b*) and (*c*) both
(*f*) none of the above.

254. A CANDU reactor uses
(*a*) only fertile material
(*b*) highly enriched uranium (85% U^{235})
(*c*) natural uranium as fuel and heavy water as moderator and coolant.

255. Fission of U^{235} releases ..... energy.
(*a*) 200 MeV (*b*) 238 MeV
(*c*) 431 MeV.

256. Fast breed reactors are best suited for India because
(*a*) of large thorium deposits
(*b*) of large uranium deposits
(*c*) of large plutonium deposits.

257. India's first nuclear power plant was started at
(*a*) Narora (U.P.)
(*b*) Tarapur (Mumbai)
(*c*) Kota (Rajasthan)
(*d*) Kalpakkam (Chennai).

POWER PLANT ECONOMICS

258. Load factor of a power station is defined as
(*a*) maximum demand/average load
(*b*) average load × maximum demand
(*c*) average load/maximum demand
(*d*) none of the above.

259. Load factor of a power station is generally
(*a*) equal to unity (*b*) less than unity
(*c*) more than unity (*d*) none of the above.

260. Diversity factor is always
(*a*) equal to unity (*b*) less than unity
(*c*) more than unity (*d*) more than twenty.

261. The load factor for heavy industries may be taken as
(*a*) 10 to 20% (*b*) 25 to 40%
(*c*) 50 to 70% (*d*) 70 to 80%.

262. The load factor of domestic load is usually
(*a*) 10 to 15% (*b*) 30 to 40%
(*c*) 50 to 60% (*d*) 60 to 70%.

263. Annual depreciation cost is calculated by
(*a*) sinking fund method (*b*) straight line method
(*c*) both (*a*) and (*b*) (*d*) estimate value.

264. Depreciation charges are high in case of
(*a*) thermal plant (*b*) diesel plant
(*c*) hydro-electric plant (*d*) any of the above.

265. Demand factor is defined as
(*a*) average load/maximum demand
(*b*) maximum demand/connected load
(*c*) connected load/maximum demand
(*d*) maximum demand × connected load.

266. High load factor indicates that
(*a*) cost of generation per unit power is increased
(*b*) total plant capacity is utilised for most of the time
(*c*) total plant capacity is not properly utilised for most of the time.

267. A load curve indicates
(*a*) average power used during the period
(*b*) average kWh (kW) energy consumption during the period
(*c*) neither (*a*) nor (*b*).

268. Approximate estimation of power demand can be made by the method/methods
(*a*) load survey method (*b*) statistical methods
(*c*) mathematical method (*d*) economic parameters
(*e*) all of the above.

269. Annual depreciation as per straight line method, is calculated by
(*a*) the capital cost divided by number of years of life
(*b*) the capital cost minus the salvage value, is divided by the number of years of life
(*c*) investing a uniform sum of money per annum at stipulated rate of interest.

270. A consumer has to pay lesser fixed charges in
(*a*) flat rate tariff (*b*) two part tariff
(*c*) maximum demand tariff.

271. In two part tariff, variation in load factor will affect
(*a*) fixed charges
(*b*) operating or running charges
(*c*) both (*a*) and (*b*).

272. In India the tariff for charging the consumers for the consumption of electricity is based on
(*a*) straight meter rate
(*b*) block meter rate
(*c*) reverse form of block meter rate
(*d*) two part tariff.

273. In Hopkinson demand rate or two part tariff the demand rate or fixed charges are
(*a*) dependent upon the energy consumed
(*b*) dependent upon the maximum demand of the consumer
(*c*) both (*a*) and (*b*)
(*d*) none of the above.

NON-CONVENTIONAL POWER GENERATION

274. The function of a solar collector is to convert
(*a*) solar energy into electricity
(*b*) solar energy into radiation
(*c*) solar energy into thermal energy.

275. Most of the solar radiation received on earth surface lies within the range of
(*a*) 0.2 to 0.4 microns
(*b*) 0.38–0.78 microns
(*c*) 0–0.38 microns.

276. Flat plate collector absorbs
(*a*) direct radiation only
(*b*) diffuse radiation only
(*c*) direct and diffuse both.

277. Main applications of solar energy may be considered in the following categories
(*a*) solar electric applications
(*b*) fuel from biomass
(*c*) direct thermal applications
(*d*) both (*a*) and (*b*)
(*e*) (*a*), (*b*) and (*c*).

278. Temperature attained by a flat-plate collector is of the
(*a*) order of about 90°C
(*b*) range of 100°C to 150°C
(*c*) above 150°C
(*d*) none of the above.

279. A pyranometer is used for measurement of
(*a*) direct radiation only
(*b*) diffuse radiation only
(*c*) direct as well as diffuse radiation.

280. Sun tracking is needed in the case of ..... collector.
(*a*) flat plate
(*b*) cylindrical parabolic and paraboloid.
(*c*) both (*a*) and (*b*).

281. In a solar collector the function of the transparent cover is to
(*a*) transmit solar radiation only
(*b*) protect the collector from dust
(*c*) decrease the heat loss from collector beneath to atmosphere.

282. Temperature attained by cylindrical parabolic collector is of the range of
(*a*) 50 to 100°C (*b*) 100 to 150°C
(*c*) 150 to 300°C (*d*) 300 to 500°C.

283. Most widely used material of a solar cell is
(*a*) arsenic (*b*) cadmium
(*c*) silicon (*d*) steel.

284. Photovoltaic cell or solar cell converts
(*a*) thermal energy into electricity
(*b*) electromagnetic radiation directly into electricity
(*c*) solar radiation into thermal energy.

285. Maximum wind energy available is proportional to
(*a*) square of the diameter of rotor
(*b*) air density
(*c*) cube of the wind velocity
(*d*) (*a*), (*b*) and (*c*).

286. ..... type of wind mill is of simple design.
(*a*) Horizontal axis wind mill
(*b*) Vertical axis wind mill
(*c*) None.

287. Cost of wind energy generator compared to conventional power plants for the same power output is
(*a*) equal (*b*) lower
(*c*) higher.

288. The turbine which is used in a tidal power plant for getting continuous power is
(*a*) simple impulse type (*b*) reversible type
(*c*) propeller type.

289. Largest geothermal plant in operation is in
(*a*) Maxico (*b*) Italy
(*c*) Russia (*d*) California.

290. Geothermal plant is suitable for
(*a*) base load power (*b*) peak load power
(*c*) none.

291. A geothermal field may yield
(*a*) hot water (*b*) wet steam
(*c*) dry steam (*d*) (*a*), (*b*) and (*c*).

292. Geothermal power plants as compared to fossil fuel plants have ..... load factor.
(*a*) equal (*b*) lower
(*c*) higher.

293. Geothermal steam and hot water may contain
(*a*) NH_3 (*b*) Na_2S
(*c*) H_2S, NH_3 and radon gas.

294. Fuel cells have conversion efficiencies of the order of
(*a*) 20% (*b*) 30%
(*c*) 50% (*d*) 70%.

295. Fuel cell is a device in which
(*a*) chemical energy is converted into electricity
(*b*) heat energy is first converted into chemical energy
(*c*) heat energy is converted into electricity.

296. The nature of the current developed by *MHD* generator is
(*a*) direct current (*b*) alternating current
(*c*) either direct or alternating.

297. In *MHD* generators the conductor employed is
(*a*) gas (*b*) liquid metal
(*c*) liquid metal or gas (*d*) none of the above.

298. Seeding material which is added with the working fluid in *MHD* generator is used for
(*a*) decreasing the conductivity of the gas
(*b*) increasing the conductivity of the gas
(*c*) creating no effect on conductivity.

299. Power output per unit volume of an *MHD* generator is proportional to
(*a*) square of the magnetic flux density
(*b*) electrical conductivity of the gas
(*c*) square of the fluid velocity
(*d*) (*a*), (*b*) and (*c*).

300. Biogas consists of
(*a*) only methane
(*b*) methane and CO_2 with some impurities
(*c*) a special organic gas
(*d*) none of the above.

301. The main byproduct of the biogas plant is
(*a*) biogas (*b*) bio-mass
(*c*) organic manure.

302. Thermo-electric energy conversion is due to
(*a*) radiation (*b*) emission effect
(*c*) thermal energy.

303. The working principle of thermo-electric generator is based on the principle of
(*a*) Hall (*b*) Seebeck
(*c*) Faraday.

304. Materials which are employed for electrodes in thermo-electric generators are of
(*a*) insulators (*b*) semiconductors
(*c*) metals (*d*) conductors.

305. Thermionic converter utilizes
(*a*) Thermionic emission effect
(*b*) Pettier effect
(*c*) Seebeck effect.

ANSWERS

1. (*b*)	**2.** (*a*)	**3.** (*a*)	**4.** (*a*)	**5.** (*c*)	**6.** (*b*)	**7.** (*a*)	**8.** (*a*)
9. (*d*)	**10.** (*a*)	**11.** (*b*)	**12.** (*d*)	**13.** (*c*)	**14.** (*c*)	**15.** (*a*)	**16.** (*d*)
17. (*b*)	**18.** (*a*)	**19.** (*b*)	**20.** (*b*)	**21.** (*b*)	**22.** (*b*)	**23.** (*a*)	**24.** (*b*)
25. (*b*)	**26.** (*a*)	**27.** (*c*)	**28.** (*b*)	**29.** (*d*)	**30.** (*b*)	**31.** (*b*)	**32.** (*b*)
33. (*c*)	**34.** (*b*)	**35.** (*b*)	**36.** (*b*)	**37.** (*a*)	**38.** (*b*)	**39.** (*b*)	**40.** (*d*)
41. (*c*)	**42.** (*b*)	**43.** (*d*)	**44.** (*d*)	**45.** (*a*)	**46.** (*c*)	**47.** (*b*)	**48.** (*d*)
49. (*c*)	**50.** (*d*)	**51.** (*a*)	**52.** (*b*)	**53.** (*c*)	**54.** (*d*)	**55.** (*d*)	**56.** (*b*)
57. (*a*)	**58.** (*c*)	**59.** (*c*)	**60.** (*a*)	**61.** (*a*)	**62.** (*a*)	**63.** (*b*)	**64.** (*c*)
65. (*d*)	**66.** (*b*)	**67.** (*a*)	**68.** (*c*)	**69.** (*c*)	**70.** (*c*)	**71.** (*c*)	**72.** (*c*)
73. (*d*)	**74.** (*c*)	**75.** (*c*)	**76.** (*d*)	**77.** (*a*)	**78.** (*a*)	**79.** (*c*)	**80.** (*b*)
81. (*a*)	**82.** (*b*)	**83.** (*d*)	**84.** (*a*)	**85.** (*d*)	**86.** (*b*)	**87.** (*a*)	**88.** (*c*)
89. (*a*)	**90.** (*c*)	**91.** (*a*)	**92.** (*a*)	**93.** (*a*)	**94.** (*d*)	**95.** (*d*)	**96.** (*c*)
97. (*d*)	**98.** (*b*)	**99.** (*c*)	**100.** (*b*)	**101.** (*a*)	**102.** (*b*)	**103.** (*d*)	**104.** (*c*)
105. (*d*)	**106.** (*e*)	**107.** (*b*)	**108.** (*b*)	**109.** (*d*)	**110.** (*b*)	**111.** (*d*)	**112.** (*b*)
113. (*d*)	**114.** (*c*)	**115.** (*c*)	**116.** (*b*)	**117.** (*b*)	**118.** (*b*)	**119.** (*b*)	**120.** (*b*)
121. (*c*)	**122.** (*d*)	**123.** (*b*)	**124.** (*d*)	**125.** (*c*)	**126.** (*c*)	**127.** (*d*)	**128.** (*a*)
129. (*b*)	**130.** (*b*)	**131.** (*e*)	**132.** (*c*)	**133.** (*c*)	**134.** (*c*)	**135.** (*c*)	**136.** (*c*)
137. (*b*)	**138.** (*b*)	**139.** (*c*)	**140.** (*a*)	**141.** (*b*)	**142.** (*b*)	**143.** (*c*)	**144.** (*b*)
145. (*b*)	**146.** (*c*)	**147.** (*a*)	**148.** (*c*)	**149.** (*b*)	**150.** (*a*)	**151.** (*c*)	**152.** (*a*)
153. (*c*)	**154.** (*c*)	**155.** (*a*)	**156.** (*c*)	**157.** (*c*)	**158.** (*d*)	**159.** (*b*)	**160.** (*b*)
161. (*a*)	**162.** (*c*)	**163.** (*a*)	**164.** (*c*)	**165.** (*b*)	**166.** (*a*)	**167.** (*a*)	**168.** (*a*)
169. (*b*)	**170.** (*c*)	**171.** (*c*)	**172.** (*a*)	**173.** (*b*)	**174.** (*a*)	**175.** (*a*)	**176.** (*c*)
177. (*b*)	**178.** (*d*)	**179.** (*b*)	**180.** (*a*)	**181.** (*b*)	**182.** (*c*)	**183.** (*d*)	**184.** (*c*)
185. (*a*)	**186.** (*b*)	**187.** (*d*)	**188.** (*b*)	**189.** (*a*)	**190.** (*a*)	**191.** (*b*)	**192.** (*c*)
193. (*d*)	**194.** (*a*)	**195.** (*d*)	**196.** (*b*)	**197.** (*a*)	**198.** (*b*)	**199.** (*c*)	**200.** (*c*)
201. (*d*)	**202.** (*c*)	**203.** (*a*)	**204.** (*a*)	**205.** (*a*)	**206.** (*b*)	**207.** (*a*)	**208.** (*b*)
209. (*b*)	**210.** (*d*)	**211.** (*a*)	**212.** (*a*)	**213.** (*c*)	**214.** (*b*)	**215.** (*b*)	**216.** (*a*)
217. (*a*)	**218.** (*b*)	**219.** (*a*)	**220.** (*c*)	**221.** (*a*)	**222.** (*b*)	**223.** (*b*)	**224.** (*c*)
225. (*b*)	**226.** (*b*)	**227.** (*b*)	**228.** (*c*)	**229.** (*b*)	**230.** (*c*)	**231.** (*b*)	**232.** (*d*)
233. (*b*)	**234.** (*a*)	**235.** (*d*)	**236.** (*a*)	**237.** (*c*)	**238.** (*a*)	**239.** (*c*)	**240.** (*b*)
241. (*a*)	**242.** (*b*)	**243.** (*a*)	**244.** (*a*)	**245.** (*b*)	**246.** (*c*)	**247.** (*a*)	**248.** (*b*)
249. (*c*)	**250.** (*c*)	**251.** (*c*)	**252.** (*c*)	**253.** (*e*)	**254.** (*c*)	**255.** (*a*)	**256.** (*a*)
257. (*b*)	**258.** (*c*)	**259.** (*b*)	**260.** (*c*)	**261.** (*d*)	**262.** (*a*)	**263.** (*c*)	**264.** (*a*)
265. (*b*)	**266.** (*b*)	**267.** (*b*)	**268.** (*e*)	**269.** (*b*)	**270.** (*c*)	**271.** (*b*)	**272.** (*c*)
273. (*b*)	**274.** (*c*)	**275.** (*a*)	**276.** (*c*)	**277.** (*e*)	**278.** (*a*)	**279.** (*c*)	**280.** (*b*)
281. (*c*)	**282.** (*c*)	**283.** (*c*)	**284.** (*b*)	**285.** (*d*)	**286.** (*b*)	**287.** (*c*)	**288.** (*b*)
289. (*b*)	**290.** (*a*)	**291.** (*d*)	**292.** (*c*)	**293.** (*c*)	**294.** (*d*)	**295.** (*a*)	**296.** (*a*)
297. (*c*)	**298.** (*b*)	**299.** (*d*)	**300.** (*b*)	**301.** (*c*)	**302.** (*b*)	**303.** (*b*)	**304.** (*b*)
305. (*a*).							

