1

Sources of Energy

1.1 Power

Power plays a great role wherever man lives and works—in industry, agriculture transportation etc. Power provides our homes with light and heat. The living standard and prosperity of a nation vary directly with increase in use of power.

As technology is advancing the consumption of power is steadily rising. 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 burning one kilogram of uranium is equivalent to the energy obtained by burning 4500 tonnes of high grade coal. In our country the total generating capacity at the beginning of first five year plan was 2.3 million kW. This capacity was raised to 3.4 million kW by the end of first five year plan, 5.6 million kW by end of second plant and 10.5 million kW by the end of third plan. In 1969-70 it was 15.5 million kW. During the fourth and fifth plan the generating capacity targets are of the order of 20 million kW and 40 million kW respectively. In our country the natural resources are found in coal lignite, oil, hydro sources and nuclear fuels. These resources should be exploited in the most efficient form by using improved technology so that power at cheaper rates becomes available, which will help to accelerate the growth of industry. It is found that these resources are located in an uneven form in the country which requires interlinking the grid system of adjoining states so that power generation by hydro, thermal and nuclear plants could be well co-ordinated. This will ensure a constant supply of power to all consumers throughout the country. In northern part of the country hydro power is the main source available whereas in Madhya Pradesh and Eastern Maharashtra coal and hydro sources are available. But in Gujarat and Western Maharashtra practically no resources are available. Therefore, power should be generated either by nuclear power

plants or by thermal power plants depending upon the relative economics. Mysore and Kerala have abundant hydro resources. Andhra Pradesh has got both hydro and coal resources and Tamil Nadu depends upon the thermal power at Neyveli. West Bengal, Southern Bihar and Orissa have abundant coal resources and, therefore, power generation by thermal power stations is cheaper. Solar energy in India has an ideal geographical situations. The northern and central parts of the country receive bright sunshine on an average for more than eight hours daily. This amounts to heat equivalent to more than 200 MW per square kilometre. This shows that there is an enormous potential for developing solar thermal power plants.

Thermal power production in India costs more than nuclear power after the recent rise in oil prices. So far as nuclear power is concerned India is fairly well endowed organisationally as well as resourcewise. The resources are available in large quantities in the form of Uranium and Thorium. Uranium deposits have been located in Bihar, Rajasthan and Tamil Nadu and thorium reserves have been found in Monazite beach sands of Kerala and in Ranchi. Assuming effective prevention of radioactive hazards it is a clean source of power which does not contributed to air pollution. Thus it is observed that in our country different power resources are available in different states and, therefore, in order to ensure constant supply to all the consumers throughout the year interlinking of various power plants in essential so that spare capacity of one power station can be utilized by the other. With this objective in view programme for integrated power generation on regional basis by interlinking the power stations of adjoining states has started working and successful functioning of regional grids may finally give way to *National Grid* system. Five regions already have interconnected power systems. The northern power grid system covers U.P., Punjab, Haryana, Bhakra Management Board (BMB). Jammu, DESU, Rajasthan and M.P. Systems with a capacity of 5504 MW. The construction of Badarpur Jaipur 220 kV line which will connect the Badarpur. DESU, BMB system with the Rajasthan system is being completed. Completion of this line will further stabilise interconnected working in the northern region. The southern region Orissa grid covers Andhra Pradesh, Kerala, Karnataka, Tamil Nadu and Orissa systems with 5525 MW capacity. The Western grid covers Maharashtra, Gujarat and Tarapur systems with 3865 MW capacity. Eastern grid covers West Bengal, Bihar, and DVC systems with 3200 MW capacity. Assam, Meghalaya and Tripura with an installed capacity of 178 MW are inter connected. An adequate grid system has the following advantages :

1. It enables the base load to be supplied by the most economical power stations and peak demand to be supplied by more expensive power stations.
2. It provides security against all normal operating hazards with a smaller margin of spare capacity thereby saving on overall capital expenditure.

Planning for power generation, capacity addition and power systems should be based on the assumption that the power systems in each region will operate in close integration and power will be exchanged between systems confirming to well established standards which will lead to optional operation of the integrated systems, the ultimate objective being formation of national power grid.

Following factors can help in improving the generation of electric power :

(*i*) To improve power plant load factor.
(*ii*) To lay stress on conservation of energy.
(*iii*) To give due importance to renewable sources of energy.
(*iv*) To improve coal supply to power plants.
(*v*) To establish more gas based power plants.
(*vi*) To promote the private agencies to produce electric power.
(*vi*) To reduce power transmission losses.
(*viii*) To use an efficient control and operation of power plants.

1.2 Source of Energy

The various sources of energy are as follows :

1. **Fuels.** The fuels are broadly classified as follows :

(*i*) *Solid fuels.* Various solid fuels used are wood, coal including bituminous coal, anthracite, lignite, peat, etc.

(*ii*) *Liquid fuels.* Liquid fuels include petroleum and its derivatives.

(*iii*) *Gaseous fuels.* Gaseous fuels consist of natural gas, producer gas, blast furnace gas, coal gas etc.

2. **Energy Stored in Water.** The potential energy of water at higher level is utilized for the generation of electrical energy.

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 but their operating costs are quite low.

3. **Nuclear Energy.** Controlled fission of heavier unstable atoms such as U^{235}, Th^{232} and artificial elements Pu^{239} liberate large amount of heat energy. This enormous release of energy from a relatively small mass of nuclear fuels makes this source of energy of great interest. The energy released by the complete fission of one

kilogram of U^{235} is equal to the heat energy obtained by burning 4500 tonnes of high grade coal. However, there are some difficulties in the use of nuclear energy namely high capital cost of nuclear power plants, limited availability of raw materials difficulties associated with disposal of radioactive wastes and dearth of well-trained personnel to handle the nuclear power plants.

Nuclear power can cater to the future needs of energy. Three stages of Indian nuclear power programme are as follows :

(*i*) natural uranium fuelled pressurised heavy water reactors.
(*ii*) fast breeder reactors utilising plutonium based fuel.
(*iii*) advanced nuclear power systems for utilisation of thorium.

4. **Wind Power.** Wind power can be made use of where wind at suitable velocity is available. Wind power is capable of generating small amounts of electrical energy. It is successfully employed for pumping water from deep wells. Wind power has served many countries as a source of power in early days and were called as wind mills. The propulsive power of wind can be used to drive multi-bladed turbine wheel. Wind turbines prove to be costly if designed to run at all wind speeds. They usually start running at wind speeds just enough to overcome the system losses and develop full power at the prevailing speed for the locality. Wind is the cheapest source of power.

Wind energy is a renewable source of energy. The wind power systems are non-polluting. However wind energy is noisy in operation and large area is required to install wind mills. Wind energy is weak and fluctuating in nature.

In India, wind velocity along coast line has a range of 10-16 km ph and a survey of wind power has revealed that wind power can be used to pump water from deep wells or for generating electric energy in smaller amount. Modern wind mills are capable of working on velocities as low as 3-7 kmph velocity while maximum efficiency is attained at a velocity ranging between 10-12 kmph.

5. **Solar Energy.** The heat energy contained in the rays of sun is utilised to boil water and generate steam which can be used to drive prime movers to generate electrical energy.

The facts speak in favour of solar energy. The world's reserves of coal, oil and gas will get exhausted with in a few decades. Atomic energy involves considerable hazards and nuclear fusion has not yet overcome all the problems of even fundamental research. Compared with these technologies the feasibility of which is still uncertain and contested, the technical utilisation of solar energy can prove very useful. Utilisation of solar energy is of great importance to India since it lies in a temperature climate of the region of the world where

sunlight is abundant for a major part of the year. The basic research in solar energy is being carried out in universities and educational and research institutions. Public sector institutions like Bharat Heavy Electricals Limited and Central Electronics Limited are carrying out a co-ordinated programme of research in solar energy. Some of the fields in which solar energy can be used are as follows:

(*i*) Solar power plants used for electric power generation.
(*ii*) Solar water pumps used for pumping water.
(*iii*) Solar water heaters used for water heating.
(*iv*) Solar cabinet type driers for drying of food grains.
(*v*) Solar kilns for drying wood etc.

Solar energy is effective, only during day time and if power supply is to be made during night also then some reservoir of energy such as storage battery or heat accumulator should be used. Solar energy cannot be used during cloudy weather and rainy season. If solar energy is used efficiently there would be enough power to meet the increasing power demand for several years to come. At present harnessing, storage and use of solar energy is much more expensive than using fossil fuel (coal oil, gas etc.). It is believed that solar power can become economically feasible with the following aims achieved :

1. Availability of better heat collectors.
2. Availability of improved materials and manufacturing techniques.
3. Better techniques for storage and cheap distribution of solar power.

While the energy crisis is mounting, any co-operation to find alternative sources of energy is certainly laudable. India has the potentialities of solar and wind energy. What it needs is the advanced technology to tap this potential.

Solar heat must cost less than conventional (oil based) heat in order to be economically feasible. When comparing both generating methods, it is important whether the solar plant operates in a monovalent, *i.e.*, as the only heat supplier, in a bivalent mode as a fuel saver, connected to a conventional plant. In the first case, the investment costs for the saved (oil) boiler should also be taken into account. In both cases, the fossil fuel—oil, gas, coal, wood, etc. — prices should be considered not only at their present level but also with regard to future price increases due to inflation and other factors.

Perhaps the great advantage of solar power is that the system is ideally suited to the human environment being free from pollution and noise. Besides, maintenance is cheap and convenient. Of all the non-conventional energy sources, solar power is much cheaper for cooking, street lighting and water heating.

6. **Tidal Power.** Ocean waves and tides contain large amount of energy. Such tides rise and fall and water can be stored during rise period and it can be discharged during fall. Due to low head of water available low head hydroelectric plants can work successfully Fig. 1.1 shows the schematic layout of a power plant using tidal power. These plants can utilise a head of just a few metres. During high tide the height of tide is above that of tidal basin and the turbine unit operates and generates power. During low tide the height of tide is lower than that of the tidal basin. At this time water is allowed to flow out to drive the turbine unit. The turbine unit does not operate if the tide sea level and basin level are equal.

In India the possible sites, identified for tidal power plants are as follows :

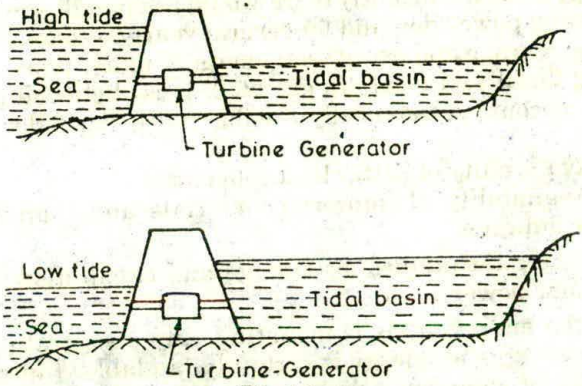


Fig. 1.1.

(*i*) Gulf of Cambay
(*ii*) Gulf of Kutch
(*iii*) Sunderban area in West Bengal.

The tidal range in the Gulf of Cambay is about 10.8 metre. Whereas the maximum range in Gulf of Kutch is 7.5 metre. The tidal range in Sunderban area is 4.3 metre.

Advantages. The various advantages of tidal power plants are as follows :

(*i*) The power generated does not depend on rain. Therefore there is certainty of power supply as the tidal cycle is very definite.
(*ii*) The tidal power plants are free from pollution.
(*iii*) Unhealthy wastes like ash, gases etc. are not produced.
(*iv*) These plants require lesser space.
(*v*) Such plants have a unique capacity to meet the peak power demand effectively when they work in combination with hydro power plants and steam power plants.

Disadvantages. The various disadvantages of tidal power plants are as follows :

(*i*) The capital cost of a tidal power plant (nearly Rs. 5000 per kW) is considerably large as compared to steam power plant and hydro power plant.

(*ii*) The supply of power is not continuous as it depends upon the timing of tides.

(*iii*) Tidal power plants are located away from load centres. This increases power transportation cost.

7. **Geothermal Energy.** According to various theories the earth has a molten core. The fact that volcanic action takes place in many places on the surface of earth supports these theories. The steam vents and hot springs come out of earth's surface. The steam from such natural steam wells is used for the generation of power. Fig. 1.2 shows schematic layout of power plant using steam from steam wells. Steam drum separates moisture and solids from steam.

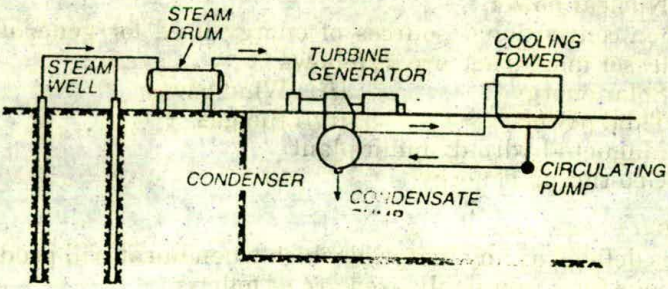


Fig. 1.2

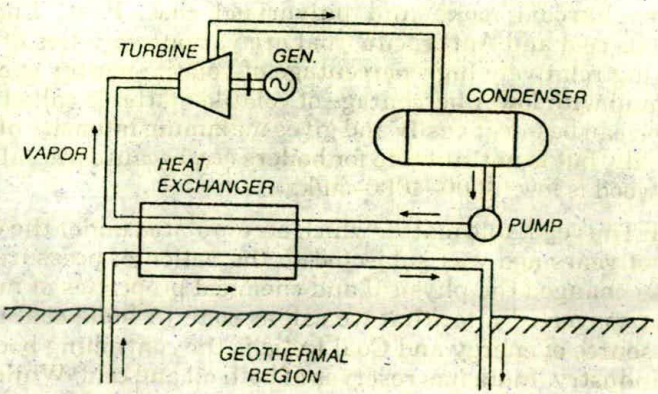


Fig. 1.2 (A)

The hot water closed (Binary) system shown in Fig. 1.2 (A) is also used where temperature and pressure of water are not sufficient to produce flash steam. In this system heat in water is used in a closed cycle. In this system Freon or Iso butane is used as working fluid which is continuously circulated. This system has the advantage that lower hot water temperature can be used. Such system is under development in USA and USSR.

8. **Thermo-electric Plant.** When the two junctions of a loop of two dissimilar metals are kept at different temperatures, an electromotive force is developed and current starts flowing in the loop. This is known as Seebeck effect. By using suitable materials this method can be used for the generation of electrical energy in small amounts.

1.2.1. Conventional and Non-conventional sources of energy. The sources of energy used for mass generation of power called conventional sources of energy are as follows :

(*i*) Thermal (*ii*) Hydro-power
(*iii*) Nuclear power.

The non-conventional sources of energy used for generating power in lesser magnitude are as follows :

(*i*) Solar energy (*ii*) Wind power
(*iii*) Tidal power (*iv*) Bio-gas
(*v*) Magneto-hydro-dynamic plant
(*vi*) Geo-thermal energy.

1.3 Fuels

Fuel is defined as any material which when burnt will produce heat. Various fuels commonly used are as follows :

1.3.1. Solid Fuels. Natural solid fuels include wood, peat, lignite, bituminous coal and anthracite coal. The prepared solid fuels are charcoal, coke and pulverised coal, Peat, Lignite, Bituminous coal and Anthracite, coal are various varieties of coal. Coal having relatively high percentage of volatile matter is called soft coal and with lower percentage of volatile matter is called hard coal. Wood can be burnt easily and gives maximum intensity of heat very quickly, but is not suitable for boilers etc. because the calorific value of wood is low (3000–4000 cal/kg).

Coal. The vegetable matter which accumulated under the earth millions of years ago was subjected to the action of pressure and heat. This changed the physical and chemical properties of matter and it got converted into what we call as coal. In India coal is the primary source of energy and Coal India is the controlling body for the coal industry. India has reserves of both oil and coal. While coal reserves in the country are sufficient to last for some hundreds of years, oil represents only a fraction of total coal reserves. The power

sector consumes nearly 37% of total coal produced and the remaining being used in industries like steel, fertilizers, cement, railways etc. The coal bearing strata of India have been classified by geologists into the following two main groups :

(*i*) Gondwana coal fields (*ii*) Tertiary coal fields

Most of Gondwana coals are bituminous and sub-bituminous in quality. Gondwana coal fields are situated at Bengal, Bihar, M.P., Orissa, Andhra Pradesh and Maharashtra. Tertiary coal fields are situated at Madras, Assam, Kashmir and Rajasthan. Tertiary coals are mostly lignite. Lignite is available in large quantities at Neyveli in Madras. The coal reserves largely of bituminous rank of our country are estimated to be about 112×10^3 Mt in coal seams of thickness 0.5 m and above and up to a depth of 1200 m.

Indian coals are generally characterised by high ash content and difficult cleaning characteristics. The coals however have a very low sulphur contents. The Indian coal resources constitute only about 0.8% of total coal reserves of the world India ranking tenth on this basis. The occurrence of coal in our country is mainly confined to one quadrant. On the eastern and south eastern parts thus necessitating long transport haul distances in northern, western and southern parts of the country.

1.4 Calorific Value of Fuel

The basic thermal characteristic of a fuel is its calorific value (heating value). The calorific value of fuel is defined as the amount of heat produced when unit quantity (one kilogram of solid or liquid fuel or one cubic metre of gaseous fuel) of fuel is completely burnt under standard conditions. The calorific value is expressed as kcal per kg or kcal, per cubic metre of gaseous fuel. The calorific value of a fual can be classified in two ways :

(*i*) Higher calorific value (H.C.V.)

(*ii*) Lower calorific value (L.C.V.)

The higher or gross of calorific value is the total amount of heat produced when unit quantity of fuel is burnt completely and the products of combustion have been cooled to room temperature generally 15°C. The lower calorific value is the net amount of heat produced when unit quantity of fuel is completely burnt and the products of combustion are not cooled to room temperature but are allowed to escape. There are several methods of finding calorific value of a fuel. According to Dulong formula the calorific value of a fuel is given by the following relation :

$$\text{H.C.V.} = \frac{1}{100}\left[8080\text{C} + 34{,}500\left(\text{H} - \frac{\text{O}}{8}\right) + 2220\,\text{S}\right] \text{ kcal/kg}$$

where C.H.O. and S. represent the percentage by weight of carbon, hydrogen, oxygen and sulphur respectively.

The net or lower calorific value (L.C.V.) is obtained by subtracting from H.C.V. the heat carried by the products of combustion especially by steam which can be taken as 588.76 kcal/kg of water vapours formed due to burning of 1 kg of fuel.

$$\therefore \quad \text{L.C.V.} = (\text{H.C.V.} - 588.76 \times W) \text{ kcal/kg.}$$

where W is the amount of water vapours formed by the combustion of 1 kg of fuel.

The higher calorific value at N.T.P. of various constituents of fuels are as follows : C = 8080 kcal/kg, S = 2220 kcal/kg,

H_2 = 34,500 kcal/kg and CO = 2430 kcal/kg.