B. Say 'Yes' or 'No'

1. 1 kg of uranium is equivalent to energy obtained by 4500 tonnes of high grade coal.
2. Presence of sulphur in the fuel is considered to be desirable.
3. Hydrogen is the main constituent of coal.
4. Peat is the first stage in the formation of coal from wood.
5. Bituminous coal has low percentage of volatile matter.
6. Anthracite is very hard coal.
7. Wood charcoal is obtained by destructive distillation of wood.
8. Liquid fuels require large space for storage.
9. The main constituents of natural gas are methane and ethane.
10. Water gas is produced by blowing steam into white hot coke or coal.
11. Capital cost of hydro-plants is less than diesel power station.

12. A normal working life of 100 years is estimated for wind mills.
13. The amount of excess air supplied varies with the type of fuel and the firing conditions.
14. Total weight of carbon in one kg of flue gas is = (2/5 CO_2 + 3/7 CO).
15. Electrical energy cannot be easily transported from one place to another.
16. Power is primarily associated with mechanical work and electrical energy.
17. A chemical fuel does not release heat energy on combustion.
18. Liquid fuels are less advantageous in comparison to solid fuels.
19. The operating cost of an hydro-electric plant is very high.
20. When methane burns in the pressure of oxygen the combustion products are carbondioxide and water vapours ?
21. Carnot cycle efficiency = $\frac{T_1 - T_2}{T_2}$.
22. Carnot cycle gives the highest thermal efficiency.
23. Industrial power plants are normally non-condensing.
24. The cooling water supply to the condenser helps in maintaining a low pressure in it.
25. The power plant capacity can be determined by studying the load duration curve and anticipated future demands.
26. A generator must operate economically at full load.
27. The consumption of steam per kWh decreases with the increased pressure.
28. A belt conveyor is very suitable means of transporting small quantities of coal over small distances.
29. Belt conveyor is not suitable for greater heights and short distances.
30. Flight conveyer requires little operational care.
31. A '*stoker*' is a power operated fuel feeding mechanism and grate.
32. In stoker firing cheap grade of fuel cannot be used.
33. In case of overfeed stokers, the coal is fed into the grate above the point of air admission.
34. Spreader stokers can burn any type of coal.
35. The *underfeed* principle is suitable for burning the semi-bituminous and bituminous coals.
36. The amount of air which is used to carry the coal and to dry it before entering into the combustion chamber is known as secondary air.
37. Coal is pulverised in order to increase its surface exposure, thus promoting rapid combustion without using large quantities of excess air.
38. In burners, too much secondary air can cool the mixture and prevent its heating to ignition temperature.
39. A turbulent burner is also called a long flame burner.
40. A wick burner is suitable for models or domestic appliances.
41. A fluidised bed may be defined as the bed of solid particles behaving as a fluid.
42. The 'collection efficiency' of a dust collector is the amount of dust removed per unit weight of dust.
43. The small pressure difference which causes a flow of gas to take place is termed as draught.
44. Forced draught is a negative pressure drop.
45. Steam jet draught is a simple and easy method of producing artificial draught.
46. The boilers which produce steam at pressures of 20 bar and above called high pressure boilers.
47. The removal of the mud and other impurities of water from the lowest part of the boiler is termed as 'blowing off'.
48. Shell diameter of the Cochran boiler is about 15 m.
49. Stirling water tube boiler is an example of bent tube boiler.
50. LaMont boiler works on a forced circulation and the circulation is maintained by a centrifugal pump, driven by a steam turbine using steam from the boiler.
51. Velox boiler makes use of pressurised combustion.
52. The feed pump is used to heat the feed water.
53. The function of an injector is to feed water into the boiler.
54. An economiser is a device in which the waste heat of the flue gases it utilised for heating the feed water.
55. The function of the air preheater is to decrease the temperature of air before it enters the furnace.
56. The function of a superheater is to increase the temperature of the steam above saturation temperature.
57. The function of a steam separator is to remove the entrained water particles from the steam conveyed to the steam engine or turbine.
58. Feed water heating with steam at a lower pressure than boiler pressure usually decreases overall plant efficiency.
59. Jet type open heaters do not work well at low pressures, specially at sub-atmospheric pressure.
60. For good performance feed water heaters must be drained and vented.
61. Factor of evaporation is defined as the ratio of heat received by 1 kg of water under working conditions to that received by 1 kg of water evaporated from and at 0°C.

62. If the boiler, economiser and superheater are considered as a single unit, then the boiler efficiency is termed as overall efficiency of the boiler plant.

63. Heat recovery equipment does not include economiser and superheater.

64. A *steam nozzle* may be defined as a passage of varying cross-section, through which heat energy of steam is converted to pressure energy.

65. In a convergent-divergent nozzle, because of the higher expansion ratio, addition of divergent portion produces steam at higher velocities as compared to convergent nozzle.

66. The steam turbine is a prime mover in which kinetic energy of steam is transformed into potential energy.

67. In an impulse turbine there is a gradual pressure drop and takes place continuously over the fixed and moving blades.

68. Velocity compounding method is used in Rateau and Zoelly turbines.

69. In general, optimum blade speed ratio (ρ) for maximum blade efficiency or maximum work done is given by

$$\rho = \frac{\cos \alpha}{2n}$$

where, α = nozzle angle

n = number of moving/rotating blade rows in series.

70. Velocity-compounded impulse turbine has high steam consumption and low efficiency.

71. The degree of reaction turbine stage is defined as the ratio of heat drop over fixed blades to the total heat drop in the stage.

72. It is the overall or net efficiency that is meant when the efficiency of a turbine is spoken of without qualification.

73. The efficiency of a steam turbine is considerably reduced if throttle governing is carried out at low loads.

74. Nozzle control can only be applied to reaction turbines.

75. A steam condenser is a device or an appliance in which steam condenses and heat released by steam is absorbed by water.

76. In jet condensers the exhaust steam and water do not come in direct contact with each other.

77. In counter-flow type jet condenser the steam and cooling water enter the condenser from opposite directions.

78. Low level counter flow jet condenser is also called barometric condenser.

79. In an ejector condenser the exhaust steam and cooling water mix in hollow truncated cones.

80. A jet condenser entails high manufacturing cost.

81. The vacuum efficiency is defined as the ratio of maximum obtainable vacuum to actual vacuum.

82. An air pump which removes the moist air alone is called a dry air pump.

83. In a cooling pond some spray or cooling devices are employed.

84. In a cooling tower water is made to trickle down drop by drop so that it comes in contact with the air moving in the opposite direction.

85. In induced draught cooling towers the fans are placed at the top of the tower and they draw the air in through towers extending all around the tower at its base.

86. The formation of scale reduces heat transfer and simultaneously raises the temperature of the metal wall.

87. Sodium carbonate is essentially responsible for the scale formation.

88. The carbondioxide is next to oxygen which is responsible for corrosion.

89. Water solids carried over in the steam leaving a boiler drum are called "carry over".

90. Deposits on turbine blade increase the efficiency.

91. 'Foaming' is the weakening of boiler steel as a result of inner crystalline cracks.

92. Coagulation is the process in which water is allowed to stand at stand-still in big tanks so that solid matter settles down.

93. The process of removing dissolved oxygen is known as deaeration.

94. Zeolites almost completely remove hardness but do not reduce alkalinity or total solids.

95. Demineralisation is often the most costly method of producing make up water for high pressure boilers.

96. pH value of water is the logarithm of the reciprocal of hydrogen ion concentration.

97. The steam pipes for high temperature application are manufactured from mild steel.

98. Chromium improves corrosion and oxidation resistance.

99. The standby losses in diesel power plants are less.

100. A diesel power plant can respond to varying load without any difficulty.

101. The cost of building and civil engineering works in case of diesel power plant is high.

102. Any type of engine or machine which derives heat energy from the combustion of fuel or any other source and converts this energy into mechanical work is termed as a heat engine.

103. In an I.C. engine the combustion of fuel takes place outside the engine cylinder.

104. The inside diameter of the cylinder is called bore.
105. The top most position of the piston towards cover end side of the cylinder is called bottom dead centre.
106. The compression ratio is the ratio of total cylinder volume to clearance volume.
107. The average speed of the piston is called the piston speed.
108. Spark plug is used in a diesel engine.
109. Petrol engine is used in cars and motorcycles.
110. In a petrol engine the power is produced by compression ignition.
111. Engines driving electrical generators have lower speeds and simple combustion chambers.
112. In an I.C. engine the temperature of the gases inside the engine cylinder may vary from 35°C or less to as high as 2750°C during the cycle.
113. The major short coming of thermo-syphon cooling is that cooling depends only on the temperature and is independent of the engine speed.
114. Lubrication is the admittance of oil between two surfaces having no relative motion.
115. Splash system is used on some small 4-stroke stationary engines.
116. Semi-pressure system of lubrication is a combination of splash and pressure systems.
117. Dry sump lubrication is generally adopted for high capacity engine.
118. Mist lubrication system is used for 4-stroke cycle engines.
119. The compressed air system is commonly used for starting large diesel engine employed for stationary power plant service.
120. In general, lower the cetane number higher are the hydrocarbon emissions and noise level.
121. Higher cetane rating of the fuel higher is the propensity for diesel knock.
122. Gas turbines are self-starting.
123. In almost all the fields open cycle gas turbine plants are used.
124. A heat exchanger is usually used in large gas turbine unit for marine propulsion or industrial power.
125. The specific heat of helium at constant pressure is about two times that of air.
126. The main demerit associated with constant volume combustion turbines is that the pressure difference and velocities of hot gases are not constant ; so the turbine speed fluctuates.
127. Natural gas is the ideal fuel for gas turbines, but this is not available everywhere.
128. Blast furnace and producer gases cannot be used for gas turbine power plant.
129. Liquid fuels of petroleum origin such as distillate oils or residual oils are most commonly used for gas turbine plant.
130. Minerals like sodium, vanadium and calcium prove very harmful for turbine blading.
131. There exists an optimum pressure ratio producing maximum thermal efficiency for a given turbine inlet temperature.
132. In a centrifugal compressor the capacity varies inversely as the speed ratio.
133. The centrifugal compressor is superior to the axial flow machine in that a high pressure ratio can be obtained in a short rugged single stage machine, though at the cost of lower efficiency and increased frontal area.
134. The primary function of the combustor is to provide for the chemical reaction of the fuel and air being supplied by the compressor.
135. Free-piston engine plants are the conventional gas turbine plants with the difference that the air compressor and combustion chamber are replaced by a free piston engine.
136. In an interconnected system the peak load is supplied by hydropower when the maximum flow demand is less than the stream flow while steam plant supplies the base.
137. The power plant should be set up near the load centre.
138. The whole area behind the dam draining into a stream or river across which the dam has been built at a suitable placed is called 'catchment area'.
139. Water held in upstream reservoir is called pondage.
140. The water behind the dam at the plant is called storage.
141. A weir is a low overflow dam across a stream for measuring flow or mountain water level, as at a lake outlet.
142. A dike is an embankment to confine water.
143. A levee is a dike near the bank of a river to keep low land from overflowing.
144. A buttress dam has a vertical upstream face.
145. An emergency spillway comes into action when the occurring flood discharge exceeds the designed flood discharge.
146. A siphon spillway is designed on the principle of a siphon.
147. A head race is a channel which conducts water from the wheels.
148. A canal is an open waterway evacuated in natural ground.
149. A flume is a closed channel erected on the surface or supported above ground on a trestle.

150. A tunnel is an open channel excavated through a natural obstruction.

151. A pipeline is a closed conduit usually supported on or above the surface of the land.

152. A penstock is a closed conduit for supplying water under pressure to turbine.

153. Open channels are generally very expensive.

154. Tunnels are generally the most costly type of conduits for a given length.

155. Penstocks are used where the slope is too great for a canal.

156. Reinforced concrete penstocks are suitable upto 5 m head.

157. Steel penstocks can be designed for any head, with the thickness varying with the pressure and diameter.

158. Exposed penstocks last longer and are more accessible for inspection and maintenance.

159. Overflow surge tank is very satisfactory and economical.

160. Inclined surge tank is more costlier than ordinary type.

161. Restricted orifice surge tank is also called throttled surge tank.

162. In a reaction turbine the pressure energy of water is converted into kinetic energy.

163. The plants which cater for the base load of the system are called base load plants.

164. Microhydel plants make use of standardised bulb sets with unit output ranging from 100 to 1000 kW working under heads between 1.5 to 10 metres.

165. A hydraulic turbine converts the potential energy of water into mechanical energy.

166. The specific speed of a turbine is defined as the speed of a geometrically similar turbine that would develop one brake horsepower under a head of 2 metres.

167. Specific speed, $N_s = \dfrac{N\sqrt{P_t}}{H^{3/4}}$

where N = The normal working speed (r.p.m.)
P_t = Power output of the turbine
H = The net or effective head (m).

168. Turbines with low specific speeds work under a high head and low discharge condition.

169. The Pelton wheel is a tangential flow impulse turbine.

170. The hydraulic efficiency of a Pelton wheel is maximum when the velocity of the wheel is $\frac{3}{4}$th the velocity of the jet of water at inlet.

171. In a Pelton wheel the angle of deflection of the jet through the buckets is taken as 120° if no angle of deflection is given.

172. In reaction turbines the runner utilizes both potential and kinetic energies.

173. In Francis turbine the ratio of width of the wheel to its diameter varies from 0.10 to 0.20.

174. In Francis turbine the flow ratio varies from 0.4 to 0.6.

175. In the Kaplan turbine the blades are adjustable.

176. The runner of too low specific speed with low available head increases the cost of generator due to the low turbine speed.

177. An increase in specific speed of turbine is accompanied by lower maximum efficiency and greater depth of excavation of the draft tube.

178. The ratio of the volume of the water actually striking the runner to the volume of water supplied to the turbine is called volumetric efficiency.

179. The cavitation effect cannot be reduced by polishing the surfaces.

180. Spear regulation is satisfactory when a relatively large penstock feeds a small turbine and the fluctuation of load is small.

181. Hydrology is a science which deals with the depletion and replenishment of water resources.

182. Precipitation includes all the water that falls from atmosphere to earth surface.

183. Transfer of water from liquid to vapour state is called transpiration.

184. Run-off can also be named as discharge or stream flow.

185. Hydrograph indicates the power available from the stream at different times of day, week or year.

186. The basic concept of unit hydrograph is that the hydrographs of run-off from two identical storms would not be same.

187. Flow duration curve is plotted between flow available during a period versus the fraction of time.

188. Flow duration curve cannot be used for preliminary studies.

189. The 'firm power' is also known as the 'primary power'.

190. A 'mass curve' is the graph of the cumulative values of water quantity (run off) against time.

191. The mass curve will always have a negative value.

192. Those pairs of atoms which have the same atomic number and hence similar chemical properties but different atomic mass number are called isotopes.

193. Those atoms whose nuclei have the same number of neutrons are called isotones.

194. The phenomenon of spontaneous emission of powerful radiations exhibited by light elements is called radioactivity.

195. Radioactive radiations are less penetrating.

196. Prompt-fission gamma rays are produced as a result of the fissioning of a U^{235} (or other fissible material) nucleus.

197. Capture gamma rays are emitted by nucleus of an atom instantaneously upon the capture of a neutron.

198. The amount of mass defect is inversely proportional to the amount of energy released.

199. The intensity of emitted radiation is termed activity.

200. Half life represents the rate of decay of the radioactive isotopes.

201. The mean life is twice half life.

202. During a nuclear reaction, the charge in mass of the particle represents the release or an absorption of energy.

203. When a fast moving neutron hits the U^{235} nucleus, the nucleus is excited and there is an emission of gamma quantum.

204. When the nucleus is excited too much, it splits into four mostly equal masses.

205. Cross-sections are measures of the probability that a given reaction will take place between a nucleus or nuclei and incident radiation.

206. Fission is accompanied by the emission of neutrons and gamma rays.

207. The release of about 1.2 neutrons/fission makes it possible to produce sustained fissioning.

208. A chain reaction is that process in which the number of neutrons keeps on multiplying rapidly (in geometrical progression) during fission till whole of the fissionable material is disintegrated.

209. If K (multiplication factor) > 1, chain reaction cannot be maintained.

210. The minimum quantity of fuel required for any specific reactor system is called the 'critical mass'.

211. 'Nuclear fusion' is the process of combining or fusing two lighter nuclei into a stable and heavier nuclide.

212. In heterogeneous reactor the fuel and moderator are mixed to form a homogeneous material.

213. Light water, heavy water and graphite are the most common moderators used in reactors.

214. A breeder reactor converts fertile materials into fissionable materials such as U^{238} and Th^{232} to Pu^{239} and U^{233} respectively besides the power production.

215. The reflector of the reactor consists of an assemblage of fuel elements, control rods and coolant.

216. In a nuclear reactor the function of a moderator is to slow down the neutrons from high velocities.

217. A reactor coolant should have high viscosity.

218. In a pressurised water reactor (PWR) water acts both as coolant as well as moderator.

219. In a boiling water reactor enriched fuel is used.

220. In a gas cooled reactor there is ample corrosion problem.

221. Sodium-graphite reactor is one of the typical liquid metal reactor.

222. The specific power of a breeder reactor is very high.

223. The proportion of the fissible material in the fuel is of considerable importance in determining the critical size of the reactor.

224. The capital cost of a nuclear power station is always high.

225. The maintenance cost of a nuclear power station is always low.

226. The disposal of fission products is a big problem.

227. The main purpose of design and operation of the plant is to bring out the cost of energy produced to minimum.

228. $$\text{Demand factor} = \frac{\text{connected load}}{\text{maximum demand}}.$$

229. $$\text{Load factor} = \frac{\text{average load}}{\text{maximum demand}}.$$

230. $$\text{Diversity factor} = \frac{\text{maximum demand of entire group}}{\text{sum of individual maximum demands}}.$$

231. The utilisation factor is defined as the ratio of the maximum generator demand to the generator capacity.

232. Traction load includes electrical power need for pumps driven by electric motor to supply water to fields.

233. The peak load indicated by the load curve/graph represents the maximum demand of the power station.

234. The area under the load duration curve and the corresponding chronological load curve is equal and represents total energy delivered by the generating station.

235. Firm power may also be called prime power.

236. Hot reserve is that generating capacity which is not in operation but can be made available for the service.

237. Spinning reserve is that reserve generating capacity which is connected to the bus and is ready to take the load.

238. Interest is the difference between money borrowed and money returned.

239. Straight line method of calculating depreciation cost is most cumbersome and is rarely used.

240. Sinking fund method is based on the conception that the annual uniform deduction from income for depreciation will accumulate to the capital value of the plant at the end of the life of the plant or equipment.

241. Maintenance includes periodic cleaning, greasing, adjustments and overhauling of the equipment.

242. As the capacity of the unit decreases there is a corresponding reduction in floor space per kW.

243. Primemovers used for industrial purpose should be non-condensing so that steam after exhausting could be used for processing.

244. As the capacity of diesel engines is limited therefore they are not suitable for bigger power stations.

245. Diesel power stations should be worked for fluctuating loads or as standby.

246. Running of large sets for long periods at lower than maximum continuous rating decreases the cost of unit generated.

247. The useful life of a power plant is that after which repairs become so frequent and extensive that it is found economical to replace the power plant by a new one.

248. The useful life of a diesel power plant is about 70 years.

249. The fixed charges of a hydro-plant depend upon the station output.

250. The general input-output may be represented as follows :

$$I = a + bL + cL^2 + dL^3$$

where I = Input

L = Output

a, b, c and d = Constants.

251. Incremental rate is defined as the ratio of additional input required to increase additional output.

252. Hopkinson demand rate method charges the consumer according to his maximum demand only.

253. The main feature of the tidal cycle is the difference in water surface elevations at the high tide and at the low tide.

254. Sedimentation and silteration of basins are the problems associated with tidal power plants.

255. The solar farm consists of a whole field covered with parabolic trough concentrators.

256. In case of 'solar farm' temperature at the point of focus can reach several thousand degrees celsius.

257. Geothermal energy is the heat from high pressure steam coming from within the earth.

258. The source of heat for a thermoelectric generator may be a small oil or gas burner, a radio-isotope or direct solar radiation.

259. Work function is defined as the energy required to extract an electron from the metal.

260. A solar cell is much different from a photovoltaic cell.

261. A solar cell is very costly.

262. MHD generator is a device which converts the heat energy of a fuel directly into electrical energy without a conventional electric generator.

263. By two-wire generators are meant such generators as have only two line terminals, one known as the positive terminal and the other as the negative terminal.

264. An electrical generator is a machine which converts electrical energy into mechanical energy.

265. The action of the cumulator is to reverse connections to the external circuit simultaneously and at the same instant the direction of e.m.f. reverses in each of the coil sides.

266. The output e.m.f. of an electrical generator may be made less pulsating by using a small number of coils and cummutator segments.

267. The armature of a D.C. machines is built up of thin laminations of low loss silicon steel.

268. In D.C. machines two layer winding with diamond shaped coils is used.

269. The use of copper brushes is made for machines designed for small currents at high voltages.

270. Box type brush holders are used in all ordinary D.C. machines.

271. The differential compound generator is used as a constant current generator for the same constant current applications as the series generator.

272. The exciter is generally a series wound D.C. machine.

273. The gaseous hydrogen is better cooling medium than air.

274. A transformer operates on the principle of mutual inductance between two (and sometimes more) inductively coupled coils.

275. One 3-phase transformer is costlier than three single-phase transformers.

276. Three-phase transformers are much more difficult and costlier to repair than single-phase transformers.

277. The switchgear constitutes all parts or equipments of the power plant whose function is to receive and distribute electric power.

278. Fuses are used to protect circuits of very high capacity against abnormal currents.

279. The function of a circuit breaker is to break a circuit when various abnormal conditions arise and create a danger for electrical equipment in an installation.

280. Earthing provides improved lightning protection.

281. Steel towers are rarely used.

282. Poreclain has very good electrical characteristics as well as high mechanical strength.

283. The substations serve as sources of energy supply for local areas of distribution in which these are located.

284. Pole-mounted substations are very costly.

285. Some substations are simply switching stations.

ANSWERS

1. Yes	**2.** No	**3.** No	**4.** Yes	**5.** No	**6.** Yes	**7.** Yes	**8.** No
9. Yes	**10.** Yes	**11.** No	**12.** No	**13.** Yes	**14.** No	**15.** No	**16.** Yes
17. No	**18.** No	**19.** No	**20.** Yes	**21.** No	**22.** Yes	**23.** Yes	**24.** Yes
25. Yes	**26.** No	**27.** Yes	**28.** No	**29.** Yes	**30.** Yes	**31.** Yes	**32.** No
33. Yes	**34.** Yes	**35.** Yes	**36.** No	**37.** Yes	**38.** Yes	**39.** No	**40.** Yes
41. Yes	**42.** Yes	**43.** Yes	**44.** No	**45.** Yes	**46.** No	**47.** Yes	**48.** No
49. Yes	**50.** Yes	**51.** Yes	**52.** No	**53.** Yes	**54.** Yes	**55.** No	**56.** Yes
57. Yes	**58.** No	**59.** Yes	**60.** Yes	**61.** No	**62.** Yes	**63.** No	**64.** No
65. Yes	**66.** No	**67.** No	**68.** No	**69.** Yes	**70.** Yes	**71.** No	**72.** Yes
73. Yes	**74.** No	**75.** Yes	**76.** No	**77.** Yes	**78.** No	**79.** Yes	**80.** No
81. No	**82.** Yes	**83.** No	**84.** Yes	**85.** Yes	**86.** Yes	**87.** No	**88.** Yes
89. Yes	**90.** No	**91.** No	**92.** No	**93.** Yes	**94.** Yes	**95.** No	**96.** Yes
97. No	**98.** Yes	**99.** Yes	**100.** Yes	**101.** No	**102.** Yes	**103.** No	**104.** Yes
105. No	**106.** Yes	**107.** Yes	**108.** No	**109.** Yes	**110.** No	**111.** Yes	**112.** Yes
113. No	**114.** No	**115.** Yes	**116.** Yes	**117.** Yes	**118.** No	**119.** Yes	**120.** Yes
121. No	**122.** No	**123.** Yes	**124.** Yes	**125.** No	**126.** Yes	**127.** Yes	**128.** No
129. Yes	**130.** Yes	**131.** Yes	**132.** No	**133.** Yes	**134.** Yes	**135.** Yes	**136.** No
137. Yes	**138.** Yes	**139.** No	**140.** Yes	**141.** Yes	**142.** Yes	**143.** Yes	**144.** No
145. Yes	**146.** Yes	**147.** No	**148.** Yes	**149.** No	**150.** No	**151.** Yes	**152.** Yes
153. No	**154.** Yes	**155.** Yes	**156.** No	**157.** Yes	**158.** Yes	**159.** No	**160.** Yes
161. Yes	**162.** No	**163.** Yes	**164.** Yes	**165.** Yes	**166.** No	**167.** No	**168.** Yes
169. Yes	**170.** No	**171.** No	**172.** Yes	**173.** Yes	**174.** No	**175.** Yes	**176.** Yes
177. Yes	**178.** Yes	**179.** No	**180.** Yes	**181.** Yes	**182.** Yes	**183.** No	**184.** Yes
185. Yes	**186.** No	**187.** Yes	**188.** No	**189.** Yes	**190.** Yes	**191.** No	**192.** Yes
193. Yes	**194.** No	**195.** No	**196.** Yes	**197.** Yes	**198.** No	**199.** Yes	**200.** No
201. No	**202.** Yes	**203.** Yes	**204.** No	**205.** Yes	**206.** Yes	**207.** No	**208.** Yes
209. No	**210.** Yes	**211.** Yes	**212.** No	**213.** Yes	**214.** No	**215.** No	**216.** Yes
217. No	**218.** Yes	**219.** Yes	**220.** No	**221.** Yes	**222.** No	**223.** Yes	**224.** Yes
225. No	**226.** Yes	**227.** Yes	**228.** No	**229.** Yes	**230.** No	**231.** Yes	**232.** No
233. Yes	**234.** Yes	**235.** No	**236.** No	**237.** Yes	**238.** Yes	**239.** No	**240.** Yes
241. Yes	**242.** No	**243.** Yes	**244.** Yes	**245.** Yes	**246.** No	**247.** Yes	**248.** No
249. Yes	**250.** Yes	**251.** Yes	**252.** No	**253.** Yes	**254.** Yes	**255.** Yes	**256.** No
257. Yes	**258.** Yes	**259.** Yes	**260.** No	**261.** Yes	**262.** Yes	**263.** Yes	**264.** No
265. Yes	**266.** No	**267.** Yes	**268.** Yes	**269.** No	**270.** Yes	**271.** Yes	**272.** No
273. Yes	**274.** Yes	**275.** No	**276.** Yes	**277.** Yes	**278.** No	**279.** Yes	**280.** Yes
281. No	**282.** Yes	**283.** Yes	**284.** No	**285.** Yes.			