1.5 To Calculate Approximate Flue Gas Loss

Percentage of net calorific value (Btu) lost in flue gas

$$= K_1 \times \frac{(T_1 - T_2)}{CO_2}$$

where K_1 = constant = 0.35 for Bituminous coal

= 0.37 for Anthracite coal = 0.39 for Coke

= 0.31 for Oil

T_1 = Temperature of exit gases °F

T_2 = Temperature of inlet air °F

CO_2 = percentage of CO_2 in exit gases at point where temperature T_1 is measured.

The value of constant K_1 becomes as follows if centigrade scale used

K_1 = 0.63 for Bituminous coal

= 0.68 for Anthracite coal = 0.70 for Coke

= 0.56 for Oil.

1.6 Types of Coal

1. **Peat.** It consists of decayed vegetable matter mainly decomposed water plants and mosses etc. It has high moisture content and should be dried before burning. Its approximate composition is :

C = 60%, H = 58%, O = 33%, Ash = 1.2%.

Its calorific value is 3500 kcal/kg.

2. **Lignite or Brown Coal.** It is brown in colour, it burns with a brightly slightly, smoky yellow flame. Its calorific value is 5000 kcal/kg and its approximate composition is C = 67%, H = 5%, O = 20% and Ash = 8%.

Neyveli in Tamil Nadu is the only major lignite mine in India producing about 6 Mt. of coal. Developed as a complete project lignite mined at Neyveli is used primarily for power generation. Some lignite is also used for production of fertilizers and briquettes. Briquette fuel is used by domestic and industrial consumers.

3. **Bituminous Coal.** It is soft, consists of large amount of volatile matter and is widely used as fuel. It burns with a long yellow and smoky flame. Its calorific value is 7800 kcal/kg and approximate composition is

C = 83.5%, H = 5%, O = 5%, Ash = 6.5%.

4. **Sub-bituminous Coal.** Sub-bituminous coal contains 12 to 25% moisture. It is of black-colour and the approximate calorific value of this coal is 4600 kcal/kg.

5. **Anthracite Coal.** It is black in colour and burns with a short bluish flame and the amount of ash produced due to its burning is very little. Its calorific value is 8500 kcal/kg and approximate composition is as follows :

C = 90%, O = 2%, H = 3% and Ash = 5%.

Indian coals are known to be low in sulphur (0.3–0.9%) and high in ash content (30–50%). The average value of calorific value varies between 4000–5000 kcal/kg. Table 1.1 (A) indicates the typical analysis of Indian coal (average).

Table 1.1 (A)

Content	*Percentage (%)*
Carbon	21– 50
Hydrogen	2.3—3.5
Nitrogen	0.7- -1.4
Sulphur	0.3-—0.9
Ash	30—50
Oxygen	1.7—11
Volatile	15—26
Moisture	7—20

Composition and properties of lignite found at Neyveli are indicated in Table 1.1(B) on

(*i*) air dried basis

(*ii*) d.m.m.f. (Dry mineral matter free) basis.

Table 1.1(B)
Proximate Analysis

%Air-dried			%d.m.m.f.		
Moisture	*Ash*	*Volatile matter*	*Fixed carbon*	*Volatile matter*	*Fixed carbon*
10-30	3.5-7.5	40-45	30-35	52-60	40-48
Ultimate Analysis (% d.m.m.f.)					
	Carbon	*Hydrogen*	*Oxygen*	*Nitrogen*	*Sulphur*
	70-73	4.6-5.5	22-26	0.6-1.0	0.6-1.5
Calorific Value, kcal/kg					
		Air-dried		*d.m.m.f.*	
Neyveli		4,000-5,500		6,500-6,600	

A typical composition of various types of coals is given in Table 1.1 (C).

Table 1.1 (C)

Fuels	*Proximate Analysis, %*				*Ultimate Analysis, %*						*Calorific value kcal/kg*	
	Moisture	*Volatile matter*	*Fixed carbon*	*Ash*	*C*	H_2	O_2	N_2	*S*	*Ash*	*As reported*	*Dry basis*
Peat	57	26	11	6	23	10	59	1.5	0.5	6	2000	4600
Lignite	35	28	31	6	42	7	43	1	1	6	4000	6000
Bituminous Coal												
Low volatile	3.5	16	72	8.5	79.5	4.5	4.5	1.5	1	9	7600	7900
Medium volatile	3	24	62	11	77	5	5	1.5	0.5	11	7500	7700
High volatile	8	36	49	7	68.5	5.5	16.5	1.5	1	7	6750	7400
Sub-bituminous	19	31	46	4	59	6	29.5	1	0.5	4	5600	7000
Semi-anthracite	3	8.5	79	9.5	80	3.5	4.5	1.5	0.5	10	7500	7700
Anthracite	2.5	3	87.5	7	86.5	2.5	3	0.5	0.5	7	7500	7700

1.7 Liquid Fuels

Liquid fuels include petroleum and its derivatives. Fractional distillation of crude petroleum helps in separating it into its various varieties such as gasoline, kerosene oil gas light diesel fuels and residual oil. During distillation of petroleum, gasoline is obtained

between the range of 30 – 200°C whereas kerosene oil is obtained between the range of 150 – 300°C and diesel oil is obtained between 200 – 320°C. The calorific value of the gasoline is 11,250 kcal/kg and that of kerosene.oil is 11,100 kcal/kg. The calorific values of diesel oil and fuel oil are 11,000 and 10,350 kcal/kg respectively.

The general index of classification of fuel oil is the specific gravity of the oil. The specific gravity of fuel compared with water at 60°F is expressed in the degrees API (American Petroleum Institute) and can be found by the use of the following formula :

$$\text{Degrees API} = \frac{141.5}{\text{Specific gravity at } \frac{60^\circ F}{60^\circ F}} - 131.5$$

Specific gravity in API helps is finding the calorific value of fuel using the following relation :

Btu/lb of oil = 17687 + 57.7 (API gravity at 60°F).

The API gravity of commercial fuel oil varies from 10 to 40. Liquid fuels are commercially classified as light, medium and heavy domestic oil and as light, medium and heavy industrial oils. API value of light and heavy domestic oils varies between 38–40 and 34–32 respectively whereas API value of heavy industrial oil is between 14–16.

While burning fuel or oil it is desirable that it should be finely atomised to ensure mixing of oil and air. To facilitate pumping and for correct atomisation of fuel oil it is essential that viscosity of oil should be lowered. This is achieved by providing heating coils in the oil storage tank to maintain temperature of about 40 – 50 °C. The oil leaving the storage tank is passed through another heater before it enters the burner.

Commercial gasoline (petrol) and diesel oil are mixtures of various hydrocarbons. The average properties of these fuels are as follows :

Property	*Gasoline*	*Diesel*
(*i*) A.P.I. gravity at 15°C	57	34
(*ii*) Specific gravity	0.76	0.85
(*iii*) Viscosity (CS) at 10°C	0.72	4.5
at 40°C	0.55	2.4
(*iv*) Cetane number	18	45 to 55
(*v*) Composition %		
(*a*) Paraffins and Napthenes	51.5	65
(*b*) Olefins	30.5	7
(*c*) Aromatics	18	17

1.7.1 Oil Properties. Petroleum or any of its derivatives is usually analysed on the basis of the following properties :

(*i*) Calorific value (*ii*) Viscosity
(*iii*) Specific heat (*iv*) Specific gravity
(*v*) Flash point.

It is the temperature at which oil vapour flashes or burns steadily.

(*vi*) Pour point.

It is the lowest temperature at which oil flows.

(*vii*) Coefficient of volumetric expansion.
(*viii*) Carbon residue.
(*ix*) moisture and sediment.
(*x*) Sulphur content.

1.8 Advantages of Liquid Fuels over Solid Fuels

1. Handling of liquid fuels is easy and they require less storage space.
2. Liquid fuels can be fired easily and the maximum temperature is attained in lesser time as compared to solid fuels. The solid fuels containing higher percentage of moisture burn with great difficulty.
3. The solid fuels leave a large quantity of ash after burning and the disposal of ash becomes a problem. Whereas the liquid fuels leave very little ash after burning.
4. In case of liquid fuels the continuous firing the furnace is achieved without any difficulty.
5. The combustion of liquid fuels is uniform.
6. The combustion of liquid fuels can be easily controlled.

Therefore, the change in load, can be easily met.

The disadvantages of liquid fuels are as follows :

(*i*) They are costly as compared to solid fuels.
(*ii*) They require special type of burners for their burning.
(*iii*) Sometimes they give unpleasant odours.
(*iv*) There is danger of explosions.
(*v*) In cold climates the oil stored in tanks is to be heated in order to avoid stoppage of oil flow.

1.9 Gaseous Fuels

The gaseous fuels can be classified as follows :

(*i*) Natural - Natural gas.
(*ii*) Prepared - coal gas, blast furnance gas, producer gas, water gas etc.

(*a*) **Natural Gas.** Natural gas comes out of gas wells and petroleum wells. It is mainly composed of methane (CH_4) = 85%, ethane (C_2H_6) = 10% and other hydrocarbons = 5%. It is colourless

and non poisonous. The calorific value of natural gas is 525 kcal/cubic metre.

(*b*) **Blast Furnace Gas.** This gas is obtained as a by-product from blast furnace used for producing pig iron. Its approximate composition is CO = 30%, N_2 = 52%, H_2 = 3%, CO_2 = 2%, CH_4 = 3%.

The calorific value of this gas is 970 kcal/cubic metre.

(*c*) **Coal Gas.** Coal gas is a by-product obtained during the destructive distillation of coal. Its calorific value is 7600 kcal/cu metre. Its approximate composition is CH_4 = 35%, H = 45%, CO = 8%, N = 6%, CO_2 = 2% and other hydrocarbons = 4%.

(*d*) **Producer Gas.** Producer gas is produced during incomplete combustion of coke in current of air. Its main constituents are nitrogen and carbon monoxide. Its approximate composition is N = 62%, CO = 23%, H_2 = 6%, CO_2 = 5%, CH_4 = 4%. Its calorific value is 1200 kcal/cu metre.

(*e*) **Water Gas.** Water gas is obtained by passing a blast of steam through a deep bed of red hot coke. Its main constituents are CO_2, CO and H_2.

1.10 Advantages of Gaseous Fuels over Solid Fuels

1. It is easy to control the length and nature of flame and hence temperature control is easier.
2. Gaseous fuels do not contain ash and other foreign matter and burn completely. Their use is economical as compared to solid and liquid fuels. No ash removal is required.
3. Handling of gaseous fuel is not required as they can be easily piped into the furnace.
4. Lesser amount of excess air is needed to burn them completely.
5. Greater cleanliness is assured as the soot and smoke is practically nil. Gas fired burners operate on pressures ranging from 0.15 to 1.5 kg/cm^2.

1.10.1 Composition of Liquid Fuels. The composition by weight of liquid fuels are given in Table 1.2.

Table 1.2

Fuel	*Specific gravity*	*Composition by weight*		
		C	*H*	*S*
Heavy fuel	0.95	86.1	11.8	2.1
Diesel oil	0.87	86.3	12.8	0.9
Paraffin	0.79	86.3	13.6	0.1
Petrol (Gasoline)	0.74	85.4	14.6	—

1.11 Comparison of Sources of Power

The main sources for generating power in India are coal and hydro (water). Nuclear power is also being used successfully. The various sources of power can be compared as follows :

(*i*) The capital cost of a hydro-electric power plant is higher than a steam power plant whereas the operating cost of a steam power plant is more than a hydro power plant. The initial cost of a nuclear power plant is highest and its operating cost can be as low as that of a steam power plant. The cost of erection of a diesel plant is low as compared to cost of erection of steam plant.

(*ii*) Steam power station can be located at the load centre whereas a hydro power plant has to be located where water is available in large quantities. As the performance of a hydro power plant depends upon the availability of water which in turn mainly depends upon the natural phenomenon of rain, therefore, seasonal variations in rainfall greatly affect the power output from a hydropower plant. The nuclear power plants are best suited for areas which are distant from collieries and fuel costs are high. The amount of raw materials required for generating a given quantity of power is the least in a nuclear power plant.

(*iii*) India has the largest thorium reserves in the world. It would help development of nuclear power. The other countries having significant thorium reserves are U.S.A. and Brazil. Although conversion of thorium into uranium 233 a fissionable form of uranium on commercial scale has not been achieved but it is hoped that it would be possible to do so and thus thorium would be successfully used for power generation. This will solve India's power problems to a great extent. The nuclear reactors using thorium-uranium cycle are economical and have longer life. The utilization of thorium in fast breeder reactors is quite successful. The steam power stations depend upon coal which is exhaustible. According to one estimate the coal deposits in India are estimated to be about 40,000 million tonnes excluding lignite, the lignite reserves being nearly 2442 million tonnes. The hydro power plants depend upon water an

inexhaustible source. The water power potential of India is estimated to be the order of 40×10^3 MW.

(*iv*) A hydro-electric power plant can be used for supplying peak load. It can also be used as base load plant and in such case diesel power plant or a steam power plant is used for supplying peak load. Nuclear power plants are used as base load plants because they are economical only when used as such. Diesel power stations are of limited generation capacity and are used for supplying peak loads. The capacity of power plants using gas is also not large.

(*v*) In nuclear power plants the disposal of radio active wastes is a costly problem. In steam power stations there is nuisance of smoke, ash etc. Hydro power plant is the cleanest way of producing power.

(*vi*) A hydro-electric power plant can be easily started from cold conditions as no warming up period is required.

(*vii*) Running cost of a hydro power plant is less than a steam power plant. Running cost of a nuclear power plant is perhaps least of all.

(*viii*) The overall thermal efficiency of a diesel power plant is higher than steam plant.

(*ix*) Hydro power plants are more reliable than steam power plants and usually give some advance indication of loss of power, hence their need be less spinning reserve.

(*x*) It takes about 4 to 8 years for planning and building of hydro electro power plant whereas the time taken in case of nuclear power station is 3-6 years and for steam power station 2-3 years. The hydro power plant has long life whereas average life of nuclear power plant is about 20 years and that of steam power plant about 20-25 years.

1.12 Sources of Energy in India

World wide rising prices of oil since 1973 have put considerable strains on our economy and generated the urgent need to undertake new efforts in research and technology to find new sources of energy. On the other hand, the acceleration of the process of industrialisation and urbanisation following the determined effort of the developing countries like India to improve their economic well being is inevitably leading to larger and larger demands of electrical energy.

The industrialised countries consume nearly 80% of the world's total annual energy generation.

The per capita consumption of energy in India is quite low as compared to U.S.A., Japan and other developed countries.

An American consumes nearly as much energy in a single day as two West Germans, or Australians, three Swedens or Japanese, six Yugoslavs, nine Mexicans or Cubans or 53 Indians.

Even this low demand of energy in our country has not been met and power cuts have become common. Power shortage is mainly due to the three separately identifiable factors as follows :

(*i*) Due to inadequate installed capacity.

(*ii*) Arising from inability to get the best of installed capacity.

(*iii*) Inability to optimise the utilization of the available energy.

To improve electrical energy generation in our country efforts should be made to increase the generation capacities instead of increasing installed capacities. Our present generation ratio at about 52% is one of the lowest in the world. In industrially advanced countries the average generation ranges between 80% to 85% of installed capacity while Austria, West Germany and Switzerland obtain 92%, 90% and 95% respectively.

The common sources of energy in our country are coal, water, oil and gas. Nuclear power is recently being encouraged and has still its teething troubles. Other non-conventional sources like wood, bio-gas, solar, geothermal and tidal are still in experimental stage.

Coal is the most important commercial source of energy in India. Thermal power generation can be most reliable because coal reserves in our country are sufficient to last for some hundreds of years. However the quality of coal produced must be improved. The Indian coal has on an average 18 to 22% ash content as compared to coal available in Europe and U.S.A. which contains ash 8 to 10% whereas coal available in Japan contains ash 6 to 8% Power generated through super thermal power plants constructed near coal pit heads can be more economical.

The second important source of power is water. But hydropower has its shortcomings. Power generation from hydro-power plants mainly depends upon the 'water reserve available' in the storage reservoirs and face unavoidable constraints due to poor monsoon, cyclic drought conditions and necessary withdrawal of water from these reservoirs for irrigation purposes. A judicious combination of both hydro and thermal power is the optimum solution for proper power generation. In India the development of pumped storage plants is likely to assume importance in near future.

A vast hydel potential exists in north-eastern region of our country. The region's hydel potential is estimated to be about 21,000 MW which is nearly 30% of the total hydel potential of the country. Arunachal alone possesses 17,000 MW of hydro-potential out of 21,000 MW of hydel potential of the region.

Himachal Pradesh has vast hydel potential of about 20,000 MW which is nearly one-fifth of our country's potential for generating hydel power.

The reasonably assured uranium reserves in our country are placed at about 34,000 tonnes of uranium oxide of which about 15,000 tonnes are considered to be economically exploitable. The established uranium resources are capable of supporting natural uranium reactors of about 8,000 MW of installed capacity. This shows that the share of nuclear power generation in the total power programme will remain modest. However when the fast breeder reactor technology is fully developed and U-233 cycle used then there will be a large increase in nuclear power as there exist an estimated deposits of about 363,000 tonnes of thorium.

It is expected that in our country by the year 2000 A.D. the installed capacity of nuclear power will be 10,000 MW. India has the world's largest thorium reserves which will prove to be quite economical fuel in fast breeder reactors.

By the end of century the share of nuclear power is expected to increase from 2 to 10 per cent of total production. India at present has five operation nuclear power stations : two at Tarapur (near Bombay) of 210 MWs capacity each, one unit of 220 MW of Kota in Rajasthan and two at Kalpakkam (near Madras) of 235 MWs each.

In addition, two nuclear power stations of 235 MWs capacity each at Narora (UP) and another two of 235 MW each at Kakrapar (Gujarat) are in an advanced stage of construction. Work has commenced at Kaiga in Karnataka Rawabhatt in Rajasthan on twin units of 235 MWe. The second phase programme consists installation of 500 MW capacity fast breeder reactors.

A nuclear power plant of 2000 MW capacity i. two units each of 1000 MW will be installed at Koodankulan in Tamil Nadu. Nuclear power is playing a major role in meeting the increasing electricity needs.

Bulk of power generation however would come from the traditional sources of thermal and hydel.

Energy requirements are primarily met by coal, oil, hydropower, gas and nuclear power. There has been a considerable increase in production of gas. The gas production was nearly 1.4 billion cubic metre in 1970-71 which rose to about 5 billion cubic metre in 1982-83. The main thrust of the nuclear power programme in the sixth plan is to continue with the development of the natural uranium based HWR power plants and pursue of *R* and *D* activities relating to the development of FBR technology. Need for making an urgent and all out scientific efforts to promote the development of

utilisation of solar and other forms of renewable energy to reduce our dependence on fossil fuels (coal, oil, hydro) and to help safeguard environment is essential.