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STEAM TABLES

and

Mollier Diagram

(SI Units)

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SYMBOLS AND UNITS USED IN THE TABLES

t = Temperature, °C

t_s = Saturation temperature, °C

p = Pressure, bar

h_f = Specific enthalpy of saturated liquid, kJ/kg

h_{fg} = Specific enthalpy of evaporation (latent heat), kJ/kg

h_g = Specific enthalpy of saturated vapour, kJ/kg

s_f = Specific entropy of saturated liquid, kJ/kg K

s_{fg} = Specific entropy of evaporation, kJ/kg K

s_g = Specific entropy of saturated vapour, kJ/kg K

v_f = Specific volume of saturated liquid, m^3/kg

v_g = Specific volume of saturated steam, m^3/kg

TABLE I

Saturated Water and Steam (Temperature) Tables

Temp. (°C)	*Absolute pressure* (bar)	*Specific enthalpy* (kJ / kg)			*Specific entropy* (kJ / kg K)			*Specific volume* (m^3 / kg)	
t	p	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_g
0	0.0061	– 0.02	2501.4	2501.3	– 0.0001	9.1566	9.1565	0.0010002	206.3
0.01	0.0061	0.01	2501.3	2501.4	0.000	9.156	9.156	0.0010002	206.2
1	0.0065	4.2	2499.0	2503.2	0.015	9.115	9.130	0.0010002	192.6
2	0.0070	8.4	2496.7	2505.0	0.031	9.073	9.104	0.0010001	179.9
3	0.0076	12.6	2494.3	2506.9	0.046	9.032	9.077	0.0010001	168.1
4	0.0081	16.8	2491.9	2508.7	0.061	8.990	9.051	0.0010001	157.2
5	0.0087	21.0	2489.6	2510.6	0.076	8.950	9.026	0.0010001	147.1
6	0.0093	25.2	2487.2	2512.4	0.091	8.909	9.000	0.0010001	137.7
7	0.0100	29.4	2484.8	2514.2	0.106	8.869	8.975	0.0010002	129.0
8	0.0107	33.6	2482.5	2516.1	0.121	8.829	8.950	0.0010002	120.9
9	0.0115	37.8	2480.1	2517.9	0.136	8.789	8.925	0.0010003	113.4
10	0.0123	42.0	2477.7	2519.7	0.151	8.750	8.901	0.0010004	106.4
11	0.0131	46.2	2475.4	2521.6	0.166	8.711	8.877	0.0010004	99.86
12	0.0140	50.4	2473.0	2523.4	0.181	8.672	8.852	0.0010005	93.78
13	0.0150	54.6	2470.7	2525.3	0.195	8.632	8.828	0.0010007	88.12
14	0.0160	58.8	2468.3	2527.1	0.210	8.595	8.805	0.0010008	82.85
15	0.0170	63.0	2465.9	2528.9	0.224	8.557	8.781	0.0010009	77.93
16	0.0182	67.2	2463.6	2530.8	0.239	8.519	8.758	0.001001	73.33
17	0.0194	71.4	2461.2	2532.6	0.253	8.482	8.735	0.001001	69.04
18	0.0206	75.6	2458.8	2534.4	0.268	8.444	8.712	0.001001	65.04
19	0.0220	79.8	2456.5	2536.3	0.282	8.407	8.690	0.001002	61.29
20	0.0234	84.0	2454.1	2538.1	0.297	8.371	8.667	0.001002	57.79
21	0.0249	88.1	2451.8	2539.9	0.311	8.334	8.645	0.001002	54.51
22	0.0264	92.3	2449.4	2541.7	0.325	8.298	8.623	0.001002	51.45
23	0.0281	96.5	2447.0	2543.5	0.339	8.262	8.601	0.001002	48.57
24	0.0298	100.7	2444.7	2545.4	0.353	8.226	8.579	0.001003	45.88
25	0.0317	104.9	2442.3	2547.2	0.367	8.191	8.558	0.001003	43.36
26	0.0336	109.1	2439.9	2549.0	0.382	8.155	8.537	0.001003	40.99
27	0.0357	113.2	2437.6	2550.8	0.396	8.120	8.516	0.001004	38.77
28	0.0378	117.4	2435.2	2552.6	0.409	8.086	8.495	0.001004	36.69
29	0.0401	121.6	2432.8	2554.5	0.423	8.051	8.474	0.001004	34.73
30	0.0425	125.8	2430.5	2556.3	0.437	8.016	8.453	0.001004	32.89
31	0.0450	130.0	2428.1	2558.1	0.451	7.982	8.433	0.001005	31.17
32	0.0476	134.2	2425.7	2559.9	0.464	7.948	8.413	0.001005	29.54
33	0.0503	138.3	2423.4	2561.7	0.478	7.915	8.393	0.001005	28.01
34	0.0532	142.5	2421.0	2563.5	0.492	7.881	8.373	0.001006	26.57
35	0.0563	146.7	2418.6	2565.3	0.505	7.848	8.353	0.001006	25.22

Temp. (°C) t	*Absolute pressure* (bar) p	*Specific enthalpy* (kJ/kg) h_f	h_{fg}	h_g	*Specific entropy* (kJ/kg K) s_f	s_{fg}	s_g	*Specific volume* (m^3/kg) v_f	v_g
36	0.0595	150.9	2416.2	2567.1	0.519	7.815	8.334	0.001006	23.94
37	0.0628	155.0	2413.9	2568.9	0.532	7.782	8.314	0.001007	22.74
38	0.0663	159.2	2411.5	2570.7	0.546	7.749	8.295	0.001007	21.60
39	0.0700	163.4	2409.1	2572.5	0.559	7.717	8.276	0.001007	20.53
40	0.0738	167.6	2406.7	2574.3	0.573	7.685	8.257	0.001008	19.52
41	0.0779	171.7	2404.3	2576.0	0.586	7.652	8.238	0.001008	18.57
42	0.0821	175.9	2401.9	2577.8	0.599	7.621	8.220	0.001009	17.67
43	0.0865	180.1	2399.5	2579.6	0.612	7.589	8.201	0.001009	16.82
44	0.0911	184.3	2397.2	2581.5	0.626	7.557	8.183	0.001010	16.02
45	0.0959	188.4	2394.8	2583.2	0.639	7.526	8.165	0.001010	15.26
46	0.1010	192.6	2392.4	2585.0	0.652	7.495	8.147	0.001010	14.54
47	0.1062	196.8	2390.0	2586.8	0.665	7.464	8.129	0.001011	13.86
48	0.1118	201.0	2387.6	2588.6	0.678	7.433	8.111	0.001011	13.22
49	0.1175	205.1	2385.2	2590.3	0.691	7.403	8.094	0.001012	12.61
50	0.1235	209.3	2382.7	2592.1	0.704	7.372	8.076	0.001012	12.03
52	0.1363	217.7	2377.9	2595.6	0.730	7.312	8.042	0.001013	10.97
54	0.1502	226.0	2373.1	2599.1	0.755	7.253	8.008	0.001014	10.01
56	0.1653	234.4	2368.2	2602.6	0.781	7.194	7.975	0.001015	9.149
58	0.1817	242.8	2363.4	2606.2	0.806	7.136	7.942	0.001016	8.372
60	0.1994	251.1	2358.5	2609.6	0.831	7.078	7.909	0.001017	7.671
62	0.2186	259.5	2353.6	2613.1	0.856	7.022	7.878	0.001018	7.037
64	0.2393	267.9	2348.7	2616.5	0.881	6.965	7.846	0.001019	6.463
66	0.2617	276.2	2343.7	2619.9	0.906	6.910	7.816	0.001020	5.943
68	0.2859	284.6	2338.8	2623.4	0.930	6.855	7.785	0.001022	5.471
70	0.3119	293.0	2333.8	2626.8	0.955	6.800	7.755	0.001023	5.042
75	0.3858	313.9	2321.4	2635.3	1.015	6.667	7.682	0.001026	4.131
80	0.4739	334.9	2308.8	2643.7	1.075	6.537	7.612	0.001029	3.407
85	0.5783	355.9	2296.0	2651.9	1.134	6.410	7.544	0.001033	2.828
90	0.7014	376.9	2283.2	2660.1	1.192	6.287	7.479	0.001036	2.361
95	0.8455	397.9	2270.2	2668.1	1.250	6.166	7.416	0.001040	1.982
100	1.0135	419.0	2257.0	2676.0	1.307	6.048	7.355	0.001044	1.673

TABLE II

Saturated Water and Steam (Pressure) Tables

Absolute pressure (bar) p	*Temp. (°C)* t_s	*Specific enthalpy (kJ/kg)* h_f	h_{fg}	h_g	*Specific entropy (kJ/kg K)* s_f	s_{fg}	s_g	*Specific volume (m^3/kg)* v_f	v_g
0.006113	0.01	0.01	2 501.3	2 501.4	0.000	9.156	9.156	0.0010002	206.14
0.010	7.0	29.3	2 484.9	2 514.2	0.106	8.870	8.976	0.0010000	129.21
0.015	13.0	54.7	2 470.6	2 525.3	0.196	8.632	8.828	0.0010007	87.98
0.020	17.0	73.5	2 460.0	2 533.5	0.261	8.463	8.724	0.001001	67.00
0.025	21.1	88.5	2 451.6	2 540.1	0.312	8.331	8.643	0.001002	54.25
0.030	24.1	101.0	2 444.5	2 545.5	0.355	8.223	8.578	0.001003	45.67
0.035	26.7	111.9	2 438.4	2 550.3	0.391	8.132	8.523	0.001003	39.50
0.040	29.0	121.5	2 432.9	2 554.4	0.423	8.052	8.475	0.001004	34.80
0.045	31.0	130.0	2 428.2	2 558.2	0.451	7.982	8.433	0.001005	31.13
0.050	32.9	137.8	2 423.7	2 561.5	0.476	7.919	8.395	0.001005	28.19
0.055	34.6	144.9	2 419.6	2 565.5	0.500	7.861	8.361	0.001006	25.77
0.060	36.2	151.5	2 415.9	2 567.4	0.521	7.809	8.330	0.001006	23.74
0.065	37.6	157.7	2 412.4	2 570.1	0.541	7.761	8.302	0.001007	22.01
0.070	39.0	163.4	2 409.1	2 572.5	0.559	7.717	8.276	0.001007	20.53
0.075	40.3	168.8	2 406.0	2 574.8	0.576	7.675	8.251	0.001008	19.24
0.080	41.5	173.9	2 403.1	2 577.0	0.593	7.636	8.229	0.001008	18.10
0.085	42.7	178.7	2 400.3	2 579.0	0.608	7.599	8.207	0.001009	17.10
0.090	43.8	183.3	2 397.7	2 581.0	0.622	7.565	8.187	0.001009	16.20
0.095	44.8	187.7	2 395.2	2 582.9	0.636	7.532	8.168	0.001010	15.40
0.10	45.8	191.8	2 392.8	2 584.7	0.649	7.501	8.150	0.001010	14.67
0.11	47.7	199.7	2 388.3	2 588.0	0.674	7.453	8.117	0.001011	13.42
0.12	49.4	206.9	2 384.2	2 591.1	0.696	7.390	8.086	0.001012	12.36
0.13	51.0	213.7	2 380.2	2 593.9	0.717	7.341	8.058	0.001013	11.47
0.14	52.6	220.0	2 376.6	2 596.6	0.737	7.296	8.033	0.001013	10.69
0.15	54.0	226.0	2 373.2	2 599.2	0.754 9	7.254 4	8.009 3	0.001014	10.022
0.16	55.3	231.6	2 370.0	2 601.6	0.772 1	7.214 8	7.986 9	0.001015	9.433
0.17	56.6	236.9	2 366.9	2 603.8	0.788 3	7.177 5	7.965 8	0.001015	8.911
0.18	57.8	242.0	2 363.9	2 605.9	0.803 6	7.142 4	7.945 9	0.001016	8.445
0.19	59.0	246.8	2 361.1	2 607.9	0.818 2	7.109 0	7.927 2	0.001017	8.027
0.20	60.1	251.5	2 358.4	2 609.9	0.832 1	7.077 3	7.909 4	0.001017	7.650
0.21	61.1	255.9	2 355.8	2 611.7	0.845 3	7.047 2	7.892 5	0.001018	7.307
0.22	62.2	260.1	2 353.3	2 613.5	0.858 1	7.018 4	7.876 4	0.001018	6.995
0.23	63.1	264.2	2 350.9	2 615.2	0.870 2	6.990 8	7.861 1	0.001019	6.709
0.24	64.1	268.2	2 348.6	2 616.8	0.882 0	6.964 4	7.846 4	0.001019	6.447

Absolute pressure (bar) p	*Temp. (°C)* t_s	*Specific enthalpy (kJ/kg)* h_f	h_{fg}	h_g	*Specific entropy (kJ/kg K)* s_f	s_{fg}	s_g	*Specific volume (m^3/kg)* v_f	v_g
0.25	65.0	272.0	2 346.4	2 618.3	0.893 2	6.939 1	7.832 3	0.001020	6.205
0.26	65.9	275.7	2 344.2	2 619.9	0.904 1	6.914 7	7.818 8	0.001020	5.980
0.27	66.7	279.2	2 342.1	2 621.3	0.914 6	6.891 2	7.805 8	0.001021	5.772
0.28	67.5	282.7	2 340.0	2 622.7	0.924 8	6.868 5	7.793 3	0.001021	5.579
0.29	68.3	286.0	2 338.1	2 624.1	0.934 6	6.846 6	7.781 2	0.001022	5.398
0.30	69.1	289.3	2 336.1	2 625.4	0.944 1	6.825 4	7.769 5	0.001022	5.229
0.32	70.6	295.5	2 332.4	2 628.0	0.962 3	6.785 0	7.747 4	0.001023	4.922
0.34	72.0	301.5	2 328.9	2 630.4	0.979 5	6.747 0	7.726 5	0.001024	4.650
0.36	73.4	307.1	2 325.5	2 632.6	0.995 8	6.711 1	7.707 0	0.001025	4.408
0.38	74.7	312.5	2 322.3	2 634.8	1.011 3	6.677 1	7.688 4	0.001026	4.190
0.40	75.9	317.7	2 319.2	2 636.9	1.026 1	6.644 8	7.670 9	0.001026	3.993
0.42	77.1	322.6	2 316.3	2 638.9	1.040 2	6.614 0	7.654 2	0.001027	3.815
0.44	78.2	327.3	2 313.4	2 640.7	1.053 7	6.584 6	7.638 3	0.001028	3.652
0.46	79.3	331.9	2 310.7	2 642.6	1.066 7	6.556 4	7.623 1	0.001029	3.503
0.48	80.3	336.3	2 308.0	2 644.3	1.079 2	6.529 4	7.608 6	0.001029	3.367
0.50	81.3	340.6	2 305.4	2 646.0	1.091 2	6.503 5	7.594 7	0.001030	3.240
0.55	83.7	350.6	2 299.3	2 649.9	1.119 4	6.442 8	7.562 3	0.001032	2.964
0.60	86.0	359.9	2 293.6	2 653.6	1.145 4	6.387 3	7.532 7	0.001033	2.732
0.65	88.0	368.6	2 288.3	2 656.9	1.169 6	6.336 0	7.505 5	0.001035	2.535
0.70	90.0	376.8	2 283.3	2 660.1	1.192 1	6.288 3	7.480 4	0.001036	2.369
0.75	92.0	384.5	2 278.6	2 663.0	1.213 1	6.243 9	7.457 0	0.001037	2.217
0.80	93.5	391.7	2 274.0	2 665.8	1.233 0	6.202 2	7.435 2	0.001039	2.087
0.85	95.1	398.6	2 269.8	2 668.4	1.251 8	6.162 9	7.414 7	0.001040	1.972
0.90	96.7	405.2	2 265.6	2 670.9	1.269 6	6.125 8	7.395 4	0.001041	1.869
0.95	98.2	411.5	2 261.7	2 673.2	1.286 5	6.090 6	7.377 1	0.001042	1.777
1.0	99.6	417.5	2 257.9	2 675.4	1.302 7	6.057 1	7.359 8	0.001043	1.694
1.1	102.3	428.8	2 250.8	2 679.6	1.333 0	5.994 7	7.327 7	0.001046	1.549
1.2	104.8	439.4	2 244.1	2 683.4	1.360 9	5.937 5	7.298 4	0.001048	1.428
1.3	107.1	449.2	2 237.8	2 687.0	1.386 8	5.884 7	7.271 5	0.001050	1.325
1.4	109.3	458.4	2 231.9	2 690.3	1.410 9	5.835 6	7.246 5	0.001051	1.236
1.5	111.3	467.1	2 226.2	2 693.4	1.433 6	5.789 8	7.233 4	0.001053	1.159
1.6	113.3	475.4	2 220.9	2 696.2	1.455 0	5.746 7	7.201 7	0.001055	1.091
1.7	115.2	483.2	2 215.7	2 699.0	1.475 2	5.706 1	7.181 3	0.001056	1.031
1.8	116.9	490.7	2 210.8	2 701.5	1.494 4	5.667 8	7.162 2	0.001058	0.977
1.9	118.6	497.8	2 206.1	2 704.0	1.512 7	5.631 4	7.144 0	0.001060	0.929
2.0	120.2	504.7	2 201.6	2 706.3	1.530 1	5.596 7	7.126 8	0.001061	0.885
2.1	121.8	511.3	2 197.2	2 708.5	1.546 8	5.563 7	7.110 5	0.001062	0.846
2.2	123.3	517.6	2 193.0	2 710.6	1.562 7	5.532 1	7.094 9	0.001064	0.810
2.3	124.7	523.7	2 188.9	2 712.6	1.578 1	5.501 9	7.080 0	0.001065	0.777
2.4	126.1	529.6	2 184.9	2 714.5	1.592 9	5.472 8	7.065 7	0.001066	0.746

Absolute pressure (bar) p	*Temp. (°C)* t_s	*Specific enthalpy (kJ/kg)* h_f	h_{fg}	h_g	*Specific entropy (kJ/kg K)* s_f	s_{fg}	s_g	*Specific volume (m^3/kg)* v_f	v_g
2.5	127.4	535.3	2 181.0	2 716.4	1.607 1	5.444 9	7.052 0	0.001068	0.718
2.6	128.7	540.9	2 177.3	2 718.2	1.620 9	5.418 0	7.038 9	0.001069	0.693
2.7	129.9	546.2	2 173.6	2 719.9	1.634 2	5.392 0	7.026 2	0.001070	0.668
2.8	131.2	551.4	2 170.1	2 721.5	1.647 1	5.367 0	7.014 0	0.001071	0.646
2.9	132.4	556.5	2 166.6	2 723.1	1.659 5	5.342 7	7.002 3	0.001072	0.625
3.0	133.5	561.4	2 163.2	2 724.7	1.671 6	5.319 3	6.990 9	0.001074	0.606
3.1	134.6	566.2	2 159.9	2 726.1	1.683 4	5.296 5	6.979 9	0.001075	0.587
3.2	135.7	570.9	2 156.7	2 727.6	1.694 8	5.274 4	6.969 2	0.001076	0.570
3.3	136.8	575.5	2 153.5	2 729.0	1.705 9	5.253 0	6.958 9	0.001077	0.554
3.4	137.8	579.9	2 150.4	2 730.3	1.716 8	5.232 2	6.948 9	0.001078	0.538
3.5	138.8	584.3	2 147.4	2 731.6	1.727 3	5.211 9	6.939 2	0.001079	0.524
3.6	139.8	588.5	2 144.4	2 732.9	1.737 6	5.192 1	6.929 7	0.001080	0.510
3.7	140.8	592.7	2 141.4	2 734.1	1.747 6	5.172 9	6.920 5	0.001081	0.497
3.8	141.8	596.8	2 138.6	2 735.3	1.757 4	5.154 1	6.911 6	0.001082	0.486
3.9	142.7	600.8	2 135.7	2 736.5	1.767 0	5.135 8	6.902 8	0.001083	0.473
4.0	143.6	604.7	2 133.0	2 737.6	1.776 4	5.117 9	6.894 3	0.001084	0.462
4.2	145.4	612.3	2 127.5	2 739.8	1.794 5	5.083 4	6.877 9	0.001086	0.441
4.4	147.1	619.6	2 122.3	2 741.9	1.812 0	5.050 3	6.862 3	0.001088	0.423
4.6	148.7	626.7	2 117.2	2 743.9	1.828 7	5.018 6	6.847 3	0.001089	0.405
4.8	150.3	633.5	2 112.2	2 745.7	1.844 8	4.988 1	6.832 9	0.001091	0.390
5.0	151.8	640.1	2 107.4	2 747.5	1.860 4	4.958 8	6.819 2	0.001093	0.375
5.2	153.3	646.5	2 102.7	2 749.3	1.875 4	4.930 6	6.805 9	0.001094	0.361
5.4	154.7	652.8	2 098.1	2 750.9	1.889 9	4.903 3	6.793 2	0.001096	0.348
5.6	156.2	658.8	2 093.7	2 752.5	1.904 0	4.876 9	6.780 9	0.001098	0.337
5.8	157.5	664.7	2 089.3	2 754.0	1.917 6	4.851 4	6.769 0	0.001099	0.326
6.0	158.8	670.4	2 085.0	2 755.5	1.930 8	4.826 7	6.757 5	0.001101	0.315
6.2	160.1	676.0	2 080.9	2 756.9	1.943 7	4.802 7	6.746 4	0.001102	0.306
6.4	161.4	681.5	2 076.8	2 758.2	1.956 2	4.779 4	6.735 6	0.001104	0.297
6.6	162.6	686.8	2 072.7	2 759.5	1.968 4	4.756 8	6.725 2	0.001105	0.288
6.8	163.8	692.0	2 068.8	2 760.8	1.980 2	4.734 8	6.715 0	0.001107	0.280
7.0	165.0	697.1	2 064.9	2 762.0	1.991 8	4.713 4	6.705 2	0.001108	0.273
7.2	166.1	702.0	2 061.1	2 763.2	2.003 1	4.692 5	6.695 6	0.001110	0.265
7.4	167.2	706.9	2 057.4	2 764.3	2.014 1	4.672 1	6.686 2	0.001111	0.258
7.6	168.3	711.7	2 053.7	2 765.4	2.024 9	4.652 2	6.677 1	0.001112	0.252
7.8	169.4	716.3	2 050.1	2 766.4	2.035 4	4.632 8	6.668 3	0.001114	0.246
8.0	170.4	720.9	2 046.5	2 767.5	2.045 7	4.613 9	6.659 6	0.001115	0.240
8.2	171.4	725.4	2 043.0	2 768.5	2.055 8	4.595 3	6.651 1	0.001116	0.235
8.4	172.4	729.9	2 039.6	2 769.4	2.065 7	4.577 2	6.642 9	0.001118	0.229
8.6	173.4	734.2	2 036.2	2 770.4	2.075 3	4.559 4	6.634 8	0.001119	0.224
8.8	174.4	738.5	2 032.8	2 771.3	2.084 8	4.542 1	6.626 9	0.001120	0.219

Absolute pressure (bar) p	*Temp. (°C)* t_s	*Specific enthalpy (kJ/kg)* h_f	h_{fg}	h_g	*Specific entropy (kJ/kg K)* s_f	s_{fg}	s_g	*Specific volume (m^3/kg)* v_f	v_g
9.0	175.4	742.6	2 029.5	2 772.1	2.094 1	4.525 0	6.619 2	0.001121	0.215
9.2	176.3	746.8	2 026.2	2 773.0	2.103 3	4.508 3	6.611 6	0.001123	0.210
9.4	177.2	750.8	2 023.0	2 773.8	2.112 2	4.492 0	6.604 2	0.001124	0.206
9.6	178.1	754.8	2 019.8	2 774.6	2.121 0	4.475 9	6.596 9	0.001125	0.202
9.8	179.0	758.7	2 016.7	2 775.4	2.129 7	4.460 1	6.589 8	0.001126	0.198
10.0	179.9	762.6	2 013.6	2 776.2	2.138 2	4.444 6	6.582 8	0.001127	0.194
10.5	182.0	772.0	2 005.9	2 778.0	2.158 8	4.407 1	6.565 9	0.001130	0.185
11.0	184.1	781.1	1 998.5	2 779.7	2.178 6	4.371 1	6.549 7	0.001133	0.177
11.5	186.0	789.9	1 991.3	2 781.3	2.197 7	4.336 6	6.534 2	0.001136	0.170
12.0	188.0	798.4	1 984.3	2 782.7	2.216 1	4.303 3	6.519 4	0.001139	0.163
12.5	189.8	806.7	1 977.4	2 784.1	2.233 8	4.271 2	6.505 0	0.001141	0.157
13.0	191.6	814.7	1 970.7	2 785.4	2.251 0	4.240 3	6.491 3	0.001144	0.151
13.5	193.3	822.5	1 964.2	2 786.6	2.267 6	4.210 4	6.477 9	0.001146	0.146
14.0	195.0	830.1	1 957.7	2 787.8	2.283 7	4.181 4	6.465 1	0.001149	0.141
14.5	196.7	837.5	1 951.4	2 788.9	2.299 3	4.153 3	6.452 6	0.001151	0.136
15.0	198.3	844.7	1 945.2	2 789.9	2.314 5	4.126 1	6.440 6	0.001154	0.132
15.5	199.8	851.7	1 939.2	2 790.8	2.329 2	4.099 6	6.428 9	0.001156	0.128
16.0	201.4	858.6	1 933.2	2 791.7	2.343 6	4.073 9	6.417 5	0.001159	0.124
16.5	202.8	865.3	1 927.3	2 792.6	2.357 6	4.048 9	6.406 5	0.001161	0.120
17.0	204.3	871.8	1 921.5	2 793.4	2.371 3	4.024 5	6.395 7	0.001163	0.117
17.5	205.7	878.3	1 915.9	2 794.1	2.384 6	4.000 7	6.385 3	0.001166	0.113
18.0	207.1	884.6	1 910.3	2 794.8	2.397 6	3.977 5	6.375 1	0.001168	0.110
18.5	208.4	890.7	1 904.7	2 795.5	2.410 3	3.954 8	6.365 1	0.001170	0.107
19.0	209.8	896.8	1 899.3	2 796.1	2.422 8	3.932 6	6.355 4	0.001172	0.105
19.5	211.1	902.8	1 893.9	2 796.7	2.434 9	3.911 0	6.345 9	0.001174	0.102
20.0	212.4	908.6	1 888.6	2 797.2	2.446 9	3.889 8	6.336 6	0.001177	0.0995
20.5	213.6	914.3	1 883.4	2 797.7	2.458 5	3.869 0	6.327 6	0.001179	0.0971
21.0	214.8	920.0	1 878.2	2 798.2	2.470 0	3.848 7	6.318 7	0.001181	0.0949
21.5	216.1	925.5	1 873.1	2 798.6	2.481 2	3.828 8	6.310 0	0.001183	0.0927
22.0	217.2	931.0	1 868.1	2 799.1	2.492 2	3.809 3	6.301 5	0.001185	0.0907
22.5	218.4	936.3	1 863.1	2 799.4	2.503 0	3.790 1	6.293 1	0.001187	0.0887
23.0	219.5	941.6	1 858.2	2 799.8	2.513 6	3.771 3	6.284 9	0.001189	0.0868
23.5	220.7	946.8	1 853.3	2 800.1	2.524 1	3.752 8	6.276 9	0.001191	0.0849
24.0	221.8	951.9	1 848.5	2 800.4	2.534 3	3.734 7	6.269 0	0.001193	0.0832
24.5	222.9	957.0	1 843.7	2 800.7	2.544 4	3.716 8	6.261 2	0.001195	0.0815
25.0	223.9	962.0	1 839.0	2 800.9	2.554 3	3.699 3	6.253 6	0.001197	0.0799
25.5	225.0	966.9	1 834.3	2 801.2	2.564 0	3.682 1	6.246 1	0.001199	0.0783
26.0	226.0	971.7	1 829.6	2 801.4	2.573 6	3.665 1	6.238 7	0.001201	0.0769
26.5	227.1	976.5	1 825.1	2 801.6	2.583 1	3.648 4	6.231 5	0.001203	0.0754
27.0	228.1	981.2	1 820.5	2 801.7	2.592 4	3.632 0	6.224 4	0.001205	0.0740