The various aims of research and development (*R* and *D*) activities in the energy sector are as follows :

(*i*) To develop new techniques for the exploration of energy resources.

(*ii*) To develop technologies to maximise energy production and recovery.

(*iii*) Improvement and adaptation of existing technologies with emphasis on conservation.

(*iv*) Development of technologies for harnessing alternative sources of energy.

(*v*) To develop new and more efficient technologies for utilising indigenous onergy resources.

The commission for Additional sources of energy (CASE) under the central Government is responsible for formulating policies and programmes for the development of new and renewable sources of energy.

The department of non-conventional Energy Sources is responsible for activities initiated based on the recommendation of CASE covering areas of bio-gas development, solar energy, wind energy, energy from bio-mass etc.

Our country has embarked on an extremely ambitious programme of oil exploration. Over 30% of the country's total petroleum product consumption is in the from of diesel both in stationary and vehicular engines. The total production of crude oil in our country during 1984-85 is expected to be 29.7 million tonnes against the requirement of about 45 million tonnes.

Natural gas is fast emerging as an attractive substitute for oil and as an important future energy source. India has vast reserves of natural gas estimated at over one hundred billion cubic metres. Natural gas is produced in Assam, Tripura, Gujarat and Western offshore. Reserves of natural gas have also been established in the K.G. Basin and Caveri Basin.

In view of the mounting problem of power shortages and the economies available from using gas-based thermal power plants in meeting power requirements the importance of gas-based power generation acquires greater relevance.

Natural gas although a new-comer on the energy scene will play a significant role in future power generation. Natural gas can easily be used in place of liquid or solid energy source as fuel. Natural gas is a premium source of energy for domestic and commercial sector

where the user is benefitted from assured uninterrupted supply and the environmental compatibility.

Natural gas does not only provides the option of replacing liquid petroleum in various sectors but offers great potential of conservation of energy in these applications due to its inherent properties and also on account of up dated technology and equipment available for utilisation of natural gas for achieving higher efficiency.

For India, solar and wind energy and use of bio-mass fuels are generally agreed to be most relevant, as the potential of geothermal energy and tidal energy etc. are rather limited. Development of wind power offers a promoting prospect in meeting the energy requirements. India with its long coastline, blessed with steady winds almost throughout the year has tremendous potentialities of wind power which can be harnessed with immense benefits. Many industrialised countries like USA, UK, Japan and USSR have gathered vast experience in designing and commercial operation of wind power stations.

Utilization of solar energy is of great importance to India since it lies in a temperature climate of region of world where sunlight is abundant for a major part of the year. With the availability of improved materials, manufacturing techniques and better heat collectors in the near future solar power may become economically feasible.

Generation of electricity using photo voltaic (PV) cells should be exploited commercially. The PV modules serve as an efficient source of power supply to remove locations. These can also be used successfully by hospitals, schools, offices, railway stations, airports and factories.

The thrust of the research efforts in our country in the solar energy has been directed both towards solar thermal applications and direct conservation of solar electricity. Utilisation of solar energy is of great importance to the country as it lies in tropical climatic region where sunlight is abundant for a major part of the year.

Under an action plan formulated by the Ministry of Non-conventional Sources of Energy, the targets for power generation from non-conventional energy sources have been upgraded to 2,000 mega watts from 600 mega watts for Eighth Plan.

The most promising and fast moving solar technology today is that of solar cells, flat metallic blue chips made of highly pure silicon that can convert sunlight into electricity. Though silicon is available in abundance in every country of the world, the process of refining silicon to more than 99.9% is extremely complex and the cost

extremely high. Researchers in leading laboratories and universities have achieved self-reliance in this vital technology area which is essentially based the traditional and mature semiconductor process industry.

These solar photovoltaic cells are being used in rural areas and isolated locations for a variety of applications such as water pumping for micro irrigation and drinking water supply, community and street lighting, power supplies for microwave repeater station, communications equipment, radio and television receivers. A programme is on for supply of one million solar lanterns and 50,000 deep well solar pumps in villages.

Table 1.1 (A) indicates expected power demand. To meet the growing power demand emphasis will have to be laid on new and Non-conventional methods of generation of electrical energy.

Table 1.2A
Electrical Energy Generation

Year	*Generation in Billion kWh*
1970–71	61.2
1980–81	119.3
1986–87	202.1
1987–88	217.2
1999–2000	
Projected Demand	424/465

The use of bio-gas for lighting and irrigation opens up new possibilities for self-contained rural communities. In the long run our energy economy would have to be built around land based biomass fuels and plentiful sun shine which we receive virtually throughout the year.

In a bid to provide a simple and cheap method of energy production, the scientists have developed a number of designs of biogas plants which make use of wide range of agricultural wastes like animal dung, human excreta, vegetable waster, water hyacinth and produce fuel in the form of gas, simultaneously with high quality manure.

The installed capacity in power sector in India is indicated in Table 1.3.

Table 1.3

Year	*Hydel (MW)*	*Thermal (MW)*	*Nuclear (MW)*	*Total (MW)*
1951	575	1,261	—	1,836
1960-61	1,917	2,736	—	4,653

1970–71	6,383	7,906	420	14,709
1978–79	13,000	19,550	1020	33,570
1983–84	20,000	31,000	1900	53,000

To improve power generation the generation capacity of power plants must be increased. Following factors help in improving the generating capacity of a thermal power station.

(*i*) Adequate supply of a reasonable good and uniform quality of coal. The coal not only has ash but other extraneous materials like stones, silica, alumina and shale which should be removed before hand.

(*ii*) Improved maintenance of power equipment.

(*iii*) Use of better operation and maintenance techniques.

(*iv*) Better spare part management.

(*v*) Reduction of transmission and distribution losses.

(*vi*) Prevention of theft and pilferages of electrical energy.

By the end of Sixth Five Year Plan (1880-1885) India would have a total installed power capacity of about 50,700 MW with actual power generation around 33 million kW on account of a very low generating capacity of about 52%.

The installed capacity will be nearly 78,000 MW by 1990.

In view of rapid increase in the cost of energy the utilities should make efforts to focus attention of the consumers towards energy conservation. Particular attention should be paid to installation of LT capacitors which reduce losses along distribution lines.

A better balance between hydel and thermal power is required. This will reduce the cost of electrical power. The hydel thermal mix was 40 : 60 at the end of fifth plant, was 33.7 : 66.3 at the end of sixth plan and is likely to be 30.7 : 69.3 at the end of seventh plan. Without adequate hydel back up the overall cost of meeting the power demand will be expensive. It is, therefore, necessary to take up corrective measures during the course of seventh and successive plans towards a better hydel thermal balance.

Small hydel units should be installed because they can provide economic power supply to rural and remote areas in a decentralised manner. The potential of these units is said to be about 5000 MW out of which the installed capacity is only 160 MW.

By generating electrical energy from non-conventional sources like wind, solar energy, and bio-gas it would become much more easier to meet the energy requirement of people living in rural and far flung areas in a decentralised manner. India has vast potential to harness energy from these sources.

A few experimental solar power plants in the range of one to 5 kW have been installed in a number of villages in Andhra Pradesh,

Goa, Karnataka, Tamilnadu, Uttar Pradesh, Lakshadweep and Tripura. Two larger plants of 20 to 25 kW are under installation in Haryana and Orissa.

The total potential of wind resources is estimated to be about 20,000 MW for power generation. At present six wind power generating units with an aggregate capacity of about 6 MW have been set up in Gujarat, Maharashtra, Tamil Nadu and Orissa.

Following measures can help in meeting the increasing power demand :

(*i*) Conventional sources of energy are being consumed at faster rate. These fuels must be saved for commercial applications. Therefore harnessing of renewable sources of energy like solar energy wind energy bio-gas, ocean energy must be encouraged continuously on a long term basis. They are non-polluting and well suited for decentralised use.

(*ii*) Sustained efforts should be made through system improvement to reduce losses and to improve transmission efficiency.

(*iii*) Renovation and modernisation schemes in existing power stations should be thought of as a continuing process.

(*iv*) On going power generation schemes should be commissioned at a faster rate.

(*v*) To maintain the hydel thermal mix at the desired level of 40 : 60 more hydro projects should be taken up. Although it takes more time to build hydro power plants and their initial installation cost is more but the operational cost of hydro-power plants is much less than thermal power plants.

(*vi*) Energy conservation should be achieved by improving plant load factor and by reducing power transmission and distribution losses.

(*vii*) National grid should be set up. This will help in proper distribution of load among various power plants.

(*viii*) The power plants should be run at as high load factors as possible.

In India, power demand has been assessed at about 48 GW and 62 GW for the Eighth and Ninth Plan respectively. Eighth five year plan is expected to provide additional 38000 MW power. Strengthening of transmission net work is therefore essential so that benefits can be reaped optimally from targetted additional power generation during 1990-2000 A.D. Effective transmission systems are required to deliver power from regional projects to user states and to ex-

change power between inter connected systems. Use of UHV and EHV lines should be introduced.

Out country can not depend on using fossil fuels to large extent in the century to come. Conservation of petroleum products is the subject deserving the highest priority. The oil exploration effort, both off shore and on shore—be intensified. Non-conventional sources of energy such as wind energy, solar energy, electricity generation from use of agricultural wastes etc. should be continuously explored and exploited. This can help our country in becoming self reliant in power generation.

Increasing energy demand, depleting fuel resources and growing environmental pollution have led to the development of alternate energy sources. These include several renewable sources such as solar, wind, hydro, etc. as well as depletable energy sources as geothermal and synthetic fuels. The need of the hour is to exploit the non-depleting sources of energy that are environmentally acceptable.

Electrical energy is a resource that has been in short supply. It is a yard stick measuring Industrial development as also quality of life. Currently the total energy supply picture has been dominated by conventional 'fossil' fuels with contribution also from hydro power and nuclear sources. Other sources, termed as 'non-conventional' or renewable are not yet developed to any great degree and therefore cannot be compared to conventional sources. One major hurdle in achieving commercial status in these renewable sources is that they are widely distributed and relatively diffused. Supplies are essentially limitless. Renewable sources however hold much promise in an energy-starved world. Present trends have shown that capital costs for renewable energy projects are decreasing and its reliability is increasing. With increasing debate on the balance of the environment and energy economics, it is clear now that the potential and contribution of renewable energy sources will be a key factor in future developmental issues.

In addition to the conventional hydro source, the renewable energy sources include, *inter alia,* the following areas of interest : solar, wind, geothermal, biomass ocean and hydrogen. In our country some of these such as solar, wind and biomass have seen some development. But these efforts have been sporadic and have not yet been integrated into the mainstream.

It is desirable :

(*a*) that the conventional energy sources, particularly the fossil sources are exhaustible and are to be consumed at regulated level only ;

(*b*) that renewable energy sources have to be relied upon to the maximum extent possible ;

(*c*) that the subject of energy from non-conventional energy sources should be given utmost priority on commercial basis and for captive needs ;

(*d*) that all energy generation in future shall be environment pollution free.

In our country the peak load demand will be about 86000 MW by the end of 8th plan period. To meet this demand matching additional generating capacity should be installed. Present peak level generation of about 65% of the installed capacity should be improved to about 75%.

Other areas which require attention are as follows :

(*i*) reduction of transmission losses ;

(*ii*) power factor improvement ;

(*iii*) use of equipment with higher mechanical and electrical efficiency.

1.12.1 Conservation of Energy

Due to prohibitive cost of creating additional sources for power generation countries like India have a particular need to conserve energy. Some of the methods by which electrical energy can be conserved are as follows :

(*i*) Minimisation of transmission and distribution losses.

(*ii*) Minimisation of coal burnt in thermal power plant.

(*iii*) Use of high efficiency motors.

(*iv*) Optical reactive power scheduling.

(*v*) Efficient energy system planning.

(*vi*) Improving power plant load factor by better operation and maintenance procedures.

(*vii*) Optimum utilisation of installed capacity. Conservation of electrical energy remains in the circumstances the most viable option because it is cheaper in terms of investment and also because the gestation period of conservation measures is short and results quicker.

In our country the energy conservation has been identified as priority area of activity in power generation for the eighth plan period (1990-95) and beyond.

Conservation of electrical energy helps to maintain demand-supply equilibrium. There is huge waste of electrical energy due to low power factor and improper distribution net work. Proper ways and means should be used to reduce transmission and distribution losses. So far petroleum products are concerned out of total consumption of petroleum products in our country about 30% is produced indigenously and balance 70% is imported from other

petroleum producing countries. The world is mostly depending on petroleum fuel for its energy requirements. Fossil fuels are getting depleted at fast rate. This requires that alternate, new reliable and eco-friendly sources of energy should be found which can help in melting the increasing electrical energy demand.

Economic development is not possible without electric power which used to be a luxury earlier but is now part and parcel of common man's life.

In our country per capita energy consumption is only 300 units against nearly 3000 units abroad. Although electric energy consumption of common man is increasing but we are unable to meet out due to resources crunch.

Our country has vast hydro energy potential yet we have not been able to tap the same. Inexhaustible Hydroenergy if properly utilised can save other sources of energy such as coal and petroleum products.

Biomass–a major clean and convenient source of energy when converted into modern energy carriers like fluid fuels and electricity–has given new hopes to scientists all over the world to sustain the ultimate, irreducible essence of the universe. Defined as all organic matters except fossil fuels, biomass includes all crop and forest products, animal matters, microbial cell mass, residues and by products that are renewable. It serves as food, feed, fibre, bedding, structural material, soil organic matter and fuel.

Biomass comes in as a potential source of energy to meet this ever-increasing demand. Bio-energy plantations on rural degraded land can make local population self-sufficient in their energy requirements. Domestic, agricultural and industrial energy needs can also be met through this decentralised power generating system.

In fact, the third world is already deriving 43% of its energy from biomass and over two billion people are almost totally reliant on biomass fuels for their energy needs. The dispersed rural 70% of the world population are also sustaining on biomass. If all families in developing countries that are now using biomass fuels were to change to kerosene, the third world's demand for oil would rise by about 20%.

At present biomass energy production is associated with agricultural and forestry activities. In industrial countries, a major part of the bio-energy component is produced from residues from pape nd timber industries. There is also a growing realisation that those countries with large reserves of agricultural land can utilise this resource to produce energy, thus cutting oil import requirements and also reducing crop surpluses if necessary. Large-scale

ethanol programmes using maize in the USA and sugarcane in Brazil have demostrated that substantial quantities of liquid fuel can be generated from biomass.

Many technologies exist for converting biomass to heat energy through direct combustion, or to liquid or gaseous fuels through thermo-chemical, extraction or biological processes. The sugar and starch, cellulose, lignin and other constituents of biomass may be burnt directly to produce heat or mechanical work in an external combustion engine.

To cope up the shortage in electric power generation, it is observed that the MHD system is a promising feature for developing countries like India.

1.13 Combustion of Fuels

It deals with various reactions taking place concerning different elements which constitute the fuel. The combustion of fuels may be defined as a chemical combination of oxygen in the atmospheric air and hydro-carbons. It is usually expressed both

(*i*) qualitatively and (*ii*) quantitatively

by equations known as chemical equations which indicate the nature of chemical reactions taking place.

Adequate supply of oxygen is very essential for the complete combustion of a fuel in order to obtain maximum amount of heat from a fuel.

Combustion of fuels is accomplished by mixing fuel and air at elevated temperature. The combustion process may be simply expressed as follows :

Fuel + Air = Products of combustion + Heat liberated

The oxygen contained in the air unites chemically with carbon, hydrogen and other elements in fuel to produce heat. The amount of heat liberated during the combustion process depends on the amount of oxidation of the constituents of fuel and the nature of fuel (chemical composition of fuel).

In order that the combustion of fuel may take place with high efficiency, the following conditions must be fulfilled :

1. The amount of air supplied should be such that it is sufficient to burn the fuel completely. Complete combustion of fuel means complete oxidation of all the combustible material in the fuel. A deficiency of air causes incomplete combustion of fuel which results in considerable unburnt fuel being discharged from the furnace whereas too much supply of air simply dilutes the gases and cools the furnace.

2. The air and fuel should be thoroughly mixed so that each combustible particle comes in intimate contact with the oxygen contained in the air.
3. The fuel should remain in the furnace for sufficient time till it get burnt completely.
4. The temperature in the furnace should be high enough to ignite the incoming air fuel mixture.

1.14 Products of Combustion

The complete combustion of fuel produces various gases such as carbon dioxide (CO_2), sulphur dioxide (SO_2), water vapour nitrogen (N_2) and oxygen (O_2). Nitrogen comes from air supply and oxygen from excess air. Water vapour is produced from the following three sources :

(*i*) Moisture originally contained in the coal
(*ii*) Vapour produced by combustion of hydrogen
(*iii*) The water vapour of atmospheric humidity.

If all the carbon present in the fuel does not get burn completely then carbon monoxide (CO) is also produced. The flue gases will have considerable amount of carbon monoxide in them if the oxygen supply is less. However, large excess of air would mean that a large amount of sensible heat would be lost in flue gases. Analysis of flue gases give a correct idea of how the fuel is burning.

1.15 Combustion Chemistry

The combustion process involves chemical reactions. The combustible elements in fuels consists of carbon, hydrogen and sulphur.

The chemical equations represent the combustion of C, H_2, S, CH_4, etc., are described as follows :

(*i*) **Combustion of Carbon**

$$C + O_2 \rightarrow CO_2$$

Substituting the values of molecular weight in equation.

$$12 + 16 \times 2 = 12 + 16 \times 2$$

$$12 + 32 = 12 + 32$$

$$1 + \frac{8}{3} = 1 + \frac{8}{3}$$

$$1 + \frac{8}{3} = \frac{11}{3}$$

This means that 1 kg of carbon requires 8/3 kg of oxygen for its complete combustion and produces 11/3 kg of carbon dioxide.

If the amount of oxygen supplied is not sufficient the combustion of carbon is incomplete and the product of combustion will be carbon monoxide.

$$2C + O_2 \rightarrow 2CO$$

$$2 \times 12 + 16 \times 2 = 2\,(12 + 16)$$

$$24 + 32 = 56$$

$$1 + \frac{4}{3} = \frac{7}{3}$$

which means that 1 kg of carbon needs 4/3 kg of oxygen to produce 7/3 kg of carbon monoxide. Further burning of CO produces CO_2.

$$2CO + O_2 \rightarrow 2CO_2$$

$$2\,(12 + 16) + 16 \times 2 \rightarrow 2\,(12 + 32)$$

$$56 + 32 \rightarrow 88$$

$$1 + \frac{4}{7} \rightarrow \frac{11}{7}$$

This means that 1 kg of CO needs 4/7 kg of oxygen and produces 11/7 kg of CO_2.

(*ii*) **Combustion of Hydrogen.** Burning of hydrogen with oxygen produces water vapours,

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$2(1 + 1) + 16 \times 2 \rightarrow 2\,(2 + 16)$$

$$4 + 32 \rightarrow 36$$

$$1 + 8 \rightarrow 9$$

This means that 1 kg of hydrogen combines with 8 kg of oxygen to produce 9 kg of water.