Absolute pressure (bar) p	*Temp. (°C)* t_s	*Specific enthalpy (kJ/kg)* h_f	h_{fg}	h_g	*Specific entropy (kJ/kg K)* s_f	s_{fg}	s_g	*Specific volume (m^3/kg)* v_f	v_g
27.5	229.1	985.9	1 816.0	2 801.9	2.601 6	3.615 8	6.217 3	0.001207	0.0727
28.0	230.0	990.5	1 811.5	2 802.0	2.610 6	3.599 8	6.210 4	0.001209	0.0714
28.5	231.0	995.0	1 807.1	2 802.1	2.619 5	3.584 1	6.203 6	0.001211	0.0701
29.0	232.0	999.5	1 802.6	2 802.2	2.628 3	3.568 6	6.196 9	0.001213	0.0689
29.5	233.0	1 004.0	1 798.3	2 802.2	2.637 0	3.553 3	6.190 2	0.001214	0.0677
30.0	233.8	1 008.4	1 793.9	2 802.3	2.645 5	3.538 2	6.183 7	0.001216	0.0666
30.5	234.7	1 012.7	1 789.6	2 802.3	2.653 9	3.523 3	6.177 2	0.001218	0.0655
31.0	235.6	1 017.0	1 785.4	2 802.3	2.662 3	3.508 7	6.170 9	0.001220	0.0645
31.5	236.5	1 021.2	1 781.1	2 802.3	2.670 5	3.494 2	6.164 7	0.001222	0.0634
32.0	237.4	1 025.4	1 776.9	2 802.3	2.678 6	3.479 9	6.158 5	0.001224	0.0624
32.5	238.3	1 029.6	1 772.7	2 802.3	2.686 6	3.465 7	6.152 3	0.001225	0.0615
33.0	239.2	1 033.7	1 768.6	2 802.3	2.694 5	3.451 8	6.146 3	0.001227	0.0605
33.5	240.0	1 037.8	1 764.4	2 802.2	2.702 3	3.438 0	6.140 3	0.001229	0.0596
34.0	240.9	1 041.8	1 760.3	2 802.1	2.710 1	3.424 4	6.134 4	0.001231	0.0587
34.5	241.7	1 045.8	1 756.3	2 802.1	2.717 7	3.410 9	6.128 6	0.001233	0.0579
35.0	242.5	1 049.8	1 752.2	2 802.0	2.725 3	3.397 6	6.122 8	0.001234	0.0570
35.5	243.3	1 053.7	1 748.2	2 801.8	2.732 7	3.384 4	6.117 1	0.001236	0.0562
36.0	244.2	1 057.6	1 744.2	2 801.7	2.740 1	3.371 4	6.111 5	0.001238	0.0554
36.5	245.0	1 061.4	1 740.2	2 801.6	2.747 4	3.358 5	6.105 9	0.001239	0.0546
37.0	245.7	1 065.2	1 736.2	2 801.4	2.754 7	3.345 8	6.100 4	0.001242	0.0539
37.5	246.5	1 069.0	1 732.3	2 801.3	2.761 8	3.333 2	6.095 0	0.001243	0.0531
38.0	247.3	1 072.7	1 728.4	2 801.1	2.768 9	3.320 7	6.089 6	0.001245	0.0524
38.5	248.1	1 076.4	1 724.5	2 800.9	2.775 9	3.308 3	6.084 2	0.001247	0.0517
39.0	248.8	1 080.1	1 720.6	2 800.8	2.782 9	3.296 1	6.078 9	0.001249	0.0511
39.5	249.6	1 083.8	1 716.8	2 800.5	2.789 7	3.284 0	6.073 7	0.001250	0.0504
40.0	250.3	1 087.4	1 712.9	2 800.3	2.796 5	3.272 0	6.068 5	0.001252	0.0497
41.0	251.8	1 094.6	1 705.3	2 799.9	2.809 9	3.248 3	6.058 2	0.001255	0.0485
42.0	253.2	1 101.6	1 697.8	2 799.4	2.823 1	3.225 1	6.048 2	0.001259	0.0473
43.0	254.6	1 108.5	1 690.3	2 798.8	2.836 0	3.202 3	6.038 3	0.001262	0.0461
44.0	256.0	1 115.4	1 682.9	2 798.3	2.848 7	3.179 9	6.028 6	0.001266	0.0451
45.0	257.4	1 122.1	1 675.6	2 797.7	2.861 2	3.157 9	6.019 1	0.001269	0.0440
46.0	258.7	1 128.8	1 668.3	2 797.0	2.873 5	3.136 2	6.009 7	0.001272	0.0430
47.0	260.1	1 135.3	1 661.1	2 796.4	2.885 5	3.114 9	6.000 4	0.001276	0.0421
48.0	261.4	1 141.8	1 653.9	2 795.7	2.897 4	3.093 9	5.991 3	0.001279	0.0412
49.0	262.6	1 148.2	1 646.8	2 794.9	2.909 1	3.073 3	5.982 3	0.001282	0.0403
50.0	263.9	1 154.5	1 639.7	2 794.2	2.920 6	3.052 9	5.973 5	0.001286	0.0394
51.0	265.1	1 160.7	1 632.7	2 793.4	2.931 9	3.032 8	5.964 8	0.001289	0.0386
52.0	266.4	1 166.8	1 625.7	2 792.6	2.943 1	3.013 0	5.956 1	0.001292	0.0378
53.0	267.6	1 172.9	1 618.8	2 791.7	2.954 1	2.993 5	5.947 6	0.001296	0.0371
54.0	268.7	1 178.9	1 611.9	2 790.8	2.965 0	2.974 2	5.939 2	0.001299	0.0363

Absolute pressure (bar) p	*Temp. (°C)* t_s	*Specific enthalpy (kJ/kg)* h_f	h_{fg}	h_g	*Specific entropy (kJ/kg K)* s_f	s_{fg}	s_g	*Specific volume (m^3/kg)* v_f	v_g
55.0	269.9	1 184.9	1 605.0	2 789.9	2.975 7	2.955 2	5.930 9	0.001302	0.0356
56.0	271.1	1 190.8	1 598.2	2 789.0	2.986 3	2.936 4	5.922 7	0.001306	0.0349
57.0	272.2	1 196.6	1 591.4	2 788.0	2.996 7	2.917 9	5.914 6	0.001309	0.0343
58.0	273.3	1 202.3	1 584.7	2 787.0	3.007 1	2.899 5	5.906 6	0.001312	0.0336
59.0	274.4	1 208.0	1 578.0	2 786.0	3.017 2	2.881 4	5.898 6	0.001315	0.0330
60.0	275.5	1 213.7	1 571.3	2 785.0	3.027 3	2.863 5	5.890 8	0.001318	0.0324
61.0	276.6	1 219.3	1 564.7	2 784.0	3.037 2	2.845 8	5.883 0	0.001322	0.0319
62.0	277.7	1 224.8	1 558.0	2 782.9	3.047 1	2.828 3	5.875 3	0.001325	0.0313
63.0	278.7	1 230.3	1 551.5	2 781.8	3.056 8	2.810 9	5.867 7	0.001328	0.0308
64.0	279.8	1 235.7	1 544.9	2 780.6	3.066 4	2.793 8	5.860 1	0.001332	0.0302
65.0	280.8	1 241.1	1 538.4	2 779.5	3.075 9	2.776 8	5.852 7	0.001335	0.0297
66.0	281.8	1 246.5	1 531.9	2 778.3	3.085 3	2.760 0	5.845 2	0.001338	0.0292
67.0	282.8	1 251.8	1 525.4	2 777.1	3.094 6	2.743 3	5.837 9	0.001341	0.0287
68.0	283.8	1 257.0	1 518.9	2 775.9	3.103 8	2.726 8	5.830 6	0.001345	0.0283
69.0	284.8	1 262.2	1 512.5	2 774.7	3.112 9	2.710 5	5.823 3	0.001348	0.0278
70.0	285.8	1 267.4	1 506.0	2 773.5	3.121 9	2.694 3	5.816 2	0.001351	0.0274
71.0	286.7	1 272.5	1 499.6	2 772.2	3.130 8	2.678 2	5.809 0	0.001355	0.0269
72.0	287.7	1 277.6	1 493.3	2 770.9	3.139 7	2.662 3	5.802 0	0.001358	0.0265
73.0	288.6	1 282.7	1 486.9	2 769.6	3.148 4	2.646 5	5.794 9	0.001361	0.0261
74.0	289.6	1 287.7	1 480.5	2 768.3	3.157 1	2.630 9	5.788 0	0.001364	0.0257
75.0	290.5	1 292.7	1 474.2	2 766.9	3.165 7	2.615 3	5.781 0	0.001368	0.0253
76.0	291.4	1 297.6	1 467.9	2 765.5	3.174 2	2.599 9	5.774 2	0.001371	0.0249
77.0	292.3	1 302.5	1 461.6	2 764.2	3.182 7	2.584 6	5.767 3	0.001374	0.0246
78.0	293.2	1 307.4	1 455.3	2 762.8	3.191 1	2.569 5	5.760 5	0.001378	0.0242
79.0	294.1	1 312.3	1 449.1	2 761.3	3.199 4	2.554 4	5.753 8	0.001381	0.0239
80.0	294.9	1 317.1	1 442.8	2 759.9	3.207 6	2.539 5	5.747 1	0.001384	0.0235
81.0	295.8	1 321.9	1 436.6	2 758.4	3.215 8	2.524 6	5.740 4	0.001387	0.0232
82.0	296.7	1 326.6	1 430.3	2 757.0	3.223 9	2.509 9	5.733 8	0.001391	0.0229
83.0	297.5	1 331.4	1 424.1	2 755.5	3.232 0	2.495 2	5.727 2	0.001394	0.0225
84.0	298.4	1 336.1	1 417.9	2 754.0	3.239 9	2.480 7	5.720 6	0.001397	0.0222
85.0	299.2	1 340.7	1 411.7	2 752.5	3.247 9	2.466 3	5.714 1	0.001401	0.0219
86.0	300.1	1 345.4	1 405.5	2 750.9	3.255 7	2.451 9	5.707 6	0.001404	0.0216
87.0	300.9	1 350.0	1 399.3	2 749.4	3.263 6	2.437 6	5.701 2	0.001408	0.0213
88.0	301.7	1 354.6	1 393.2	2 747.8	3.271 3	2.423 5	5.694 8	0.001411	0.0211
89.0	302.5	1 359.2	1 387.0	2 746.2	3.279 0	2.409 4	5.688 4	0.001414	0.0208
90.0	303.3	1 363.7	1 380.9	2 744.6	3.286 7	2.395 3	5.682 0	0.001418	0.0205
91.0	304.1	1 368.3	1 374.7	2 743.0	3.294 3	2.381 4	5.675 7	0.001421	0.0202
92.0	304.9	1 372.8	1 368.6	2 741.4	3.301 8	2.367 6	5.669 4	0.001425	0.0199
93.0	305.7	1 377.2	1 362.5	2 739.7	3.309 3	2.353 8	5.663 1	0.001428	0.0197
94.0	306.4	1 381.7	1 356.3	2 738.0	3.316 8	2.340 1	5.656 8	0.001432	0.0194

Absolute pressure (bar) p	*Temp. (°C)* t_s	*Specific enthalpy (kJ/kg)* h_f	h_{fg}	h_g	*Specific entropy (kJ/kg K)* s_f	s_{fg}	s_g	*Specific volume (m^3/kg)* v_f	v_g
95.0	307.2	1 386.1	1 350.2	2 736.4	3.324 2	2.326 4	5.650 6	0.001435	0.0192
96.0	308.0	1 390.6	1 344.1	2 734.7	3.331 5	2.312 9	5.644 4	0.001438	0.0189
97.0	308.7	1 395.0	1 338.0	2 733.0	3.338 8	2.299 4	5.638 2	0.001442	0.0187
98.0	309.4	1 399.3	1 331.9	2 731.2	3.346 1	2.285 9	5.632 1	0.001445	0.0185
99.0	310.2	1 403.7	1 325.8	2 729.5	3.353 4	2.272 6	5.625 9	0.001449	0.0183
100.0	311.1	1 408.0	1 319.7	2 727.7	3.360 5	2.259 3	5.619 8	0.001452	0.0181
102.0	312.4	1 416.7	1 307.5	2 724.2	3.374 8	2.232 8	5.607 6	0.001459	0.0176
104.0	313.8	1 425.2	1 295.3	2 720.5	3.388 9	2.206 6	5.595 5	0.001467	0.0172
106.0	315.3	1 433.7	1 283.1	2 716.8	3.402 9	2.180 6	5.583 5	0.001474	0.0168
108.0	316.6	1 442.2	1 270.9	2 713.1	3.416 7	2.154 8	5.571 5	0.001481	0.0164
110.0	318.0	1 450.6	1 258.7	2 709.3	3.430 4	2.129 1	5.559 5	0.001488	0.0160
112.0	319.4	1 458.9	1 246.5	2 705.4	3.444 0	2.103 6	5.547 6	0.001496	0.0157
114.0	320.7	1 467.2	1 234.3	2 701.5	3.457 4	2.078 3	5.535 7	0.001504	0.0153
116.0	322.1	1 475.4	1 222.0	2 697.4	3.470 8	2.053 1	5.523 9	0.001511	0.0149
118.0	323.4	1 483.6	1 209.7	2 693.3	3.484 0	2.028 0	5.512 1	0.001519	0.0146
120.0	324.6	1 491.8	1 197.4	2 689.2	3.497 2	2.003 0	5.500 2	0.001527	0.0143
122.0	325.9	1 499.9	1 185.0	2 684.9	3.510 2	1.978 2	5.488 4	0.001535	0.0139
124.0	327.1	1 508.0	1 172.6	2 680.6	3.523 2	1.953 3	5.476 5	0.001543	0.0137
126.0	328.4	1 516.0	1 160.1	2 676.1	3.536 0	1.928 6	5.464 6	0.001551	0.0134
128.0	329.6	1 524.0	1 147.6	2 671.6	3.548 8	1.903 9	5.452 7	0.001559	0.0131
130.0	330.8	1 532.0	1 135.0	2 667.0	3.561 6	1.879 2	5.440 8	0.001567	0.0128
132.0	332.0	1 540.0	1 122.3	2 662.3	3.574 2	1.854 6	5.428 8	0.001576	0.0125
134.0	333.2	1 547.9	1 109.5	2 657.4	3.586 8	1.830 0	5.416 8	0.001584	0.0123
136.0	334.3	1 555.8	1 096.7	2 652.5	3.599 3	1.805 3	5.404 7	0.001593	0.0120
138.0	335.5	1 563.7	1 083.8	2 647.5	3.611 8	1.780 7	5.392 5	0.001602	0.0117
140.0	336.6	1 571.6	1 070.7	2 642.4	3.624 2	1.756 0	5.380 3	0.001611	0.0115
142.0	337.7	1 579.5	1 057.6	2 637.1	3.636 6	1.731 3	5.367 9	0.001619	0.0112
144.0	338.8	1 587.4	1 044.4	2 631.8	3.649 0	1.706 6	5.355 5	0.001629	0.0110
146.0	339.9	1 595.3	1 031.0	2 626.3	3.661 3	1.681 8	5.343 1	0.001638	0.0108
148.0	341.1	1 603.1	1 017.6	2 620.7	3.673 6	1.656 9	5.330 5	0.001648	0.0106
150.0	342.1	1 611.0	1 004.0	2 615.0	3.685 9	1.632 0	5.317 9	0.001658	0.0103
152.0	343.2	1 618.9	990.3	2 609.2	3.698 1	1.607 0	5.305 1	0.001668	0.0101
154.0	344.2	1 626.8	976.5	2 603.3	3.710 3	1.581 9	5.292 2	0.001678	0.00991
156.0	345.3	1 634.7	962.6	2 597.3	3.722 6	1.556 7	5.279 3	0.001689	0.00971
158.0	346.3	1 642.6	948.5	2 591.1	3.734 8	1.531 4	5.266 3	0.001699	0.00951
160.0	347.3	1 650.5	934.3	2 584.9	3.747 1	1.506 0	5.253 1	0.001710	0.00931
162.0	348.3	1 658.5	920.0	2 578.5	3.759 4	1.480 6	5.239 9	0.001721	0.00911
164.0	349.3	1 666.5	905.6	2 572.1	3.771 7	1.455 0	5.226 7	0.001733	0.00893
166.0	350.3	1 674.5	891.0	2 565.5	3.784 2	1.429 0	5.213 2	0.001745	0.00874
168.0	351.3	1 683.0	875.6	2 558.6	3.797 4	1.402 1	5.199 4	0.001757	0.00855

Absolute pressure (bar) p	*Temp. (°C)* t_s	*Specific enthalpy (kJ/kg)* h_f	h_{fg}	h_g	*Specific entropy (kJ/kg K)* s_f	s_{fg}	s_g	*Specific volume (m^3/kg)* v_f	v_g
170.0	352.3	1 691.7	859.9	2 551.6	3.810 7	1.374 8	5.185 5	0.001769	0.00837
172.0	353.2	1 700.4	844.0	2 544.4	3.824 0	1.347 3	5.171 3	0.001783	0.00819
174.0	354.2	1 709.0	828.1	2 537.1	3.837 2	1.319 8	5.157 0	0.001796	0.00801
176.0	355.1	1 717.6	811.9	2 529.5	3.850 4	1.292 2	5.142 5	0.001810	0.00784
178.0	356.0	1 726.2	795.6	2 521.8	3.863 5	1.264 3	5.127 8	0.001825	0.00767
180.0	356.9	1 734.8	779.1	2 513.9	3.876 5	1.236 2	5.112 8	0.001840	0.00750
182.0	357.8	1 743.4	762.3	2 505.8	3.889 6	1.207 9	5.097 5	0.001856	0.00733
184.0	358.7	1 752.1	745.3	2 497.4	3.902 8	1.179 2	5.082 0	0.001872	0.00717
186.0	359.6	1 760.9	727.9	2 488.8	3.916 0	1.150 1	5.066 1	0.001889	0.00701
188.0	360.5	1 769.7	710.1	2 479.8	3.929 4	1.120 5	5.049 8	0.001907	0.00684
190.0	361.4	1 778.7	692.0	2 470.6	3.942 9	1.090 3	5.033 2	0.001926	0.00668
192.0	362.3	1 787.8	673.3	2 461.1	3.956 6	1.059 4	5.016 0	0.001946	0.00652
194.0	363.2	1 797.0	654.1	2 451.1	3.970 6	1.027 8	4.998 3	0.001967	0.00636
196.0	364.0	1 806.6	634.2	2 440.7	3.984 9	0.995 1	4.980 0	0.001989	0.00620
198.0	364.8	1 816.3	613.5	2 429.8	3.999 6	0.961 4	4.961 1	0.002012	0.00604
200.0	365.7	1 826.5	591.9	2 418.4	4.014 9	0.926 3	4.941 2	0.002037	0.00588
202.0	366.5	1 837.0	569.2	2 406.2	4.030 8	0.889 7	4.920 4	0.002064	0.00571
204.0	367.3	1 848.1	545.1	2 393.3	4.047 4	0.851 0	4.898 4	0.002093	0.00555
206.0	368.2	1 859.9	519.5	2 379.4	4.065 1	0.809 9	4.875 0	0.002125	0.00538
208.0	368.9	1 872.5	491.7	2 364.2	4.084 1	0.765 7	4.849 8	0.002161	0.00521
210.0	369.8	1 886.3	461.3	2 347.6	4.104 8	0.717 5	4.822 3	0.002201	0.00502
212.0	370.6	1 901.5	427.4	2 328.9	4.127 9	0.663 9	4.791 7	0.002249	0.00483
214.0	371.3	1 919.0	388.4	2 307.4	4.154 3	0.602 6	4.756 9	0.002306	0.00462
216.0	372.1	1 939.9	341.6	2 281.6	4.186 1	0.529 3	4.715 4	0.002379	0.00439
218.0	372.9	1 967.2	280.8	2 248.0	4.227 6	0.434 6	4.662 2	0.002483	0.00412
220.0	373.7	2 011.1	184.5	2 195.6	4.294 7	0.285 2	4.579 9	0.002671	0.00373
221.2	374.1	2 107.4	0.0	2 107.4	4.442 9	0.0	4.442 9	0.003170	0.00317

TABLE III

Superheated Steam at Various Pressures and Temperatures

↓p (bar) (t_s)	t (°C) →	50	100	150	200	250	300	400	500
	v	149.1	172.2	195.3	218.4	241.5	264.5	310.7	356.8
0.01	u	2445.4	2516.4	2588.4	2661.6	2736.9	2812.2	2969.0	3132.4
(7.0)	h	2594.5	2688.6	2783.6	2880.0	2978.4	3076.8	3279.7	3489.2
	s	9.242	9.513	9.752	9.967	10.163	10.344	10.671	10.960
	v	29.78	34.42	39.04	48.66	48.28	52.9	62.13	71.36
0.05	u	2444.8	2516.2	2588.4	2661.9	2736.6	2812.6	2969.6	3133.0
(32.9)	h	2593.7	2688.1	2783.4	2879.9	2977.6	3076.7	3279.7	3489.2
	s	8.498	8.770	9.009	9.225	9.421	9.602	9.928	10.218
	v	14.57	17.19	19.51	21.82	24.14	26.44	31.06	35.68
0.1	u	2443.9	2515.5	2587.9	2661.3	2736.0	2812.1	2968.9	3132.3
(45.8)	h	2592.6	2687.5	2783.0	2879.5	2977.3	3076.5	3279.6	3489.1
	s	8.175	8.448	8.688	8.904	9.100	9.281	9.608	9.898
	v		34.18	3.889	43.56	4.821	5.284	6.209	7.134
0.5	u		2511.6	2585.6	2659.9	2735.0	2811.3	2968.5	3132.0
(81.3)	h		2682.5	2780.1	2877.7	2976.0	3075.5	3278.9	3488.7
	s		7.695	7.940	8.158	8.356	8.537	8.864	9.155
	v		2.27	2.587	2.900	3.211	3.520	4.138	4.755
0.75	u		2509.2	2584.2	2659.0	2734.4	2810.9	2968.2	3131.8
(92.0)	h		2679.4	2778.2	2876.5	2975.2	3074.9	3278.5	3488.4
	s		7.501	7.749	7.969	8.167	8.349	8.677	8.967
	v		1.696	1.936	2.172	2.406	2.639	3.103	3.565
1.0	u		2506.2	2582.8	2658.1	2733.7	2810.4	2967.9	3131.6
(99.6)	h		2676.2	2776.4	2875.3	2974.3	3074.3	3278.2	3488.1
	s		7.361	7.613	7.834	8.033	8.216	8.544	8.834
	v			1.912	2.146	2.375	2.603	3.062	3.519
1.01325	u			2582.6	2658.0	2733.6	2810.3	2967.8	3131.5
(100)	h			2776.3	2875.2	2974.2	3074.2	3278.1	3488.0
	s			7.828	7.827	8.027	8.209	8.538	8.828
	v			1.285	1.143	1.601	1.757	2.067	2.376
1.5	u			2579.8	2656.2	2732.5	2809.5	2967.3	3131.2
(111.4)	h			2772.6	2872.9	2972.7	3073.1	3277.4	3487.6
	s			7.419	7.643	7.844	8.027	8.356	8.647
	v			0.960	1.080	1.199	1.316	1.549	1.781
2.0	u			2576.9	2654.4	2731.2	2808.6	2966.7	3130.8
(120.2)	h			2768.8	2870.5	2971.0	3071.8	3276.6	3487.1
	s			7.279	7.507	7.709	7.893	8.222	8.513

↓p (bar) (t_s)	t (°C) →	50	100	150	200	250	300	400	500
	v			0.764	0.862	0.957	1.052	1.238	1.424
2.5	u			2574.7	2655.7	2734.9	2813.8	2973.9	3139.6
(127.4)	h			2764.5	2868.0	2969.6	3070.9	3275.9	3486.5
	s			7.169	7.401	7.604	7.789	8.119	8.410
	v			0.634	0.716	0.796	0.875	1.031	1.187
3.0	u			2570.8	2650.7	2728.7	2806.7	2965.6	3130.0
(133.5)	h			2761.0	2865.6	2967.6	3069.3	3275.0	3486.1
	s			7.078	7.311	7.517	7.702	8.033	8.325
	v			0.471	0.534	0.595	0.655	0.773	0.889
4.0	u			2564.5	2646.8	2726.1	2804.8	2964.4	3129.2
(143.6)	h			2752.8	2860.5	2964.2	3066.8	3273.4	3484.9
	s			6.930	7.171	7.379	7.566	7.899	8.191

↓p (bar) (t_s)	t (°C) →	200	250	300	350	400	450	500	600
	v	0.425	0.474	0.523	0.570	0.617	0.664	0.711	0.804
5.0	u	2642.9	2723.5	2802.9	2882.6	2963.2	3045.3	3128.4	3299.6
(151.8)	h	2855.4	2960.7	3064.2	3167.7	3271.9	3377.2	3483.9	3701.7
	s	7.059	7.271	7.460	7.633	7.794	7.945	8.087	8.353
	v	0.352	0.394	0.434	0.474	0.514	0.553	0.592	0.670
6.0	u	2638.9	2720.9	2801.0	2881.2	2962.1	3044.2	3127.6	3299.1
(158.8)	h	2850.1	2957.2	3061.6	3165.7	3270.3	3376.0	3482.8	3700.9
	s	6.967	7.182	7.372	7.546	7.708	7.859	8.002	8.267
	v	0.300	0.336	0.371	0.406	0.440	0.473	0.507	0.574
7.0	u	2634.8	2718.2	2799.1	2879.7	2960.9	3043.2	3126.8	3298.5
(165.0)	h	2844.8	2953.6	3059.1	3163.7	3268.7	3374.7	3481.7	3700.2
	s	6.886	7.105	7.298	7.473	7.635	7.787	7.930	8.196
	v	0.261	0.293	0.324	0.354	0.384	0.414	0.443	0.502
8.0	u	2630.6	2715.5	2797.2	2878.2	2959.7	3042.3	3126.0	3297.8
(170.4)	h	2839.3	2950.1	3056.5	3161.7	3267.1	3373.4	3480.6	3699.4
	s	6.816	7.038	7.233	7.409	7.572	7.724	7.867	8.133
	v	0.230	0.260	0.287	0.314	0.341	0.367	0.394	0.446
9.0	u	2626.3	2712.7	2795.2	2876.7	2958.5	3041.3	3125.2	3297.3
(175.4)	h	2833.6	2946.3	3053.8	3159.7	3265.5	3372.1	3479.6	3698.6
	s	6.752	6.979	7.175	7.352	7.516	7.668	7.812	8.078
	v	0.206	0.233	0.258	0.282	0.307	0.330	0.354	0.401
10.0	u	2621.9	2709.9	2793.2	2875.2	2957.3	3040.3	3124.4	3296.8
(179.9)	h	2827.9	2942.6	3051.2	3157.8	3263.9	3370.7	3478.5	3697.9
	s	6.694	6.925	7.123	7.301	7.465	7.618	7.762	8.029