(*iii*) **Combustion of Sulphur.** When sulphur burns with oxygen it produces sulphur dioxide.

$$S + O_2 \rightarrow SO_2$$

$$32 + 16 \times 2 \rightarrow 32 + 16 \times 2$$

$$32 + 32 \rightarrow 32 + 32 \rightarrow 64$$

1 kg of sulphur + 1 kg of oxygen → 2 kg of sulphur dioxide

(*iv*) **Combustion of Methane (CH_4)**

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$(12 + 4) + 2 \times 32 \rightarrow (12 + 32) + 2 \times 18$$

$$16 + 64 \rightarrow 44 + 36$$

$$1 + 4 \rightarrow \frac{11}{1} + \frac{9}{4}$$

1 kg methane + 4 kg oxygen → 11/4 kg.

Carbon dioxide + 9/4 kg of water.

The various values are summarised in Table 1.4.

Table 1.4

Substance (1 kg)	*(Oxygen reqd. kg.)*	*Products of Combustion (kg)*			
		CO	CO_2	H_2O	SO_2
C	8/3	—	11/3	—	—
CO	4/7	—	11/7	—	—
H_2	8	—	—	9	—
S	1	—	—	—	2
CH_4	4	—	11/4	9/4	—

1.16 Combustion of Gaseous Fuels

Gaseous fuels are usually measured by volume (in cubic metres). The various chemical equations are described as follows :

(*i*) **Combustion of Hydrogen**

$$2H_2 + O_2 \rightarrow 2H_2O$$

2 vol. + 1 vol. → 2 vol.

1 cu-metre $+ \frac{1}{2}$ cu-metre →1 cu-metre. This means that one cu-metre of hydrogen requires $\frac{1}{2}$ cu-metre of oxygen to produce one cu-metre of water.

(*ii*) **Combustion of Methane.** When methane (Marsh Gas) burns with oxygen it gives CO_2.

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$$

1 vol. + 2 vol. → 2 vol. + 1 vol.

1 cu–metre $+ \frac{1}{2}$ cu–metre → 2 cu–metre + 1 cubic–metre.

Thus 1 cu-metre of methane needs 2 cu-metre of oxygen for combustion and produces 2 cu-metre of water and 1 cu-metre of CO_2.

(*iii*) **Combustion of CO.** When carbon monoxide burns in oxygen, it gives CO_2.

$$2CO + O_2 \rightarrow 2CO_2$$

$$2 \text{ vol.} + 1 \text{ vol.} \rightarrow 2 \text{ vol.}$$

$$1 \text{ cu-metre} + \frac{1}{2} \text{ cu-metre} \rightarrow 1 \text{ cubic metre.}$$

Thus one cu-metre of CO needs $\frac{1}{2}$ cu-metre of oxygen to produce one cu-metre of CO_2.

(*iv*) **Combustion of Ethylene (C_2H_4).** When C_2H_4 burns in oxygen it gives CO_2 and H_2O.

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$$

$$1 \text{ vol.} + 3 \text{ vol.} \rightarrow + 2 \text{ vol.} + 2 \text{ vol.}$$

1 cu-metre + 3 cu-metre → 2 cu-metre + 2 cu-metre.

Thus 1 cu-metre of ethylene combines with 3 cu-metre of oxygen to produce 2 cu-metre of CO_2 and 2 cu-metre of water vapours.

The combustion products of various gaseous fuels are summarised in Table 1.5.

Table 1.5

Gas (1 cu-metre)	*Oxygen reqd. (cu-metre)*	*Products of combustion (cu-metre)*	
		CO_2	H_2O
H_2	$\frac{1}{2}$	—	1
CH_4	2	1	2
CO	$\frac{1}{2}$	1	—
C_2H_4	3	2	2

1.17 Weight of Air Required for Complete Combustion of Fuel

The weight of air required for the complete combustion of fuel is calculated from the analysis of fuel. To calculate the amount of air required for complete combustion of fuel, firstly the oxygen required for burning each of the constituent fuel is calculated and then the air required is found out. The atmospheric air consists of oxygen, nitrogen and small amount of carbon dioxide, and other gases such as neon, argon, krypton etc. For calculating the air

required for burning a fuel, the following composition of air can be taken :

By weight :	Oxygen = 23%
	Nitrogen = 77%
By volume :	Oxygen = 21%
	Nitrogen = 79%

If it is found that the fuel already contains some amount of oxygen, then it should be deducted from the calculated value of oxygen.

1.18 Coal Selection

While selecting coal for steam power plant the following properties should be considered :

1. *Size and Grade.* The size and grade of coal will determine the type of equipment to be used for burning the coal.

2. *Heating Value.* The coal selected should have high heating value (calorific value).

3. *Contents of moisture, volatile matter, fixed carbon ash and sulphur.* The slagging characteristics depend on ash temperature and corrosion characteristics depend on sulphur contents.

4. Coking and caking tendency of coal that is retention of original shape during combustion *VS* softening.

5. Physical properties such as resistance to degradation and size consistency.

6. Various constituents indicated by approximate the ultimate analysis.

7. Grindability *i.e.* the ease with which a coal can be pulverised. Grindability index is expressed by a number.

1.18.1 Ranking and grading of coal

According to ASME and ASTM,

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

(*ii*) Lower ranking is done on the heating value on the moist basis.

For example a coal having 6% C and a calorific value of 5000 kcal/kg is ranked as (60-500) rank.

Grading of coal is done on the following basis :

(*i*) Size
(*ii*) Heating value
(*iii*) Ash content
(*iv*) Ash softening temperature

(*v*) Sulphur content.

For example a coal of grade written as 6-10 cm, 500-A8-F24 S 1.7 means

(*a*) coal has a size of 5-10 cm

(*b*) coal heating value is 5000 k-cal/kg

(*c*) coal has ash content 8 to 10%

(*d*) ash softening temp is 2400°F

(*e*) sulphur content of coal is 1.7%.

1.19 Composition of Solid Fuels

The various constituents of solid fuels are carbon, hydrogen, oxygen, sulphur, nitrogen and mineral matter.

Following methods of analysis are used to determine the composition of coal :

1. Ultimate analysis. 2. Proximate analysis.

1. **Ultimate Analysis.** The analysis is used to express in percentage by weight of carbon, hydrogen, nitrogen, sulphur, oxygen and ash and their sum is taken as 100%. Moisture is expressed separately. This analysis enables to find the amount of air required for the combustion of 1 kg of coal and to calculate the heating value of coal.

The ultimate analysis of most of the coals indicates the following ranges of various constituents.

Constituents:	C	H_2	O_2	S	N_2	Ash
Percentage :	50–90%	2–5.5%	2–40%	0.5–3%	0.5–7%	2–30%

2. **Proximate Analysis.** This analysis is used to determine the following components :

(*i*) Moisture

(*ii*) Volatile matter (carbon combined with hydrogen and other gases that are driven off on heating).

(*iii*) Ash

(*iv*) Fixed carbon

They are expressed percentage by weight and their sum is taken as 100%. Sulphur is expressed separately.

To find the volatile matter 1 gm of finely divided coal free from moisture is heated in a crucible for 7 minutes to about 950 ± 20°C. The crucible is then cooled and the difference in weight indicates the amount of volatile matter. The sample is then burnt in an open pan so that it gets burnt completely. The amount of residue left behind is ash. Weight of original sample minus weight of moisture, volatile matter and ash gives the weight of fixed carbon.

Ultimate analysis and proximate analysis are expressed in terms of :

(*i*) Coal 'as received' or 'as fired' : Coal 'as fired' is in the same conditions as it comes out of the bunkers.

(*ii*) Coal 'moisture free' or 'dry'.

(*iii*) Coal 'moisture and ash free' or 'combustible'.

The ultimate analysis of coal is a more precise test to find the chemical composition of coal whereas proximate analysis of coal gives good indication about heating and burning properties of coal.

The proximate analysis of most of the coal indicates the following ranges of various constituents.

Constituents :	Fixed C	Moisture	Volatile Matter	Ash
Percentage :	16–92%	3–28%	3–50%	2–30%

1.19.1 Ash

Ash is the combustion product of mineral matters presents in the coal. It comprises mainly of silica (SiO_2), alumina (Al_2O_3) and ferric oxide with varying amounts of other oxides such as CaO, MgO, Na_2O etc. High ash content in coal is undesirable in general.

A coal with high ash content has following properties :

(*i*) is harder and stronger

(*ii*) has lower calorific value

(*iii*) produces more slag (impurities) in the blast furnace when coke made out of it is used therein.

Ash content of the coal is reduced by its washing.

1.19.2 Volatile Matter

Certain gases like CO, CO_2, CH_4 H_2, N_2, O_2, hydrocarbons etc. are present in the coal which comes out during its heating. These are called the volatile matter of the coal.

The coal with higher volatile matter content has following properties :

(*i*) ignites easily *i.e.* it has lower ignition temperature

(*ii*) burns with long smoky yellow flame

(*iii*) has lower calorific value

(*iv*) will give more quantity of coke oven gas when it is heated in absence of air

(*v*) will require larger furnace volume for its combustion

(*vi*) has a higher tendency of catching fire (due to low temperature exothermic oxidation) when stored in open space.

1.20 Weight of Excess Air Supplied

The weight of excess air required during combustion of coal is calculated from the weight of unused oxygen in flue gases after CO is present in flue gases is burnt to CO_2.

Let W_1 = Weight of flue gases per kg of fuel

W_2 = Percentage weight of oxygen present in flue gases

W_3 = Percentage weight of CO present in flue gases

As 1 kg of CO need 4/7 kg of oxygen to burn to CO_2.

$\therefore$ Oxygen required to burn W_3 kg of CO to CO_2.

$$= \frac{W_3}{100} \times \frac{4}{7} = W_4 \text{ (say)}$$

$$\therefore \text{ Excess Oxygen } (W_5) = \frac{W_2}{100} - W_4$$

Weight of excess oxygen per kg of fuel (W_6)

= Weight of excess oxygen per kg flue gas × Weight of flue gas per kg of fuel

$$W_6 = W_5 \times W_1$$

Therefore, the weight of excess air supplied

$$= W_6 \times \frac{100}{23}$$

Proper control of the right amount of excess air maintains optimum combustion efficiency. CO_2 and O_2 in combustion gases are index of excess air. Air feed should be controlled so that optimum amount of CO_2 or O_2 is produced. Smoke formation and slagging of boiler surfaces also play an important part in determining the optimum excess air. Practical conditions of fuel type furnace arrangements and heat transfer arrangement determine the total amount of air needed for complete combustion.

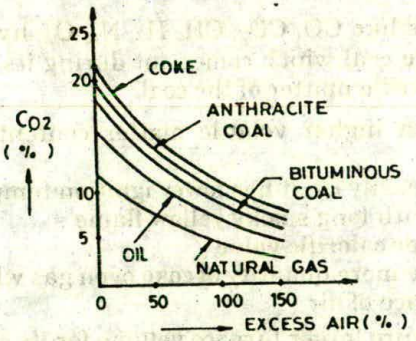


Fig. 1.3

The amount of CO_2 in flue gases depends on type of fuel and excess air supplied to the furnace. Fig. 1.3 shows typical variation

of CO_2 in flue gases (per cent by volume) and excess air (percent) for complete combustion of various types of fuels.

The total amount of air needed for complete combustion of a fuel depends on following factors :

(*i*) Type of fuel.

(*ii*) Furnace arrangements.

(*iii*) Heat transfer surface arrangement.

Typical values of excess air supplied, expressed as percentage of the quantity theoretically required are as follows :

Hand fired boiler furnace	: 100
Mechanically stokered furnace	: 40
Petrol engine	: 20
Oil engine	: 20

1.21 Requirements of Fuel

A fuel should possess the following requirements :

(*i*) *Calorific value.* The fuel selected should have high calorific value.

(*ii*) *Price.* It should be cheap.

(*iii*) *Operating efficiency.* The fuel should burn most effectively. It should produce minimum amount of dust, smoke, slagging and clinkering. In case of coal a careful study should be made about volatile matter, ash, sulphur, moisture, ash fusion temperature, ash analysis and grinding and coking characteristics.

(*iv*) *Refuse disposal.* The fuel should produce minimum ash on burning. In general oil and gas, produce ash in very small quantities and do not present any refuse disposal problem whereas coal produces sufficient amount of ash and, therefore, ash disposal equipment is required where coal is used as fuel.

(*v*) *Handling cost.* The handling cost should be minimum. Handling cost of coal at power station is maximum and gas requires minimum handling cost whereas handling cost of oil is intermediate.

(*vi*) *Operating labour cost.* The operating labour cost is maximum in coal fired plants whereas it is minimum where gas is used as fuel.

1.22 Principal Stages of Combustion

The combustion of fuel is a complicated physical and chemical process in which the combustible elements of the fuel combine with the oxygen of air with the evolution of heat attended by a sharp rise in temperature and formation of flame. During the burning of any fuel two stages are observed :

(*i*) Ignition (*ii*) Combustion.

Ignition is the period during which the fuel is gradually raised in temperature. On attaining a definite temperature the fuel is ignited and stable combustion sets in. When solid fuel is introduced into the furnace, moisture is first removed and the volatiles begin to be liberated. The resultant gaseous products of the fuel decomposition are gradually heated to the ignition point and burn in a flame over the solid part of the fuel. Combustion of the gaseous substances, heats the coke which begins to burn stably when the ignition points is reached. At this stage maximum temperature is generated. Burning down is the final stage in the combustion of solid fuel. Gasification and the combustion of solid elements are completed is this stage and enough heat is generated to maintain combustion at a sufficiently high temperature. Liquid fuel should be first atomised to increase its area of contact with the air. An additional phase in the firing of liquid fuel is evaporation. A drop of fuel oil entering the spray of burning fuel is heated and gradually reaches the temperature at which the fuel components begin to evaporate. The gases formed burn in the oxygen of air and increase the temperature of drop. At a definite temperature the molecules of the drop begin to disintegrate. The drop begins to burn at its surface. The oxygen penetrates inside where partial combustion takes place and the gases formed inside the drop further intensity the combustion.

During different stages of combustion of fuel the requir
tity of air should be supplied. Complete and incomplete com
of fuel take place depending upon the quantity of air supplied

1.23 Complete Combustion

It is process in which the combustible elements of fuel combine chemically with the oxygen of air at a definite temperature.

The flue gases produced consist of CO_2, SO_2, water vapour (H_2O), oxygen (O_2) and nitrogen (N_2).

1.24 Incomplete Combustion

A deficiency in air supplied causes in complete combustion of fuel which results in considerable unburnt fuel being discharged from the furnace along with ash and slag. The presence of carbon monoxide gas (CO) in the combustion products indicates in complete combustion. When liquid or gaseous fuel is fired incomplete combustion is accompanied by soot formation.

1.24.1 Weight of Carbon in flue gases

The weight of carbon contained in 1 kg of flue gases can be calculated from the amounts of CO_2 and CO present in it.

During the complete combustion of C to CO_2

$$C + O_2 = CO_2$$

$$12 + 16 \times 2 = 12 + 16 \times 2$$

$$12 + 32 = 44$$

$$1 + \frac{32}{12} = \frac{44}{12}$$

$$1 + \frac{8}{3} = \frac{11}{3}$$

Thus 1 kg of carbon on combustion produces 11/3 kg of CO_2. Hence 1 kg of CO_2 will contain 3/11 kg of carbon.

Now when carbon burns in insufficient supply of oxygen then the combustion of carbon is incomplete and products of combustion will be carbon monoxide.

$$2C + O_2 = 2\,CO$$

$$2 \times 12 + 16 \times 2 = 2\,(12 + 16)$$

$$24 + 32 = 56 \text{ or } 1 + \frac{32}{24} = \frac{56}{24}$$

$$1 + \frac{4}{3} = \frac{7}{3}$$

Thus 1 kg of carbon produces 7/3 kg of CO. Hence 1 kg of CO contains 3/7 kg of carbon.

$\therefore$ W_1 = weight of carbon in 1 kg of flue gases

$$= \frac{3}{11}\,CO_2 + \frac{3}{7}\,CO$$

1.24.2 Weight of flue gas per kg of fuel burnt. The actual weight of dry flue gases can be obtained by comparing the weight of carbon present in flue gases with the weight of carbon in the fuel.

Let, W_2 = weight of carbon in 1 kg of fuel

W = Weight of flue gas per kg of fuel burt

$= W_2/W_1$

where W_1 = Weight of carbon in 1 kg of flue gases.

1.25 Conditions for Proper Burning (Combustion) of Fuel

The various conditions that should be established for proper burning of fuel are as follows :

(*i*) Correct mixing and ratio of fuel and air

(*ii*) Enough time to burn the fuel completely

(*iii*) High temperature flame

(*iv*) Turbulent mixing of fuel and air
(*v*) Proper proportioning of furnace dimensions.

1.26 Temperature of Fuel Combustion

The combustion of fuel is always accompanied by heat losses. Therefore, the real temperature or actual temperature of combustion is always lower than the theoretical temperature of combustion which is obtained in ideal cases without heat losses. Table 1.5 shows the theoretical temperature of combustion for various fuels in degree centigrade.

Table 1.6

Type of fuel	*Excess AIR coefficient*			
	1.0	*1.3*	*1.5*	*2.0*
Anthracite	2270	1845	1665	1300
Lignite	1875	1590	1425	1150
Peat	1700	1510	1370	1110
Fuel oil	2125	1740	1580	1265
Gas	2000	1749	1478	1167

Example 1.1. *The percentage composition of a sample of coal was found to be as follows :*

$$C = 85\%; H_2 = 3\%;$$

$$O_2 = 2\%; Ash = 10\%.$$

Determine the minimum weight of air required for the complete combustion of one kg of coal.

Solution.

Substance	*Weight per kg of fuel*	*Oxygen required per kg of substance*	*Oxygen per kg of fuel*
C	0.85	$\frac{8}{3}$	$0.85 \times \frac{8}{3} = 2.266$
H_2	0.03	8	$0.03 \times 8 = 0.24$
O_2	0.02	—	0.02
Ash	0.10	—	—

Total oxygen required $= 2.266 + 0.24 - 0.02 = 2.486$ kg.

Weight of air required for complete combustion of 1 kg of fuel

$$= 2.486 \times \frac{100}{23} \approx 10.8 \text{ kg.} \quad \textbf{Ans.}$$

Example 1.2. *The percentage composition by weight of a sample of coal; was found to be as follows :*

$C = 24\%; H_2 = 5\%,$

$O_2 = 8\%; Ash = 63\%.$

It was also observed that the dry flue gas had the following composition by volume :

$CO_2 = 10\%; CO = 2\%;$

$O_2 = 13\%; N_2 = 75\%.$

Determine the following :

(*a*) *Minimum weight of air required for complete combustion of 1 kg of coal :*

(*b*) *Weight of excess air required per kg of coal.*

Solution. (*a*)

Substance	*Weight per kg of coal*	*Oxygen required per kg of substance*	*O_2 reqd. per kg of coal*
C	0.24	$\frac{8}{3}$	0.64
H_2	0.05	8	0.40
O_2	0.08	—	0.08
Ash	0.63	—	—

Total oxygen required $= 0.64 + 0.40 - 0.80 = 0.96$ kg.

$\therefore$ Minimum weight of air required per kg of coal

$$= \frac{0.096 \times 100}{23} = 4.18 \text{ kg.} \quad \textbf{Ans.}$$

(*b*) The composition of dry flue gas is given by volume. It can be converted into composition by weight as follows :

Gas	*Volume per m^2 of flue gas (V)*	*Molecular weight (M)*	*Proportional weight (W) $W = V \times M$*	*Weight per kg of flue was (W) $w = \frac{W}{kW}$*
CO_2	0.10	44	4.40	0.146
CO	0.02	28	0.56	0.018
O_2	0.13	32	4.16	0.140
N_2	0.75	28	21.00	0.696
			$W = 30.12$	

Weight of carbon per kg of coal = 0.24 kg

Weight of carbon per kg of the flue gas

= Weight of carbon in 0.146 kg of CO_2

+ Weight of carbon in 0.018 kg of CO

$$= \frac{3}{11} \times 0.146 + \frac{3}{7} \times 0.018$$

$$= 0.04 + 0.008 = 0.048 \text{ kg.}$$

$\therefore$ Weight of flue gas per kg of coal

$$= \frac{0.24}{0.048} = 5 \text{ kg.}$$

Weight of excess oxygen per kg of flue gas

= Amount of oxygen in flue gas – Oxygen required to burn CO

$$= 0.140 - \frac{4}{7} \times 0.018 = 0.13 \text{ kg.}$$

$\therefore$ Weight of excess oxygen per kg of coal

$$= 5 \times 0.13 = 0.65 \text{ kg.}$$

$\therefore$ Weight of excess air per kg of coal

$$= \frac{0.65 \times 100}{23} = 2.83 \text{ kg.} \quad \textbf{Ans.}$$

Example 1.3. *Calculate the amount of air required to burn one kg of fuel and product of combustion for a fuel the percentage composition of which is given as follows :*

$C = 80\%$; $H_2 = 20\%$.

Solution.

Substance	*Weight per kg of fuel*	*O_2 reqd. per kg of substance*	*O_2 reqd. per kg of fuel*
C	0.8	8/3	$0.8 \times 8/3 = 2.13$
H_2	0.2	8	$0.2 \times 8 = 1.6$

Total oxygen required $= 2.13 + 1.6 = 3.73$ kg.

$\therefore$ Weight or air required $= 3.73 \times \frac{100}{23} = 16.2$ kg. **Ans.**

Products of Combustion

$C + O_2 \rightarrow CO_2 \quad 12 + 32 \rightarrow 12 + 32$

$12 + 32 \rightarrow 44$

$\therefore$ 1 kg of C + $\frac{8}{3}$ kg of O_2 $\rightarrow$ $\frac{11}{3}$ kg of CO_2

$\therefore$ $\frac{8}{3}$ kg of O_2 gives $CO_2 = \frac{11}{3}$ kg

2.13 kg of O_2 gives $CO_2 = \frac{11}{3} \times \frac{3}{8} \times 2.13 = 2.93$ kg

$\therefore$ $CO_2 = 2.93$ kg/kg of fuel. **Ans.**

Similarly, $2H_2 + O_2 \rightarrow 2H_2O$

$4 + 32 \rightarrow 36$

$1 + 8 \rightarrow 9$

$\therefore$ 1 kg of H_2 + 8 kg of O_2 = 9 kg of H_2O

$$H_2O = \frac{9 \times 16}{8} = 1.8 \text{ kg/kg of fuel.} \quad \textbf{Ans.}$$

Example 1.4. *A gas used as fuel has the following composition by volume :*

$H_2 = 27\%$; $CO_2 = 18\%$

$CO = 12.5\%$; $CH_4 = 2.5\%$

$N_2 = 40\%$.

Calculate the volume of air required for complete combustion of one cubic-metre of the gas.

Solution. The various values are as follows :

Name of gas	*Vol. per cu. metre of fuel*	*O_2 reqd. per m^3 of constituent*	*O_2 reqd. per cu-metre of fuel*
H_2	0.27	$\frac{1}{2}$	0.135
CO_2	0.18	—	—
CO	0.125	$\frac{1}{2}$	0.062
CH_4	0.025	2	0.05
N_2	0.40	—	—

Total oxygen required = 0.135 + 0.062 + 0.05 = 0.247

$\therefore$ Volume of air = $0.247 \times \frac{100}{21} = 1.176$ m^3. **Ans.**

Example 1.5. *The percentage composition of a sample of coal is found to be as follows :*

C = 88%, H_2 = 4.3% O_2 = 3%

N_2 = 0.7%, S = 1% Ash = 2%

(a) Calculate the minimum weight of air required for complete combustion of one kg of this coal.

(b) If 40% excess air is supplied, calculate the percentage composition by volume of the dry flue gases.

Solution. (a)

Substance	*Weight per kg of coal (kg)*	*Weight of oxygen per kg of substance (kg)*	*Weight of oxygen required (kg)*	*Weight of products of Combustion*		
				CO_2	SO_2	N_3
C	0.88	8/3	2.34	3.23	—	—
O_2	0.04	—	0.04	—	—	—
H_2	0.043	8	0.344	—	—	—
N_2	0.007	—	—		—	0.007
S	0.001	1	0.01		0.02	—
Ash	0.02	—	—		—	—

Total oxygen required

$$= 2.34 + 0.04 + 0.344 + 0.01 = 2.734 \text{ kg.}$$

$\therefore$ Minimum amount of air required

$$= 2.734 \times \frac{100}{23} = 11.88 \text{ kg.} \quad \textbf{Ans.}$$

(b) As 40% excess air is supplied

$\therefore$ N_2 in actual air supply

$$= 1.188 \times \frac{77}{100} \times 1.4 = 12.8 \text{ kg.}$$

$\therefore$ Total nitrogen = 12.8 + 0.007 = 12.807 kg.

Excess oxygen $= 11.88 \times \frac{23}{100} \times 0.4 = 1.1$ kg.

Substances	*Weight per kg of coal*	*Molecular Weight*	*Parts by volume (a)*	*Percentage volume* $\frac{a}{\Sigma a} \times 100$
CO_2	3.23	44	$\frac{3.3}{44} = 0.73$	12.88%
SO_2	0.02	64	$\frac{0.02}{64} = 0.0003$	0.05%

O_2	1.1	32	$\frac{1.1}{32} = 0.034$	6%
N_2	12.8	28	$\frac{12.8}{28} = 0.46$	81.07%
		Total	0.5673	100%

Example 1.6. *The percentage composition by weight of a sample of coal is given as below.*

$$C = 65.50\%; \quad H_2 = 6.65\%$$

$$O_2 = 17.50\%; \quad S = 1.80\%$$

Using Dulong formula, calculate the calorific value of coal.

Solution. According to Dulong's formula, the higher calorific value (H.C.V.) is given by the following relation :

$$\text{H.C.V.} = \frac{1}{100}\left\{8080C + 34{,}500\left(H - \frac{O}{8}\right) + 2220\,S\right\}$$

$$= \frac{1}{100}\left\{8080 \times 65.50 + 34{,}500\left(6.65 - \frac{17.50}{8}\right) + 2220 \times 1.80\right\}$$

$$= \frac{1}{100}\{520{,}924 + 153{,}870 + 3996\} = 6787.90 \text{ kcal/kg}$$

Steam produced $= 0.0665 \times 9 = 0.5985$ kg.

$\therefore$ Lower calorific value (L.C.V.) = H.C.V. $- 0.5989 \times 588.76$

$= 6787.90 - 0.5985 \times 588.76 = 6787.90 - 352.37$

$= 6435.53$ kcal/kg. **Ans.**

Example 1.7. *A boiler uses coal of the following composition*

$C = 89\%$; $H_2 = 4\%$; $O_2 = 3.8\%$

If CO_2 records read 10% calculate the percentage of excess air supplied per kg of coal.

Substance per kg of coal	*Mol. Weight*	*Proportional vol. composition*	*Oxygen reqd. by vol.*	*Dry products of combustion by vol.*
C = 0.89	12	$\frac{0.89}{12} = 0.074$	0.074	0.074
$H_2 = 0.04$	2	$\frac{0.04}{2} = 0.02$	0.01	
$O_2 = 0.038$	32	$\frac{0.038}{32} = 0.012$	0.012	

Solution. Total oxygen required

$= 0.074 + 0.01 - 0.012 = 0.0828$

Minimum air required by volume $= 0.0828 \times \frac{100}{21} = 0.394$

Volume of N_2 with minimum air $= 0.394 - 0.0828 = 0.3112$

Let V = Volume of excess air

Percentage CO_2 in dry products

$$= \frac{CO_2}{CO_2 + N_2 + V}$$

$$10 = \frac{0.074}{0.074 + 0.3112 + V} \times 100$$

$$V = 0.2548$$

Excess air $= \frac{0.2548}{0.394} \times 100 = 64.7\%$ **Ans.**

Example 1.8. *An oil engine uses oil having gravimetric analysis as follows :*

$$C = 0.85 \; ; \; H_2 = 0.14 \; ; \; Ash = 0.02$$

The ratio of air supplied to fuel burnt is 30 : 1.

Determine the mass of various constituents of wet products and the percentage composition of dry products.

Solution. Fuel supplied = 1 kg

Total air supplied = 30 kg

Total oxygen supplied $= 30 \times \frac{23}{100} = 6.9$ kg

Total nitrogen supplied $= 30 \times \frac{77}{100} = 23.1$ kg

Various products of combustion are as follows :

Constituent	*Mass kg/kg of fuel*	*Minimum O_2 reqd. kg*	*Products of combustion (kg)*			
			CO_2	H_2O	N_2	O_2
C	0.85	$\frac{8}{3} \times 0.85 = 2.27$	$\frac{11}{3} \times 0.85 = 3.11$	—	—	—
H_2	0.14	$0.14 \times 8 = 1.12$	—	$9 \times 0.14 = 1.26$	—	—
Ash	0.02	—	—	—	—	—
Air	30	—	—	—	23.1	$6.9 - 3.39 = 3.51$
Total	31.0	3.39	3.11	1.26	23.1	3.51

Wet products and dry products are calculated as follows :

Wet products		*Dry Products*		
Constituent	*kg / kg of fuel*	*Constituent*	*kg / kg of fuel*	*% Composition*
CO_2	3.11	CO_2	3.11	10.4
H_2O	1.26			
N_2	23.1	N_2	23.1	77.7
O_2	3.51	O_2	3.51	11.9
Total	30.98		29.72	100

Example 1.9. *The volumetric analysis of a certain flue gas given by Orsat apparatus is as follows :*

$$CO_2 = 15\% \; ; \; CO = 1\%$$

$$O_2 = 5\% \; ; \; Nitrogen = 79\%.$$

Find the analysis of the flue gas by weight.

Solution. The analysis of flue gas by weight is determined as follows :

Name of gas	*Volume per m^3 of flue gas (A)*	*Molecular weight (B)*	*Proportional weight $C = A \times B$*	*Percentage composition by weight $D = \frac{C}{\Sigma C} \times 100$*
CO_2	0.15	44	0.15×44	$\frac{6.6}{30.6} \times 100$
			= 6.6	= 21.56%
CO	0.01	28	0.01×28	$\frac{0.28}{30.6} \times 100$
			= 0.28	= 0.92%
O_2	0.05	32	0.05×32	$\frac{1.6}{30.6} \times 100$
			= 1.6	= 5.23%
N_2	0.79	28	0.79×28	$\frac{22.12}{30.6} \times 100$
			22.12	= 72.29
			ΣC 30.6	Total = 100

Example 1.10. *A sample of coal has the following composition by weight C = 70%, Hydrogen 8%, nitrogen 3%, oxygen 7%, sulphur 2% and ash 10%.*

Determine higher calorific value and lower calorific value of fuel.

Solution. C = weight of carbon per kg of coal = 0.7

$$H_2 = 0.08; \; N_2 = 0.03; \; O_2 = 0.07$$

S = 0.02; Ash = 0.1.

$$\text{H.C.V.} = 8080C + 34{,}500\left(H_2 - \frac{O_2}{8}\right) + 2220\,S$$

$$= 8080 \times 0.7 + 34{,}500\left(0.08 - \frac{0.07}{8}\right) + 2220 \times 0.02$$

$$= 8770 \text{ kcal/kg}$$

$$\text{L.C.V.} = \text{HCV} - (9H_2 \times 586)$$

$$= 8770 - (9 \times 0.08 \times 586) = 8348 \text{ kcal/kg.}$$

Example 1.11. *A boiler furnace using 50% excess air burns coal with following composition :*

$C = 0.77$
$H_2 = 0.05$
$O_2 = 0.08$
$S = 0.02$
$N_2 = 0.02$
$Ash = 0.06$

The flue gases enter the chimney at 324°C and atmospheric temp. is 16°C.

$C_p = 1.007$ *kJ / kg for* O_2, N_2 *and air*

$= 1.05$ *kJ / kg for* CO_2 *and* SO_2 *from flue gas*

Heat carried away per kg of moisture from flue gas = 2930 kJ/kg

Determine the heat carried away by the flue gases in kJ / kg of coal.

Solution.

W_1 = Minimum amount of air required to burn one kg of coal

$$= \frac{100}{23}\left[\left(\frac{8}{3}C + 8H_2 + S\right) - O_2\right]$$

$$= \frac{100}{23}\left[\left(\frac{8}{3} \times 0.77 + 8 \times 0.05 + 0.02\right) - 0.08\right]$$

$$= 10.48 \text{ kg}$$

M = Mass of air required to burn one kg of coal

$$= W_1 + \text{Excess air}$$

$$= 10.48 + \frac{50}{100} \times 10.48 = 10.48 + 5.24$$

$= 15.72$ kg.

m_1 = Mass of CO_2 produced

$= \frac{11}{3} \times C$ as 1 kg of carbon produced $\frac{11}{3}$ kg of CO_2

$= \frac{11}{3} \times 0.77$

$= 2.82$ kg

m_2 = Mass of H_2O produced

$= 9 \times H_2$ as one kg of hydrogen produces 9 kg of water

$= 9 \times 0.05$

$= 0.45$ kg

m_3 = mass of SO_2 produced

$= 2 \times S$ as one kg of sulphur produces 2 kg of SO_2

$= 2 \times 0.02$

$= 0.04$ kg

m_4 = Mass of excess O_2 produced per kg of coal

$= \frac{23}{100} \times$ excess air supplied

$= \frac{23}{100} \times 5.24$

$= 1.2$ kg

m_5 = mass of N_2 produced

$= \frac{77}{100} \times$ Actual air supplied

$= \frac{77}{100} \times 15.72$

$= 12.1$ kg

T_1 = Temp. of flue gases entering the chimney = 324°C

$T_2 = 16°C$

H_1 = Heat carried away by CO_2

= Mass × Specific heat × Rise in temperature

$= m_1 \times C_p \times (T_1 - T_2)$

$= 2.82 \times 1.05 \times (324 - 16)$

$= 912$ kJ/kg

H_2 = Heat carried away by SO_2

$= m_3 \times C_p \times (T_1 - T_2)$

$= 0.04 \times 1.05 \times (324 - 16)$

$= 12.94$ kJ/kg

H_3 = Heat carried away by excess O_2

$= m_4 \times C_p \times (T_1 - T_2)$

$= 1.2 \times 1.007 \times (324 - 16)$

$= 372$ kJ/kg

H_4 = Heat carried away by N_2

$= m_5 \times C_p (T_1 - T_2)$

$= 12.1 \times 1.007 \times (324 - 16)$

$= 3753$ kJ/kg

H_5 = Heat carried away by moisture

$= 2930$ kJ $\times m_2$

$= 2930 \times 0.45$

$= 1318.5$ kJ

H = Total heat carried away be flue gas

$= H_1 + H_2 + H_3 + H_4 + H_5$

$= 912 + 12.94 + 372 + 3753 + 1318.5$

$= 6368.5$ kJ/kg of coal.

PROBLEMS

1.1. Name and explain the various sources of energy. Compare the various sources of energy.

1.2. What are the various types of solid fuels ? Describe Bituminous, Lignite and Anthracite varieties of coal.

1.3. What do you understand by higher calorific value (H.C.V.) and lower calorific value (L.C.V.) of a fuel ? Explain Dulong's formula to find H.C.V.

1.4. What is meant by composition of fuel ? Give percentage composition of some of liquid fuels. Explain ultimate analysis to find various constituents of a solid fuel.

1.5. What are the various advantages of liquid fuels and gaseous fuels over solid fuels ?

1.6. Write short notes on the following :
(*i*) Degrees A.P.I. of liquid fuel
(*ii*) Firing qualities of coal
(*iii*) Combustion of fuels
(*iv*) Types of gaseous fuels
(*v*) Ultimate analysis
(*vi*) Proximate analysis
(*vii*) Products of combustion
(*viii*) Requirements of a fuel.

1.7. A boiler uses an oil with a calorific value of 9000 kcal/kg. The analysis of the oil is 85 per cent carbon and 15 per cent hydrogen. The air supplied is double the theoretical mass required for the complete combustion of the oil. Calculate the mass of exhaust gases per kg of oil burnt.

1.8. The percentage composition by weight of a sample of coal is given below :

$C = 70\%$, $H_2 = 6\%$
$O_2 = 22\%$ $S = 2\%$

Using Dulong formula, determine the calorific value of coal.

1.9. Explain the method to find the weight of excess air required for the combustion of a fuel.

1.10. Write short *notes on the following* :
(*a*) Principal stages of fuel combustion.
(*b*) Theoretical temperature of combustion of a fuel.

1.11. A boiler uses fuel oil. Gravimetric analysis : Carbon 0.86 and hydrogen 0.14 at the rate of consumption is 500 kg/hour. The air supplied is 25% in excess of theoretical minimum air required for complete combustion. What is the total amount of air supplied per hour ? [**Ans.** 9250 kg/h]

1.12. The ultimate analysis of a sample of coal gives in percentage composition by weight. $C = 66\%$, $H_2 = 6\%$, $O_2 = 19\%$ and $S = 9\%$. Find the calorific value of coal using Dulong's formula.

1.13. Discuss the sources of energy in India.

1.14. Write short notes on the following :
(*a*) Conservation of energy
(*b*) Tidal power
(*c*) Solar energy
(*d*) Geothermal energy.

1.15. A fuel contains the following percentage of combustibles by weight :

Carbon 84%, and hydrogen 4.1%.