↓p (bar) (t_s)	t (°C) →	200	250	300	350	400	450	500	600
	v	0.132	0.152	0.169	0.187	0.203	0.219	0.235	0.267
15.0	u	2598.8	2695.3	2783.1	2867.6	2951.3	3035.3	3120.3	3293.9
(198.3)	h	2796.8	2923.3	3037.6	3147.5	3255.8	3364.2	3473.1	3694.0
	s	6.455	6.709	6.918	7.102	7.269	7.424	7.570	7.839
	v		0.111	0.125	0.139	0.151	0.163	0.176	0.200
20.0	u		2679.6	2772.6	2859.8	2945.2	3030.5	3116.2	3290.9
(212.4)	h		2902.5	3023.5	3137.0	3247.6	3357.5	3467.6	3690.1
	s		6.545	6.766	6.956	7.127	7.285	7.432	7.702
	v		0.0870	0.0989	0.109	0.120	0.130	0.140	0.159
25	u		2662.6	2761.6	2851.9	2939.1	3025.5	3112.1	3288.0
(223.9)	h		2880.1	3008.8	3126.3	3239.3	3350.8	3462.1	3686.3
	s		6.408	6.644	6.840	7.015	7.175	7.323	7.596
	v		0.0706	0.0811	0.0905	0.0994	0.108	0.116	0.132
30	u		2644.0	2750.1	2843.7	2932.8	3020.4	3108.0	3285.0
(233.8)	h		2855.8	2993.5	3115.3	3230.9	3344.0	3456.5	3682.3
	s		6.287	6.539	6.743	6.921	7.083	7.234	7.509
	v			0.0588	0.0664	0.0734	0.080	0.0864	0.0989
40	u			2725.3	2826.7	2919.9	3010.2	3099.5	3279.1
(250.4)	h			2960.7	3092.5	3213.6	3330.3	3445.3	3674.4
	s			6.362	6.582	6.769	6.936	7.090	7.369
	v			0.0453	0.0519	0.0578	0.0633	0.0686	0.0787
50	u			2698.0	2808.7	2906.6	2999.7	3091.0	3273.0
(263.9)	h			2924.5	3068.4	3195.7	3316.2	3433.8	3666.5
	s			6.208	6.449	6.646	6.819	6.976	7.259
	v			0.0362	0.0422	0.0474	0.0521	0.0567	0.0653
60	u			2667.2	2789.6	2892.9	2988.9	3082.2	3266.9
(275.5)	h			2884.2	3043.0	3177.2	3301.8	3422.2	3658.4
	s			6.067	6.333	6.541	6.719	6.880	7.168
	v			0.0295	0.0352	0.0399	0.0442	0.0481	0.0557
70	u			2632.2	2769.4	2878.6	2978.0	3073.4	3260.7
(285.8)	h			2838.4	3016.0	3158.1	3287.1	3410.3	3650.3
	s			5.931	6.228	6.448	6.633	6.798	7.089

↓p (bar) (t_s)	t (°C) →	350	375	400	450	500	550	600	700
80	v	0.02995	0.03222	0.03432	0.03817	0.04175	0.04516	0.04845	0.05481
(294.9)	h	2987.3	3066.1	3138.3	3272.0	3398.3	3521.0	3642.0	3882.4
	s	6.130	6.254	6.363	6.555	6.724	6.878	7.021	7.281
90	v	0.0258	0.02796	0.02993	0.03350	0.03677	0.03987	0.04285	0.04857
(303.3)	h	2956.6	3041.3	3117.8	3256.6	3386.1	3511.0	3633.7	3876.5
	s	6.036	6.169	6.285	6.484	6.658	6.814	6.959	7.222

↓p (bar) (t_s)	t (°C) →	350	375	400	450	500	550	600	700
100	v	0.02242	0.02453	0.02641	0.02975	0.03279	0.03564	0.03837	0.04358
(311.0)	h	2923.4	3015.4	3096.5	3240.9	3373.7	3500.9	3625.3	3870.5
	s	5.944	6.089	6.212	6.419	6.597	6.756	6.903	7.169
110	v	0.01961	0.02169	0.02351	0.02668	0.02952	0.03217	0.03470	0.03950
(318.0)	h	2887.3	2988.2	3074.3	3224.7	3361.0	3490.7	3616.9	3864.5
	s	5.853	6.011	6.142	6.358	6.540	6.703	6.851	7.120
120	v	0.01721	0.01931	0.02108	0.02412	0.02680	0.02929	0.03164	0.03610
(324.6)	h	2847.7	2958.9	3051.3	3208.2	3348.2	3480.4	3608.3	3858.4
	s	5.760	5.935	6.075	6.300	6.487	6.653	6.804	7.075
130	v	0.01511	0.01725	0.01900	0.02194	0.0245	0.02684	0.02905	0.03322
(330.8)	h	2803.3	2927.9	3027.2	3191.3	3335.2	3469.9	3599.7	3852.3
	s	5.663	5.859	6.009	6.245	6.437	6.606	6.759	7.033
140	v	0.01322	0.01546	0.01722	0.02007	0.02252	0.02474	0.02683	0.03075
(336.6)	h	2752.6	2894.5	3001.9	3174.0	3322.0	3459.3	3591.1	3846.2
	s	5.559	5.782	5.945	6.192	6.390	6.562	6.712	6.994
150	v	0.01145	0.01388	0.01565	0.01845	0.02080	0.02293	0.02491	0.02861
(342.1)	h	2692.4	2858.4	2975.5	3156.2	3308.6	3448.6	3582.3	3840.1
	s	5.442	5.703	5.881	6.140	6.344	6.520	6.679	6.957
160	v	0.00975	0.01245	0.01426	0.01701	0.01930	0.02134	0.02323	0.02674
(347.3)	h	2615.7	2818.9	2947.6	3138.0	3294.9	3437.8	3573.5	3833.9
	s	5.302	5.622	5.188	6.091	6.301	6.480	6.640	6.922
170	v		0.01117	0.01302	0.01575	0.01797	0.01993	0.02174	0.02509
(352.3)	h		2776.8	2918.2	3119.3	3281.1	3426.9	3564.6	3827.7
	s		5.539	5.754	6.042	6.259	6.442	6.604	6.889
180	v		0.00996	0.01190	0.01462	0.01678	0.01868	0.02042	0.02362
(356.9)	h		2727.9	2887.0	3100.1	3267.0	3415.9	3555.6	3821.5
	s		5.448	5.689	5.995	6.218	6.405	6.570	6.858
190	v		0.00881	0.01088	0.01361	0.01572	0.01756	0.01924	0.02231
(361.4)	h		2671.3	2853.8	3080.4	3252.7	3404.7	3546.6	3815.3
	s		5.346	5.622	5.948	6.179	6.369	6.537	6.828
200	v		0.00767	0.00994	0.01269	0.9477	0.01655	0.01818	0.02113
(365.7)	h		2602.5	2818.1	3060.1	3238.2	3393.5	3537.6	3809.0
	s		5.227	5.554	5.902	6.140	6.335	6.505	6.799
210	v		0.00645	0.00907	0.01186	0.01390	0.01564	0.01722	0.02006
(369.8)	h		2511.0	2779.6	3039.3	3223.5	3382.1	3528.4	3802.8
	s		5.075	5.483	5.856	6.103	6.301	6.474	6.772
220	v		0.00482	0.00825	0.01110	0.01312	0.01481	0.01634	0.01909
(373.7)	h		2345.1	2737.6	3017.9	3208.6	3370.6	3519.2	3796.5
	s		4.810	5.407	5.811	6.066	6.269	6.444	6.745

TABLE IV

Supercritical Steam

p(bar)	*t (°C)* →	*350*	*375*	*400*	*425*	*450*	*500*	*600*	*700*	*800*
230	*v*	0.00162	0.00221	0.00748	0.00915	0.01040	0.01239	0.01554	0.01821	0.02063
	h	1632.8	1912.2	2691.2	2869.2	2995.8	3193.4	3510.0	3790.2	4056.2
	s	3.137	4.137	5.327	5.587	5.765	6.030	6.415	6.719	6.980
250	*v*	0.00160	0.00197	0.00600	0.00788	0.00916	0.01112	0.01414	0.01665	0.01891
	h	1623.5	1848.0	2580.2	2806.3	2949.7	3162.4	3491.4	3775.5	4047.1
	s	3.680	4.032	5.142	5.472	5.674	5.959	6.360	6.671	6.934
300	*v*	0.00155	0.00179	0.00279	0.00530	0.00673	0.00868	0.01145	0.01366	0.01562
	h	1608.5	1791.5	2151.1	2614.2	2821.4	3081.1	3443.9	3745.6	4024.2
	s	3.643	3.930	4.473	5.150	5.442	5.790	6.233	6.561	6.833
350	*v*	0.00152	0.00110	0.00210	0.00343	0.00496	0.00693	0.00953	0.01153	0.01328
	h	1597.1	1762.4	1987.6	2373.4	2672.4	2994.4	3395.5	3713.5	4001.5
	s	3.612	3.872	4.213	4.775	5.196	5.628	6.118	6.463	6.745
400	*v*	0.00149	0.00164	0.00191	0.00253	0.00369	0.00562	0.00809	0.00994	0.01152
	h	1588.3	1742.8	1930.9	2198.1	2512.8	2903.3	3346.4	3681.2	3978.7
	s	3.586	3.829	4.113	4.503	4.946	5.470	6.011	6.375	6.666
500	*v*	0.00144	0.00156	0.00173	0.00201	0.00249	0.00389	0.00611	0.00773	0.00908
	h	1575.3	1716.6	1874.6	2060.0	2284.0	2720.1	3247.6	3616.8	3933.6
	s	3.542	3.764	4.003	4.273	4.588	5.173	5.818	6.219	6.529
600	*v*	0.00140	0.00150	0.00163	0.00182	0.00209	0.00296	0.00483	0.00627	0.00746
	h	1566.4	1699.5	1843.4	2001.7	2179.0	2567.9	3151.2	3553.5	3889.1
	s	3.505	3.764	3.932	4.163	4.412	4.932	5.645	6.082	6.411
700	*v*	0.00137	0.00146	0.00157	0.00171	0.00189	0.00247	0.00398	0.00526	0.00632
	h	1560.4	1687.7	1822.8	1967.2	2122.7	2463.2	3061.7	3492.4	3845.7
	s	3.473	3.673	3.877	4.088	4.307	4.762	5.492	5.961	6.307
800	*v*	0.00135	0.00142	0.00152	0.00163	0.00177	0.00219	0.00339	0.00452	0.00548
	h	1556.4	1679.4	1808.3	1943.9	2086.9	2394.0	2982.7	3434.6	3803.8
	s	3.444	3.638	3.833	4.031	4.232	4.642	5.360	5.851	6.213
900	*v*	0.00133	0.00139	0.00147	0.00157	0.00169	0.00201	0.00297	0.00397	0.00484
	h	1553.9	1673.4	1797.7	1927.2	2062.0	2346.7	2915.6	3381.1	3763.8
	s	3.419	3.607	3.795	3.984	4.174	4.554	5.247	5.753	6.128
1000	*v*	0.01308	0.00137	0.00144	0.00152	0.00163	0.00189	0.00267	0.00355	0.00434
	h	1552.7	1669.4	1790.0	1914.8	2043.8	2312.8	2859.8	3332.3	3726.1
	s	3.396	3.579	3.762	3.944	4.126	4.485	5.151	5.664	6.050

TABLE V

Conversion Factors

Force

1 newton	=	1 kg-m/sec^2
	=	0.012 kgf
1 kgf	=	9.81 N

Pressure

1 bar	=	750.06 mm Hg
	=	0.9869 atm
	=	10^5 N/m^2
	=	10^3 kg/m-sec^2
1 N/m^2	=	1 pascal
	=	10^{-5} bar
	=	10^{-2} kg/m-sec^2
1 atm	=	760 mm Hg
	=	1.03 kgf/cm^2 = 1.01325 bar
	=	1.01325×10^5 N/m^2

Work, Energy or Heat

1 joule	=	1 newton metre
	=	1 watt-sec
	=	2.7778×10^{-7} kWh
	=	0.239 cal
	=	0.239×10^{-3} kcal
1 cal	=	4.184 joule
	=	1.1622×10^{-6} kWh
1 kcal	=	4.184×10^3 joule
	=	427 kgfm
	=	1.1622×10^{-3} kWh
1 kWh	=	8.6×10^5 cal
	=	860 kcal
	=	3.6×10^6 joule
1 kgfm	=	$\left(\frac{1}{427}\right)$ kcal = 9.81 joules

Power

1 watt	=	1 joule/sec = 0.86 kcal/h
1 h.p.	=	75 mkgf/sec = 0.1757 kcal/sec
	=	735.3 watt
1 kW	=	1000 watts
	=	860 kcal/h

Specific heat

1 kcal/kg K	=	4.18 kJ/kg K

Thermal conductivity

1 watt/m-K	=	0.8598 kcal/h-m°C
1 kcal/h-m °C	=	1.16123 watt/m-K
	=	1.16123 joules/s-m-K

Heat transfer co-efficient

1 watt/m^2-K	=	0.86 kcal/m^2-h°C
1 kcal/m^2-h °C	=	1.163 watt/m^2-K

IMPORTANT ENGINEERING CONSTANTS AND EXPRESSIONS IN SI UNITS

S.No.	*Engineering constants and expressions*	*M.K.S. system*	*S.I. units*
1.	Value of g_0	9.81 kg-m/kgf-sec^2	1 kg-m/N-sec^2
2.	Universal gas constant	848 kgf-m/kg mole	848 × 9.81 = 8314 J/kg-mole K ($\because$ 1 kgf-m = 9.81 joules)
3.	Gas constant (R)	29.27 kgf m/kg K for air	$\frac{8314}{29}$ = 287 joules/kg-K for air
4.	Specific heats (for air)	c_v = 0.17 kcal/kg K c_p = 0.24 kcal/kg K	c_v = 0.17 × 4.184 = 0.71128 kJ/kg-K c_p = 0.24 × 4.184 = 1 kJ/kg-K
5.	Flow through nozzle-exit velocity (C_2)	91.5 √U where U is in kcal	44.7 √U where U is in kJ
6.	Refrigeration 1 ton	= 50 kcal/min	= 210 kJ/min
7.	**Heat transfer** The Stefan Boltzmann Law is given by :	$Q = \sigma T^4$ kcal/m^2-h when $\sigma = 4.9 \times 10^{-8}$ kcal/h-m^2 K^4	$Q = \sigma T^4$ watts/m^2-h when $\sigma = 5.67 \times 10^{-8}$ W/m^2K^4

POWER PLANT ENGINEERING

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This book on **"Power Plant Engineering"** has been written to meet exhaustively the requirements of various syllabi of this subject for courses B.E., B.Tech, B.Sc. (Engg.) of various Indian Technical Universities. It is equally suitable for U.P.S.C. (Engg. Services) and section B–A.M.I.E. (India) Examinations. The book contains 14 chapters in all and *"Objective Type Question Bank"* at the end.

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