If the air used for burning of the coal in a boiler is 16.2 by per kg of fuel, find the total heat carried away by dry flue gases and if they escape at 300 C. The specific heat of CO_2, O_2, N_2 are 0.213 and 0.219-0.50 respectively. Find the minimum amount of air required for the complete combustion of 1 kg of this fuel and the excess oxygen supplied. [*A.M.I.E. 1974*]

1.16. Write short notes on the following :
(*a*) Liquid fuel properties

(*b*) Conservation of energy
(*c*) Advantages of liquid fuels over solid fuels.

1.17. Discuss the conditions for proper burning of fuel.

1.18. Describe how to find the following :
(*a*) Weight of carbon in flue gases
(*b*) Weight of flue gas per kg of fuel burnt.

1.19. Define the following :
(*a*) Minimum air
(*b*) Excess air
(*c*) Products of combustion
(*d*) Conventional and non-conventional sources of energy.

1.20. A sample of producer gas has the following analysis by volume :

$CO_2 = 24\%$, $H_2 = 14\%$, $CH_4 = 5\%$
$CO_2 = 6\%$, $O_2 = 2\%$, $N_2 = 49\%$

Calculate the air required for complete combustion of one cubic metre of fuel. Also find the volume of dry flue gas.

1.21. Explain the advantages of having a common grid for all the power stations in a region.

2

Power Plant Economics

2.1 Power Plant

Power plant is an assembly of equipment that produces and delivers mechanical and electrical energy. Electrical equipment of a power station includes generators, transformers, switch gears and control gears. Fig. 2.1 shows the main part of a power system.

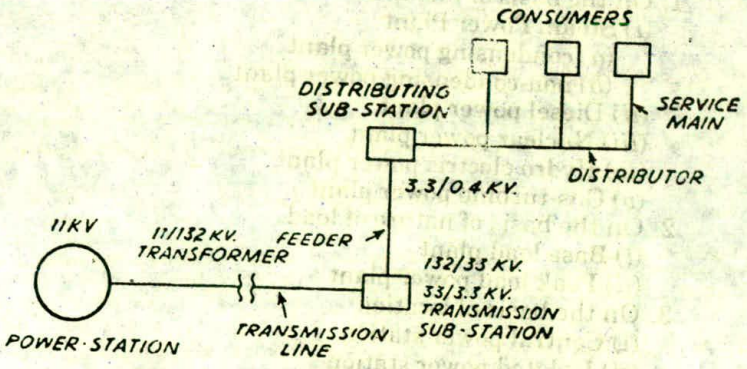


Fig. 2.1

From the economic point of view it is desirable that when large amount of electric power is to be transmitted over long distance it should be transmitted at a voltage higher than the distribution voltage. The voltage for transmission should be so chosen that it gives best efficiency, regulation and economy. Step up transformer is used to step up the generation voltage to transmission voltage which is usually 132 kV. At the transmission sub station the voltage is stepped down to medium voltage usually 33 or 3.3 kV. The feeders carry the power to the distribution sub-stations. Feeders should not be tapped for direct power supply. The function of transformers at the distribution sub-station is to step down the voltage to low

distribution voltage which is usually 400 to 230 V. Distributors are used to supply power to the consumers.

Transmission of electric power over long distances can be done most economically by using extra high voltage (E.H.V.) lines. In the world today many A.C. extra high voltage lines are in operation. These E.H.V. lines operate at voltages higher than the high voltage lines *i.e.* 230 kV. The E.H.V. lines are now in operation in Europe, USA and Canada and operate at 330 kV, 400 kV, 500 kV and 700 kV. Still higher voltage 1000 kV level are in the experimental stage. In India there is no E.H.V. line so far but it is hoped that soon such lines in the form of Super Grid will be developed.

2.2 Types of Power Plants

Based upon the various factors the power plants are classified as follows :

1. On the basis of fuel used
   - (*i*) Steam Power Plant
     - (*a*) condensing power plant
     - (*b*) non-condensing power plant
   - (*ii*) Diesel power plant
   - (*iii*) Nuclear power plant
   - (*iv*) Hydro electric power plant
   - (*v*) Gas-turbine power plant
2. On the basis of nature of load
   - (*i*) Base load plant
   - (*ii*) Peak load power plant
3. On the basis of location
   - (*i*) Central power station
   - (*ii*) Isolated power station
4. On the basis of service rendered.
   - (*i*) Stationary
   - (*ii*) Locomotive.

2.3 Requirement of Plant Design

The factors to be kept in view while designing a power station are follows :

1. Economy of expenditure *i.e.* minimum
   - (*i*) Capital cost
   - (*ii*) Operating and maintenance cost.
2. Safety of plant and personnel
3. Reliability
4. Efficiency
5. Ease of maintenance
6. Good working conditions
7. Minimum transmission loss.

2.4 Useful Life of a Power Plant

Every power plant wears as the time proceeds and it becomes less fit for use. The deterioration of the equipment takes place because of age of service, wear and tear and corrosion. By a thorough programme of preventive maintenance and repairs it is possible to keep the power station in good conditions to get proper service from it. A power plant becomes obsolete when it can be replaced by one of more modern design which operates at a reduction in total annual costs. Therefore, useful life of a power plant is that after which repairs become so frequent and expensive that it is found economical to replace the power plant by a new one. Useful life of a conventional thermal power plant is 20 to 25 years; the useful life of nuclear power plant is 15 to 20 years and useful life of a diesel power plant is about 15 years. The useful life of some of the equipment of a steam power plant is indicated in Table 2.1.

Table 2.1.

Equipment	*Useful life (years)*
Steam turbine	5—20
Steam turbo-generators	10—20
Boilers — Fire tubes	10—15
Boilers — Water tube	20
Coal and ash machinery	10—20
Pumps	15—20
Feed water heaters	20—30
Condensers	20
Stacks	10—30
Stokers	10—20
Transmission lines	10—20
Transformers	15—20
Motors	20
Electric meters and instruments	10—15

2.5 Comparison of Public Supply and Private Generating Plant

Industrial concerns may generate their own power or may purchase power from public supply company. The two are compared as follows :

(*a*) **Public Supply**

(*i*) Reliability of power is assured and over-load power demand can be available at short notices.

(*ii*) It is cheaper to purchase power from public supply company.

(*iii*) The space required for the installation of power generating unit is considerably large. The same space can be saved and utilised for some other purpose such as for the expansion of industry.

(*b*) **Private Generating Plant**

(*i*) Industries where power demand is small and where power is required continuously such as in hospitals, private power generation is preferred. In such cases power generation by diesel power plant is economical.

(*ii*) Industries where wastes produced can be used as fuel, prefer to generate their lower power. For example in sugar mills the left-over of sugarcane called begasse can be burnt as fuel in boiler which can be used for steam generation.

(*iii*) In industries like sugar mills and textile mills steam is required for processing work. Therefore, such industries generate their own power by steam turbines so that steam leaving the turbines can be used for processing work.

2.6 Prediction of Future Loads

When a power station is to be installed in a particular area it is desirable that maximum power demand of that area should be known. This help in deciding the capacity of the power station. Although it is difficult to forecast exactly the future load requirements of the area but approximate estimate about power demand should be made. Two methods are used to forecast the load requirements.

(*i*) Statistical method (*ii*) Field survey method.

In statistical method data of annual maximum demand pertaining to the area is collected for past several years and from this data expected future load can be judged. In field survey method existing requirements of the area for different loads such as industrial, agricultural, municipal and residential are found out. Then the future load requirements are decided taking into account the various factors like population growth, standard of living of the people, climate of the regions and industrial development.

The load prediction or forecasting may be done for :

(*i*) Short term covering a period of 4 to 5 years.

(*ii*) Medium term, covering a period of about 8 to 10 years.

(*iii*) Long term, covering a period of about 20 years or more.

For the installation of a new power project or for the expansion of the existing power plant, it is necessary to estimate the total amount of load that would be required to be met for various purposes. The economics of the installation or expansion of a power plant calls for the correct prediction of load. The usual practice

followed in the hydro-power plant planning is that the full potential of the project is developed in stages. The power required for immediate demand is developed in Ist stage and remaining potential being developed in subsequent stages.

There are number of formulae used for estimating power generation requirements.

Scheer formula for estimating the power generation requirements are as follows :

$$\log_{10} G = K - 0.15 \log_{10} M$$

where G = Annual growth in generation (per cent)

M = Per capita generation

K = Constant

= 0.02 (population growth rate) + 1.33

2.7 Terms and Definitions

(*i*) **Connected Load.** It is the sum of ratings in kilowatts (kW) of equipment installed in the consumer's premises. If a consumer has connections for 4 lamps of 60 watts (W) each, and power point of 500 W and a radio consuming 60 W, then the total connected load of the consumer

$$= 4 \times 60 + 500 + 60 = 240 + 500 + 60 = 800 \text{ W}.$$

(*ii*) **Maximum Demand.** It is the maximum load which a consumer uses at any time. It can be less than or equal to connected load. If all the devices fitted in consumer's house run to their fullest extent simultaneously then the maximum demand will be equal to connected load. But generally the actual maximum demand is less than the connected load because all the devices never run at full load at the same time. Maximum demand of a power station is the maximum load on the power station in a given period.

(*iii*) **Demand Factor.** It is defined as the ratio of maximum demand to connected load.

(*iv*) **Load Curve.** It is graphical representation between load in kilowatt (kW) and time in hours. It shows variation of load on the power station. When it is plotted for 24 hours of a day it is called daily load curve and if the time considered is of one year (8760 hours) then it is called annual load curve. The areas under the load curve represents the energy generated in the period considered. The area under the curve divided by the total number of hours gives the average load on the power station. The peak load indicated by the load curve represents the maximum demand on the power station.

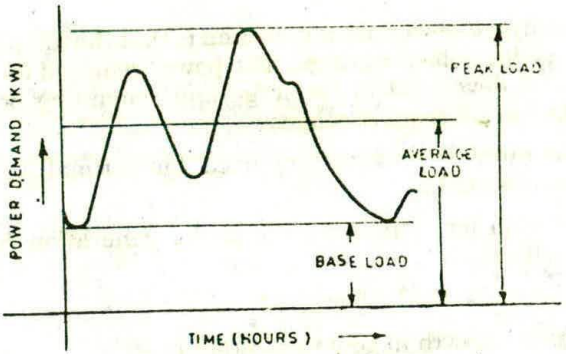


Fig. 2.2 Load Curve.

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. They also help to estimate the generating cost and to decide the operating schedule of the power station *i.e.* the sequence in which different generating units should be run. Fig. 2.2 shows a load curve.

(*v*) **Load Factor.** It is defined as the ratio of average load to maximum demand. Load factors and demand factors are always less than unity. Load factors play an important part on the cost of generation per unit. The higher the load factor the lesser will be the cost of generation per unit for the same maximum demand.

Load factors for different types of consumers are as follows :

(*i*) Residential load	10—15%
(*ii*) Commercial load	25—30%
(*iii*) Municipal load	25%
(*iv*) Industrial load	
(*a*) Small scale industries	30—50%
(*b*) Medium size industries	55—60%
(*c*) Heavy Industries	70—80%

Base load plants run on a high load factor whereas the load factor of peak load plants is usually low.

(*vi*) **Base Load and Peak Load Power Plants.** The power plants work at different load factors. The power plants used to supply the load of the base portion of load curve are called base load power plants. Base load power plants run throughout the year, are of large capacity and run at high load factors and are highly efficient. The fixed and semi-fixed cost of these plants is usually high. The power plants which supply the load on the top portion of load curve are called peak load plants. They are of smaller capacity, run for a

short period in the year and work at load low factors. Peak load plants should be capable of quick starting.

Hydro and nuclear power stations are usually classified as base load power stations. Thermal power stations may be taken as intermediate power stations whereas diesel power stations are usually classified as peak load stations. Parallel operation of different power stations and the co-ordination of generation electricity leads to considerable saving in comparison with the same load fed by independent power stations.

To meet the fluctuating power demand the power should be produced conforming to the demands. These days except a few isolated projects hydel power is used along with conventional steam power plant. In hydel power, regulation can be easily achieved by restricting the discharge through the water turbine and this can be achieved without much trouble. Time taken to activate a hydro power station is 5 to 15 minutes. The time of heating up a boiler of steam power station varies from 2 to 10 hours depending upon size. Therefore, it is now accepted practice that power system should consist of steam and hydel power each supplementing the other.

During combined working of hydro-power plant and steam power plant the hydro plant with ample water storage should be used as base load plant and steam power plant should be used as peak load plant. If the amount of water available at hydro power plant site is not sufficient then steam power plant should supply the base load and hydro power plant should supply peak load.

The major advantage of steam power plants is that they can be located near the load centre. This reduces the transmission losses and cost of transmission lines. In hydro-power plants there is more or less dependence on the availability of water which in turn depends on the natural phenomenon of rain. Although the operating cost of a hydroelectric power plant is very less but excessive, distance from the load centre may some time prohibit the use of such a plant in favour of a thermal power plant. Some hydro-power plants are supplemented by steam power plant or diesel engine power plant.

The requirements of a base load power plant are as follows :

(*i*) Its capital cost should be low.

(*ii*) It should be able to supply the load continuously.

(*iii*) Its operation cost should be low as it has to operate most of the time.

(*iv*) Its maintenance cost should be low.

The requirement of a peak load plant are as follows :

(*a*) It should be capable of being started from cold conditions within minimum time.

(*b*) Its operating cost should be low.

(*c*) Capital cost involved should be minimum.

(*vii*) **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.

$$\text{Plant capacity factor} = \frac{E}{C \times t}$$

where E = Energy produced (kWh) in a given period.

C = Capacity of the plant in kW

t = total number of hours in the given period.

(*viii*) **Plant Use Factor.** It is defined as the ratio of energy produced in given time to the maximum possible energy that could have been produced during the actual number of hours the plant was in operation.

$$\text{Plant use factor} = \frac{E}{C \times t_1}$$

where t_1 = actual number of hours the plant has been in operation.

(*ix*) **Diversity Factor.** It is defined as the ratio of sum of individual maximum demand to the simultaneous maximum demand of a system. Usually the maximum demand of various consumers do not occur at the same time and simultaneous maximum demand is less than their total maximum demand. Power station should be capable of supplying the simultaneous maximum demand. Diversity factor is more than unity.

The high value of load factor, demand factor, diversity factor and capacity factor are always desireable for economic operation of the power plant and to produce energy at cheaper rate.

Some typical demand factors are mentioned in Table 2.2.

Table 2.2

Type of Consumer		*Demand Factor*
Lighting (Residence)	up to 1/4 kW	1.00
	$\frac{1}{2}$ to 1/4 kW	0.60
	over 1 kW	0.50
Lighting (commercial)	Schools, Hostels,	0.50
	Small Industry, Theatres	0.60
	Restaurants, Offices, Stores	0.70

General Power Service	Up to 10 H.P. 10 to 20 H.P. 20 to 100 H.P. above 100 H.P.	0.75 0.65 0.55 0.50

Some typical diversity factors are mentioned in Table 2.3.

Table 2.3

Type of Consumer	*Diversity Factors*		
	Lighting (Residence)	*Lighting Commercial*	*General Power Service*
Between sub-stations	1.1	1.1	1.1
Between Feeders	1.2	1.2	1.2
Between Transformers	1.3	1.3	1.3
Between Consumers	3.5	1.5	1.5

(*x*) **Load Duration Curve.** Load duration curve represents re-arrangement of all the load elements of chronological load curve in the order of descending magnitude. This curve is derived from the chronological load curve. Consider typical daily load curve (Fig. 2.3) for a power station. It is observed that the maximum load on power station is 32 kW from 2 to 6 P.M. This is plotted in Fig. 2.4. Similarly other loads of the load curve are plotted in descending order in the same figure. This is called load duration curve.

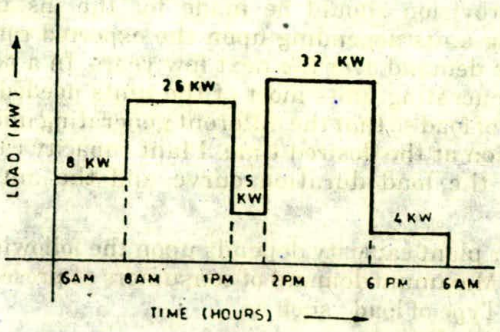


Fig. 2.3

The area under the load duration curve and the corresponding chronological load curve is equal and represents total energy delivered by the generation station. 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.

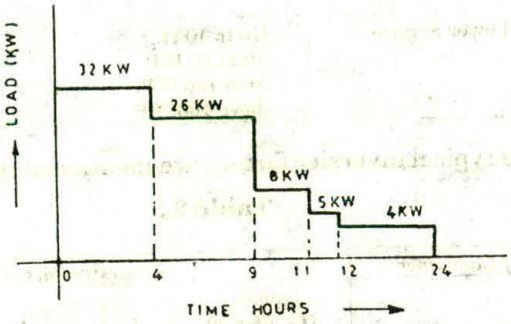


Fig. 2.4

2.8 Power Plant Capacity

The capacity of a power plant must be equal to atleast the peak load. In smaller power plants it is desirable to instal two generating units each being capable of supplying maximum demand so that if one unit is not working due to repair or breakdown the other is able to maintain uninterrupted supply of energy. In case of large power plants using several generating units the total installed capacity is kept equal to the expected maximum demand plus the capacity of the two largest generating units. The number of generating units should be kepts two or more than two so that in the event of breakdown or maintenance etc. of a unit the power can be supplied by other unit without interruption. While designing the power station provision should be made for the installation of more generating units depending upon the expected rate of increase of maximum demand over the next few years. In a power plant with several generating units most of the units needed to indicate the variation of load so that the different generating units can be placed in operation at the desired time. Plant capacity can be decided by studying the load duration curve and the anticipated future demand.

Power plant capacity depends upon the following factors :

(*i*) Maximum demand of consumers at present.

(*ii*) Type of load : such as

- (*a*) Private
- (*b*) Public
- (*c*) Industrial
- (*d*) Commercial
- (*e*) Domestic
- (*f*) Railways.

(*iii*) Future load conditions : Expected future electric power demand for at least next five years should be known.

(*iv*) Availability of fuel.

(*v*) Total cost of power plant.
(*vi*) Possibility of inter connecting the power plant to other power plants.

The advantage of having big power-plants is that it can directly generate high voltage required for long distance transportation. In this case, the loss of energy is in two ways : (*i*) long distance transportation, and (*ii*) transformation from high voltage into low voltage before use. In case of smaller plants, transportation loss is lesser because of short distance transportation but the transformation needs to be done twice, *viz.*, (*i*) from low voltage into high voltage before transportation, and (*ii*) from high voltage into low voltage before use. Additionally, construction of a number of smaller power-plants may, combined together, require more capital and infrastructure investments. Thus, a relative economic analysis along with other considerations like regional resource availability, socio-economic development, etc. would lead to an optimum capacity of a power-plant.

2.8.1 Feasibility of Electric Power Plant

Following factors should be considered while installing a new power plant :

(*i*) Estimate of probable load
(*ii*) Future load conditions
(*iii*) Power plant capacity
(*iv*) Total cost of power plant
(*v*) Annual running cost
(*vi*) The rate at which power will be sold to the consumer
(*vii*) Type of fuel to be used.

2.9 Principles of Power Plant Design

While designing a power plant the following factors should be considered :

(*i*) Low capital cost
(*ii*) Reliability of supplying power
(*iii*) Low maintenance cost
(*iv*) Low operating cost
(*v*) High efficiency
(*vi*) Low cost of energy generated
(*vii*) Reserve capacity to meet future power demand
(*viii*) Simplicity of design.

The above factors depend upon power plant site, availability of raw material, availability of water, type of load, maximum power demand, generating equipment etc.

2.10 Economic Load Sharing between Base Load and Peak Load Power Stations

Consider a system having load duration curve shown in Fig. 2.5. The load to be supplied by a base load power plant and peak load power plant.

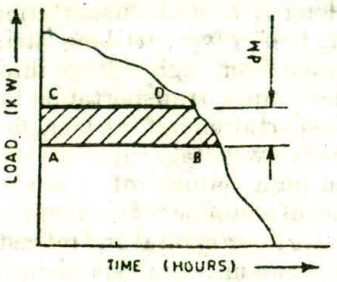


Fig. 2.5

Let C_1 = Annual cost of base load power station

C_2 = Annual cost of peak load power station

$C_1 = R_1$ kW + P_2 kWh

$C_2 = R_2$ kW + P_1 kWh

Assuming $R_1 > R_2$ and $P_1 < P_2$

Let M = Maximum demand of the system

E = Total number of unit (kWh) generated

M_1 = Peak load of base load station

E_1 = No. of units (kWh) generated by base load station

M_2 = Peak load on peak load station = $M - M_1$

E_2 = Units generated by peak load station = $E - E_1$

$C_1 = R_1M_1 + P_1E_1$

$C_2 = R_2 (M - M_1) + P_2 (E - E_1)$

P = Total annual cost of operation of the system

$C = C_1 + C_2$

$C = R_1M_1 + P_1E_1 + R_2 (M - M_1) + P_2 (E - E_1)$

Now for minimum cost

$$\frac{dC}{dM_1} = 0$$

This gives $\frac{dC}{dM_1} = 0 = R_1 + P_1 \frac{dE_1}{dM_1} - R_2 - P_2 \frac{dE_1}{dM_1}$

$$\frac{dE_1}{dM_1} = \frac{R_1 - R_2}{P_2 - P_1} \text{ hours.}$$

E_1 the number of units generated by the base load station is represented by area under straight line AB

$\therefore$ dE_1 = Area of strip $ABCD = dM_1 \times AB$

$$\therefore \quad AB = \frac{DE_1}{dM_1} = \frac{R_1 - R_2}{P_2 - P_1}$$

This indicates that for economic load sharing the peak load power station should run for $\frac{R_1 - R_2}{P_2 - P_1}$ hours in one year.

2.11 Type of Loads

The various type of loads are as follows :

Residential Load. It includes domestic lights, power needed for domestic appliances such as radio, television, water heaters, refrigerators, electric cookers and small motor for pumping water.

Commercial Load. It includes lighting for shop, advertisements and electrical appliances used in shops and restaurants etc.

Industrial Load. It consists of load demand of various industries.

Municipal Load. It consists of street lighting, power required for water supply and drainage purposes.

Irrigation Load. Electrical power need for pumps driven by electric motors to supply water to fields is included in this type of load.

Traction Load. It includes tram cars, trolley, buses and railways.

2.12 Typical Load Curves

Load curve indicates the power demand at different intervals of time. With the help of load curve the peak load can be ascertained and hence the capacity of power plant can be judged. Fig. 2.6 shows typical load curve for industrial load. The load starts increasing from 5 A.M. and it is maximum at about 8 A.M., when all the industries are working. It is constant till noon and falls for some time due to lunch break. After that it is again rising and then starts falling at about 5 P.M.

The urban load is high at about 9 A.M. It is less at noon and then starts rising and is maximum between 5.30 to 6 P.M. (Fig. 2.7)

The street lighting load (Fig. 2.8) is nearly constant.

Domestic load is maximum in the evening and is minimum during late hours of night (Fig. 2.9).

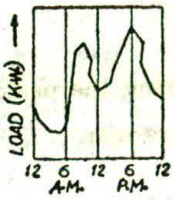


Fig. 2.6

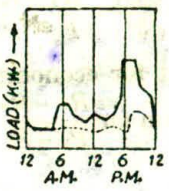


Fig. 2.7

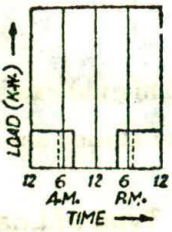


Fig. 2.8

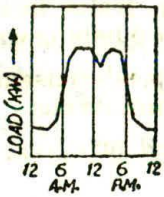


Fig. 2.9

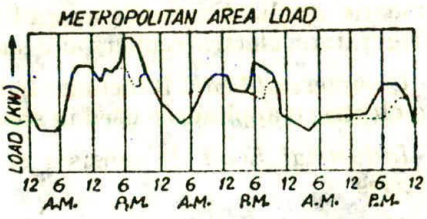


Fig. 2.10

This curve varies with cities and season. For metropolitan areas a typical daily load curve is shown in Fig. 2.10.

2.13 Cost of Electrical Energy

The total cost of electrical energy generated by a power station can be sub-divided as follows :

1. **Fixed cost.** It includes the following cost :
   (*a*) Capital cost of power plant.
      (*i*) Cost of land ;
      (*ii*) Cost of building ;
      (*iii*) Cost of equipment ;
      (*iv*) Cost of Installation ;
      (*v*) Cost of designing and planning the station.
   (*b*) Capital cost of primary distribution system which includes cost of sub-stations, cost of transmission lines etc.

   Fixed cost consists of the following :
   (*i*) Interest, taxes and insurance on the capital cost.
   (*ii*) General management cost.
   (*iii*) Depreciation cost.

Depreciation cost is the amount to be set aside per year from income to meet the depreciation caused by the age of service, wear and tear of machinery. Depreciation amount collected per year helps in replacing and repairing the equipment.

There are several methods of calculating the annual depreciation cost. The most commonly used methods are as follows :

1. Straight line method. 2. Sinking fund method.

(*a*) **Straight Line Method.** According to this method it is assumed that depreciation occurs uniformly according to a straight line law as shown in Fig. 2.11 (*a*). The annual amount to be set aside is calculated by the following expression :

$$\text{Annual depreciation reserve} = \frac{P - S}{n}$$

where A = Principal sum (capital cost of plant)

S = Salvage value or Residual value of power plant at the end of n years.

n = Probable duration of useful life of power plant in years.

The amount collected every year as depreciation fund does not depend on the interest it may draw. Any interest if earned by the depreciation amount is considered as income.

(*b*) **Sinking Fund Method.** In this method the annual amount to be set aside per year consist of annual instalments plus the interest on all the instalments.

Annual depreciation reserve

$$= (P - S)\left[\frac{r}{(1 + r)^n - 1}\right]$$

where r = rate of compound interest.

Fig. 2.11 (*b*) shows the depreciation curve.

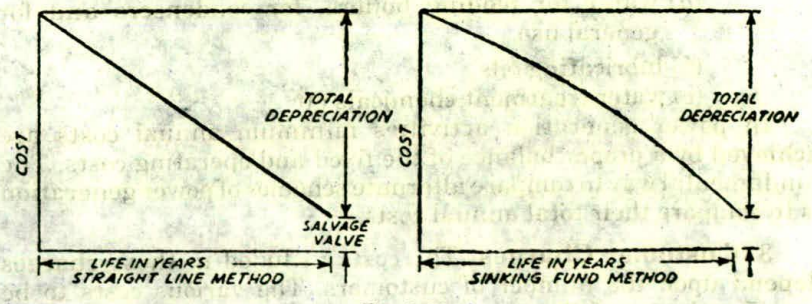


Fig. 2.11

Let P = Principal sum (capital cost of the plant)

S = Salvage value

n = Useful life in years.

r = Rate of interest

A = Annual depreciation amount.

Then the amount A after earning interest for one year

$$= A + Ar = A(1 + r)$$

The amount A after earning interest for two years

$$= A(1 + r) + A \times (1 + r) \times r = A(1 + r)^2.$$

The amount A set aside after one year will earn interest for $(n - 1)$ years.

Therefore, the sum of the amounts saved together with interest earnings should be equal to $(P - S)$

$$(P - S) = A + A(1 + r) + A(1 + r)^2 \ldots A(1 + r)^n \quad \ldots(i)$$

$$(P - S) = A[1 + (1 + r) + (1 + r)^2 \ldots (1 + r)^{n-1}]$$

Multiplying both sides by $(1 + r)$

$$(1 + r)(P - S) = A[(1 + r) + (1 + r)^2 + (1 + r)^3 \ldots (1 + r)^n] \quad \ldots(ii)$$

Substracting the two equations from each other, we get

$$r(P - S) = A[(1 + r)^n - 1]$$

$$A = (P - S)\left[\frac{r}{(1 + r)^n - 1}\right]$$

2. **Energy Cost.** It consists of the following costs :

(*i*) Cost of fuel ;

(*ii*) Cost of operating labour ;

(*iii*) Cost of maintenance labour and materials ;

(*iv*) Cost of supplies such as :

(*a*) water for feeding boilers, for condensers and for general use,

(*b*) lubricating oils,

(*c*) water treatment chemicals etc.

In power generation activities minimum annual costs are achieved by a proper balance of the fixed and operating costs. The fundamental way to compare alternate schemes of power generation is to compare their total annual costs.

3. **Customer Charges.** The costs included in these charges depend upon the number of customers. The various costs to be considered are as follows :

(*i*) Capital cost of secondary distribution system and depreciation cost, taxes and interest on this capital cost.

(*ii*) Cost of inspection and maintenance of distribution lines and the transformers.

(*iii*) Cost of labour required for meter reading and office work.

(*iv*) Cost of publicity.

4. **Investor's Profit.** The investor expects a satisfactory return on the capital investment. The rate of profit varies according to the business conditions prevailing in different localities.

Cost of power generation can be reduced by adopting the following economical measures :

(*i*) By reducing initial investment in the power plant.

(*ii*) By selecting generating units of adequate capacity.

(*iii*) By running the power plant at maximum possible load factor.

(*iv*) By increasing efficiency of fuel burning devices so that cost of fuel used is reduced.

(*v*) By simplifying the operation of the power plant so that fewer power operating men are required.

(*vi*) By installing the power plant as near the load centre as possible.

(*vii*) By reducing transmission and distribution losses.

2.14 Energy Rates (*Tariffs*)

Energy rates are the different methods of charging the consumers for the consumption of electricity. It is desirable to charge the consumer according to his 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.

Requirements of a Tariff. Tariff should satisfy the following requirements :

(*i*) It should be easier to understand.

(*ii*) It should provide low rates for high consumption.

(*iii*) It should encourage the consumers having high load factors.

(*iv*) It should take into account maximum demand charges and energy charges.

(*v*) It should provide less charges for power connections than for lighting.

(*vi*) It should avoid the complication of separate wiring and metering connections.

2.14.1 Types of Tariffs

The various types of tariffs are as follows :

(*a*) Flat demand rate

(*b*) Straight line meter rate

(*c*) Step meter rate

(*d*) Block rate tariff
(*e*) Two part tariff
(*f*) Three part tariff.

The various types of tariffs can be derived from the following general equation :

$$Y = DX + EZ + C$$

where Y = Total amount of bill for the period considered.

D = Rate per kW of maximum demand.

X = Maximum demand in kW.

E = Energy rate per kW.

Z = Energy consumed in kWh during the given period.

C = Constant amount to be charged from the consumer during each billing period.

Various type of tariffs are as follows :

(*i*) **Flat demand rate.** It is based on the number of lamps installed and a fixed number of hours of use per month or per year. The rate is expressed as a certain price per lamp or per unit of demand (kW) of the consumer. This energy rate eliminates the use of metering equipment. It is expressed by the expression

$$Y = DX$$

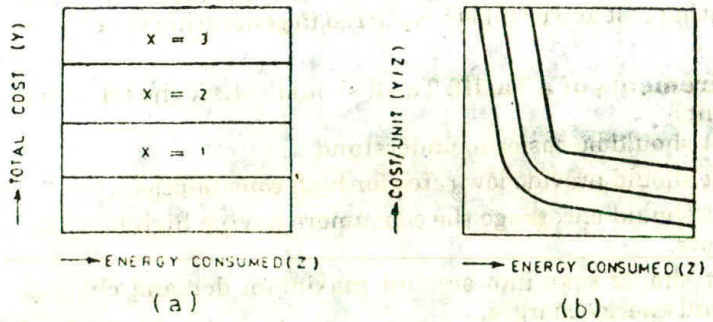


Fig. 2.12 Flat demand rate.

(*ii*) **Straight line meter rate.** According to this energy rate the amount to be charged from the consumer depends upon the energy consumed in kWh which is recorded by a means of a kilowatt hour meter. It is expressed in the form

$$Y = EZ$$

This rate suffers from a drawback that a consumer using no energy will not pay any amount although he has incurred some

expense to the power station due to its readiness to serve him. Secondly since the rate per kWh is fixed, this tariff does not encourage the consumer to use more power (Fig. 2.13).

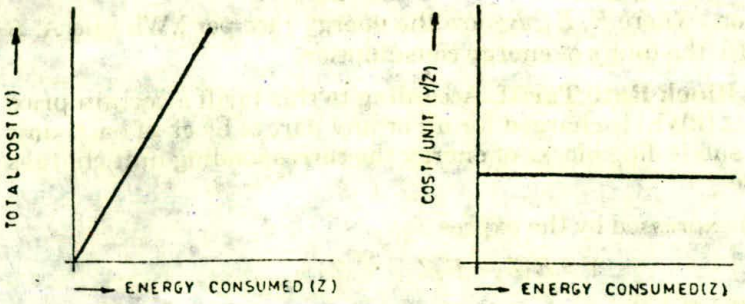


Fig. 2.13 Straight meter rate.

(iii) **Step meter rate.** According to this tariff the charge for energy consumption goes down as the energy consumption becomes more. This tariff is expressed as follows (Fig. 2.14).

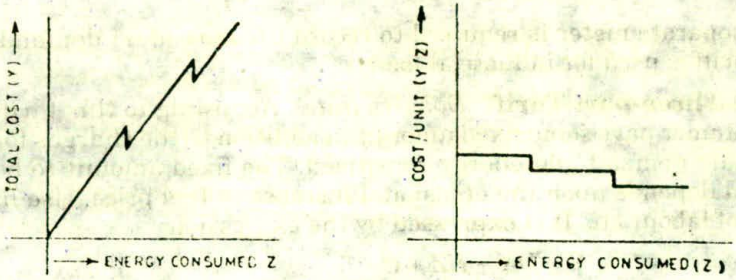


Fig. 2.14 Step meter rate.

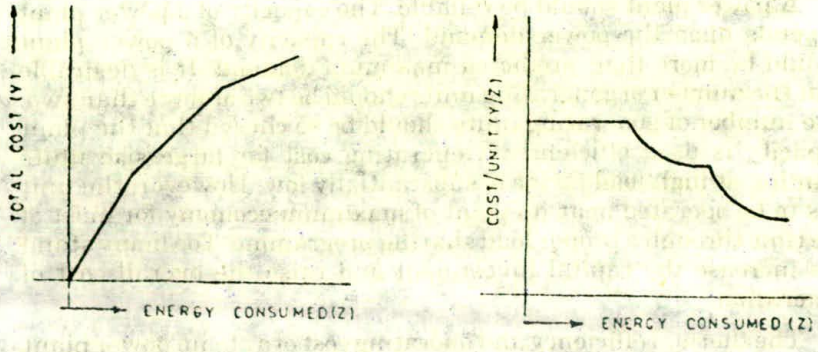


Fig. 2.15

$$Y = EZ \qquad \text{if } 0 \le Z \le A$$
$$Y = E_1Z_1 \qquad \text{if } A \le Z_1 \le B$$
$$Y = E_2Z_2 \qquad \text{if } B \le Z_2 \le C$$

and so on. Where E, E_1, E_2 are the energy rate per kWh and A, B and C are the limits of energy consumption.

(*iv*) **Block Rate Tariff.** According to this tariff a certain price per units (kWh) is charged for all or any part of block of each unit and for succeeding blocks of energy the corresponding unit charges decrease.

It is expressed by the expression

$$Y = E_1Z_1 + E_2Z_2 + E_3Z_3 + ...$$

where E_1, E_2, E_3.... are unit energy charges for energy blocks of magnitude Z_1, Z_2, Z_3,.... respectively (Fig. 2.15).

(*v*) **Two part Tariff** (*Hopkinson Demand Rate*). In this tariff the total charges are based on the maximum demand and energy consumed. It is expressed as

$$Y = D \,.\, X + EZ$$

A separate meter is required to record the maximum demand. This tariff is used for industrial loads.

(*vi*) **Three-part Tariff** (*Doherty Rate*). According to this tariff the customer pays some fixed amount in addition to the charges for maximum demand and energy consumed. The fixed amount to be charged depends upon the occasional increase in fuel price, rise in wages of labour etc. It is expressed by the expression

$$Y = DX + EZ + C.$$

2.15 Economics in Plant Selection

A power plant should be reliable. The capacity of a power plant depends upon the power demand. The capacity of a power plant should be more than predicted maximum demand. It is desirable that the number of generating units should be two or more than two. The number of generating units should be so chosen that the plant capacity is used efficiently. Generating cost for large size units running at high load factor is substantially low. However, the unit has to be operated near its point of maximum economy for most of the time through a proper load sharing programme. Too many stand bys increase the capital investment and raise the overall cost of generation.

The thermal efficiency and operating cost of a steam power plant depend upon the steam conditions such as throttle pressure and temperature.

The efficiency of a boiler is maximum at rated capacity. Boiler fitted with heat recovering devices like air preheater, economiser etc. gives efficiency of the order of 90%. But the cost of additional equipment (air preheater economiser) has to be balanced against gain in operating cost.

Power can be produced at low cost from a hydropower plant provided water is available in large quantities. The capital cost per unit installed is higher if the quantity of water available is small. While installing a hydropower plant cost of land, cost of water rights, and civil engineering works cost should be properly considered as they involve large capital expenditure.

The other factor which influences the choice of hydropower plant is the cost of power transmission lines and the loss of energy in transmission. The planning, design and construction of a hydro plant is difficult and takes sufficient time.

The nuclear power plant should be installed in an area having limited conventional power resources. Further a nuclear power plant should be located in a remote or unpopulated are to avoid damage due to radioactive leakage during an accident and also the disposal of radioactive waste should be easy and a large quantity of water should be available at the site selected. Nuclear power becomes competitive with conventional coal fired steam power plant above the unit size of 500 MW.

The capital cost of a nuclear power plant is more than a steam power plant of comparable size. Nuclear power plants require less space as compared to any other plant of equivalent size. The cost of maintenance of the plant is high.

The diesel power plant can be easily located at the load centre. The choice of the diesel power plant depends upon thermodynamic considerations. The engine efficiency improves with compression ratio but higher pressure necessitates heavier construction of equipment with increased cost. Diesel power plants are quite suitable for smaller outputs. The gas turbine power plant is also suitable for smaller outputs. The cost of a gas turbine plant is relatively low. The cost of gas turbine increases as the sample plant is modified by the inclusion of equipment like regenerator, reheater, and intercooler although there is an improvement in efficiency of the plant by the above equipment. This plant is quite useful for regions where gaseous fuel is available in large quantities.

In order to meet the variable load the prime movers and generators have to act fairly quickly to take up or shed load without variation of the voltage or frequency of the system. This requires that supply of fuel to the prime mover should be carried out by the action of a governor. Diesel and hydro-power plants are quick to

respond to load variation as the control supply is only for the prime mover. In a steam power plant control is required for the boilers as well as turbine. Boiler control may be manual or automatic for feeding air, feed water fuel etc. Boiler control takes time to act and therefore, steam powers plants cannot take up the variable load quickly. Further to cope with variable load operation it is necessary for the power station to keep reserve plant ready to maintain reliability and continuity of power supply at all times. To supply variable load combined working of power stations is also economical.

For example to supply a load the base load may be supplied by a steam power plant and peak load may be supplied by a hydropower plant or diesel power plant.

The size and number of generating units should be so chosen that each will operate on about full load or the load at which it gives maximum efficiency. The reserve required would only be one unit of the largest size. In a power station neither there should be only one generating unit nor should there be a large number of small sets of different sizes. In steam power plant generating sets of 80 to 500 MW are quite commonly used whereas the maximum size of diesel power plant generating sets is about 4000 kW. Hydro electric generating sets up to a capacity of 200 MW are in use in U.S.A.

2.16 Economic of Power Generation

Economy is the main principle of design of a power plant. Power plant economics is important in controlling the total power costs to the consumer. Power should be supplied to the consumer at the lowest possible cost per kWh. The total cost of power generation is made up of fixed cost and operating cost. Fixed cost consists of interest on capital, taxes, insurance and management cost. Operating cost consists of cost of fuel labour, repairs, stores and supervision. The cost of power generation can be reduced by,

(*i*) Selecting equipment of longer life and proper capacities.

(*ii*) Running the power station at high load factor.

(*iii*) Increasing the efficiency of the power plant.

(*iv*) Carrying out proper maintenance of power plant equipment to avoid plant breakdowns.

(*v*) Keeping proper supervision as a good supervision is reflected in lesser breakdowns and extended plant life.

(*vi*) Using a plant of simple design that does not need highly skilled personnel.

Power plant selection depends upon the fixed cost and operating cost. The fuel costs are relatively low and fixed cost and operation and maintenance charges are quite high in a case of a nuclear power plant. The fuel cost in quite high in a diesel power plant and for hydro power plant the fixed charges are high of the order of 70 to

80% of the cost of generation. Fuel is the heaviest items of operating cost in a steam power station. A typical proportion of generating cost for a steam power station is as follows :

Fuel cost	= 30 to 40%
Fixed charges for the plant	= 50 to 60%
Operation and maintenance cost	= 5 to 10%

The power generating units should be run at about full load or the load at which they can give maximum efficiency. The way of deciding the size and number of generating units in the power station is to choose the number of sets to fit the load curve as closely at possible. It is necessary for a power station to maintain reliability and continuity of power supply at all times. In an electric power plant the capital cost of the generating equipments increases with an increase in efficiency. The benefit of such increase in the capital investment will be realised in lower fuel costs as the consumption of fuel decreases with an increase in cycle efficiency.

Fig. 2.15 (*a*) shows the variation of fixed cost and operation cost with investment.

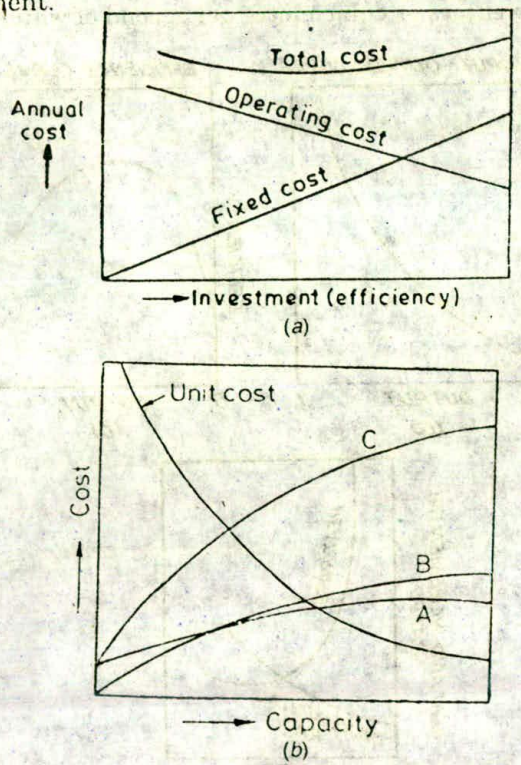


Fig. 2.15

Fig. 2.15 (*b*) shows the variation of various costs of power plant versus its capacity.

Graph *A* shows variation of engineering and labour cost where as graph *B* indicates material cost and graph *C* indicates total cost.

$$\text{Unit Cost} = \frac{\text{Total cost}}{\text{Capacity}}$$

2.17 Plant Performance and Operation Characteristics

Boilers, turbines, generators etc. of a power stations should work efficiently. Some curves are plotted to observe their performance. The various curves used are as follows :

1. *Input output curve.* Performance of a power station is most precisely described by the input-output curve which is a graphical representation between the net energy output (L) and input (I). The input is generally expressed as millions of BTU/hr or kcal/hr and load or output is expressed in megawatts. The input to hydroplant is measured in cusecs or cubic metre per second of water.

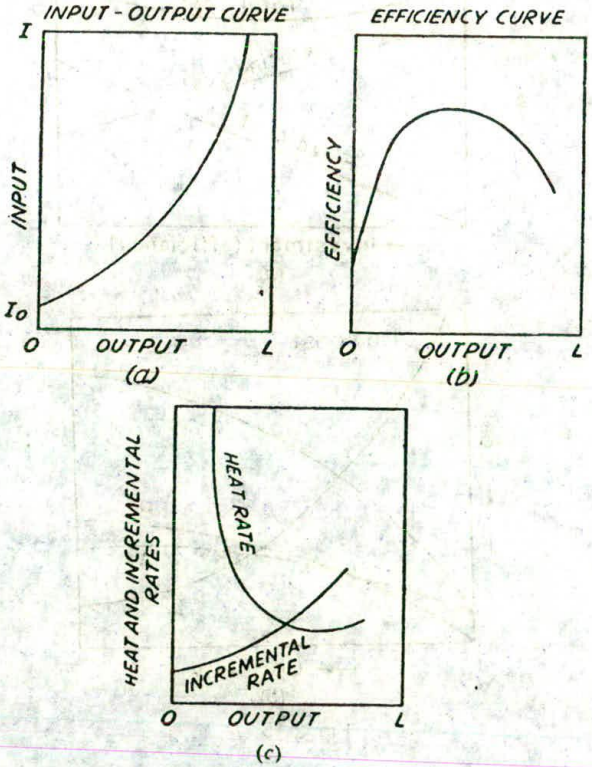


Fig. 2.16

Fig. 2.16 (*a*) shows input-output curve. In order to keep the apparatus functioning at zero load a certain input (I_o) is required to meet frictional and heat losses.

2. *Efficiency curve.* The ratio of output of power station to input is called efficiency. The efficiency curve is obtained by plotting efficiency against output. It is shown in Fig. 2.16 (*b*).

3. *Heat rate curve.* The ratio of input to output is known as heat rate (HR).

$$\text{HR} = I/L$$

Heat rate curve is obtained by plotting values of heat rate against corresponding value of output. Fig. 2.16 (*c*) shows heat rate curve.

4. *Incremental rate curve.* Incremental rate (IR) is defined as

$$\text{IR} = \frac{dI}{dL}$$

Incremental rate is obtained by plotting values of I.R. against corresponding values of output. Fig. 2.16 (*c*) shows I.R. curve. This curve expresses additional energy required to produce an added unit of output at the given load.

2.18 Economic Load Sharing

The total load to be supplied by the power station should be economically distributed among the various generating units installed at the power station. Consider a power station having two generating units *A* and *B*. Fig. 2.14 (*a*) shows the input output-curves of power generating unit *A* and *B* which supply in parallel a common load. Although unit *A* requires less input for a given output it is not essential that unit *A* should be loaded first and then unit *B*. For economical loading the combined input of units *A* and *B* should be plotted against load on unit *A* for a constant total load. Let a total load of 4 MW is to be supplied by units *A* and *B*.

$$L_C = 4 \text{ MW} = L_A + L_B$$

where L_C = Combined output

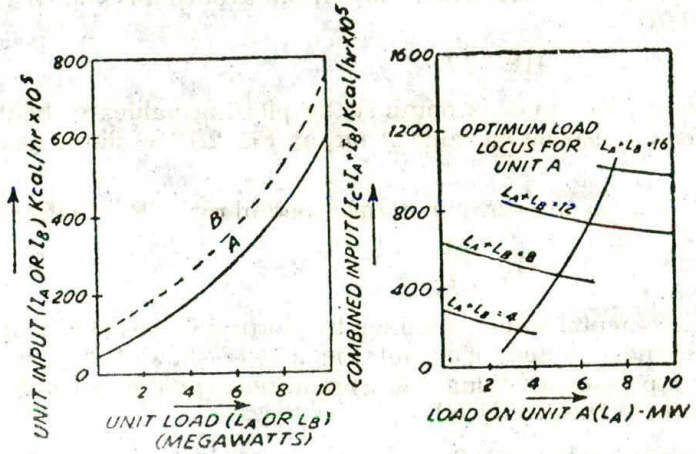
L_A = Output of unit *A*

L_B = Output of unit *B*.

Let the unit *B* supplies total load of 4 MW and unit *A* supplies zero load.

Now corresponding to zero load on unit *A* and 4 MW on unit *B* the values of input to unit *A* (I_A) and input to unit *B* (I_B) can be determined respectively from Fig. 2.17 (*a*) and thus value of ($I_A + I_B$) can be plotted against zero load on unit *A*. Again let 2 MW

is supplied by unit A and 2 MW is supplied by unit B (so that total load remains 4 MW) then values of I_A and I_B can be determined corresponding to 2 MW load on each unit and value of $(I_A + I_B)$ can be plotted against 2 MW load on unit A as shown in Fig. 2.14 (b). In this way curve for a total load of 4 MW can be plotted corresponding to different output of unit A.



(a) (b)

Fig. 2.17

Similarly curves for total load of 8 MW, 12 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 of unit A can be found. Then the load on unit B will be difference of total load and load on unit A.

This method is not easily applicable for power stations, where more than two power generating units supply the load.

Consider two units A and B sharing a total load L_C.

Let, I_C = Combined input = $I_A + I_B$ ...(i)

= Input to unit A + Input to unit B

and L_C = Combined output = $L_A + L_B$

= Output of unit A + Output of unit B.

Differentiating (i), we get

$$\frac{dI_C}{dL_A} = \frac{dI_A}{dL_A} + \frac{dI_B}{dL_A} = 0 \qquad \left[\because \frac{dI_C}{dL_A} = 0\right]$$

As I_C is constant,

$$\therefore \quad \frac{dI_A}{dL_A} = -\frac{dI_B}{dL_A} \qquad \ldots(1)$$

But $$\frac{dI_B}{dL_A} = \frac{dI_B}{dL_B} \times \frac{dL_B}{dL_A} \qquad \ldots(2)$$

Now $$L_C = L_A + L_B$$

$$\frac{dL_C}{dL_A} = \frac{dL_A}{dL_A} + \frac{dL_B}{dL_A}$$

But L_C is constant,

$$\therefore \quad \frac{dL_C}{dL_A} = 0$$

$$\therefore \quad -\frac{dL_A}{dL_A} = \frac{dL_B}{dL_A}$$

$$-1 = \frac{dL_B}{dL_A} \qquad \ldots(3)$$

Substituting in (2), we get

$$\frac{dI_B}{dL_A} = -\frac{dI_B}{dL_B} \qquad \ldots(4)$$

$\therefore$ From (1) and (4)

$$\frac{dI_A}{dL_A} = \frac{dI_B}{dL_B}$$

Therefore, to achieve best economy in load sharing, the slopes of the input-output curves for each unit must be equal at L_A and L_B (Fig. 2.18). In other words, the incremental heat rates are equal.

2.19 Condition for Maximum Efficiency

The load at which efficiency will be maximum the heat rate will be minimum at that load as efficiency is inverse of heat rate.

Efficiency $= L/I$

Heat rate (H.R.) $= I/L$

Therefore, for minimum value of heat rate

$$\frac{d}{dL}(\text{HR}) = 0$$

$$\therefore \quad \frac{d}{dL}\left(\frac{I}{L}\right) = 0$$

$$\therefore \quad \frac{LdI - IdL}{L^2} = 0$$

$$LdI = IdL$$

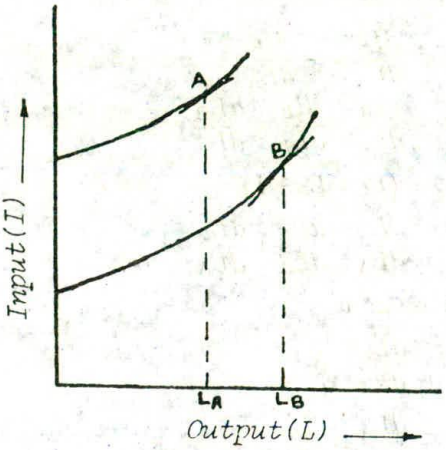


Fig. 2.18

$$\frac{I}{L} \quad \frac{dI}{dL}$$

This shows that efficiency will be maximum at a load where heat rate is equal to incremental heat rate.

2.20 Choice of Power Station

In a power station energy is converted from one form or another into electrical energy. The power plant should be able to meet power demand efficiently.

The various factors to be considered while choosing the type of power plant are as follows :

(*i*) *Type of fuel available.* If the site where power plant is to be installed if near the coal mines then steam power plant is preferred whereas a hydro power plant is chosen if water is available in larger quantity. Nuclear power plants are located near river or sea so that nuclear waste can be disposed off easily. Diesel power plant is used for supplying smaller loads.

(*ii*) *Power plant site.* The power plant site should satisfy the following requirements :

(*a*) Cost of land as well as taxes on land should be low.

(*b*) It should be nearer to load centre so that cost of transmitting energy is low.

(*c*) It should be accessible by road, rail or sea so that transportation of fuel etc. is easier.

(*d*) Sufficient quantity of cooling water should be available near the site.

(*e*) The site selected should be away from thickly populated areas in order to avoid atmospheric pollution and to reduce noise.

(*f*) Sufficient space for future expansion of power station should be available near the site.

(*g*) Site sub-soil conditions should be such that foundation can be made at reasonable depth.

(*iii*) *Type of load.* It is essential for a power plant to maintain reliability and continuity of power supply at all times.

If the load varies and is not large a diesel power plant should be chosen. If a hydro power plant of small or suitable capacity is made available it can also be used for supplying varying load as it can be started in shorter period and can take up load quickly. The large base load is supplied by hydro power plant, steam power plant or nuclear power plant. The nuclear power plants cannot be operated efficiently at varying loads. Power plant capacity must be equal to at least peak load.

(*iv*) *Generating units.* There should not be only one generating unit nor there should be large number of small generating units. It is economical to use a few generating units of larger size than using number of small size generating units for the same total capacity. The aim should be to have generating unit of different capacities which will suitably fit in load curve so that most of the generating sets when in use can be operated at nearly full load. There should be at least two generating sets whatever the total capacity of power plant may be.

Steam generators of 80 to 200 MW are in use in big power plants whereas hydro-electric generators sets up to 200 MW are in use.

(*v*) *Cost.* The initial cost of hydro power plant is high although its operating cost is low. The capital cost of a nuclear power plant is also high. But higher capacity of a nuclear power plant is an advantage. A gas turbine power plant is less expensive in initial plus operating costs than the equivalent steam power plant. The total cost of a diesel power plant per kW of the installed capacity is about 20 to 30% less than that of a steam power plant of equivalent size.

It is always desirable to run the power station at high load factor so that the installed capacity of power plant is used to the best possible extent and maximum possible amount of energy is produced which will lower the total cost both fixed and operating costs. A poor load factor increases cost per kilowatt hour.

2.21 Effect of Variable Load on Power Plant Operation and Design

The variable load problem affects power plant design and operation and the cost of generation. To supply variable load a careful study of load duration curve is needed. This will help to decide the capacity of base load plant and peak load plant. The base load plant should be run at high load factor. The peak load plant should be of as small capacity as possible to reduce cost per kilowatt hour (kWh). Economical load sharing between base load plant and peak load plant is desirable. Steam power plants and nuclear power are preferred as base load plants whereas diesel power plant and hydro power plant can be used as peak load plant. Hydro power plant with larger water storage can also be used as base load plant. If the whole of load is to be supplied by the same power plant then the prime movers and generators should act fairly quickly and take up or shed load without variation of the voltage or frequency of the system. An important requirement is therefore the control of supply of fuel to the prime mover by the action of governor. The equipment to be used for variable load conditions should be so designed that it operates at lower loads with nearly same efficiency as at full load. The size of the generators should be so chosen as to suit and fit into the portions of the predicted load curve. If the load conditions differ too much from the ideal the cost of energy increases.

Example 2.1. *A power station has a maximum demand of* 80×10^3 *kW and daily load curve is defined as follows :*

Time (hours)	*0-6*	*6-8*	*8-12*	*12-14*	*14-18*	*18-26*	*22-24*
Load (MW)	*40*	*50*	*60*	*50*	*70*	*80*	*40*

(*a*) *Determine the load factors of power station.*

(*b*) *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.*

Solution. (*a*) Load curve is shown in Fig. 2.19. Energy generated (area under the load curve)

$$= 40 \times 6 + 50 \times 2 + 60 \times 4 + 50 \times 2 + 70 \times 4 + 8 \times 4 + 40 \times 2$$

$$= 1360 \text{ MWh} = 1360 \times 10^3 \text{ kWh.}$$

$$\therefore \text{ Average load} = \frac{1360 \times 10^3}{24} = 56{,}666 \text{ kW.}$$

Maximum demand $= 80 \times 10^3$ kW.

$$\text{Load Factor} = \frac{\text{Average load}}{\text{Max. demand}} = \frac{56{,}666}{80{,}000} = \mathbf{0.71.}\ \textbf{Ans.}$$

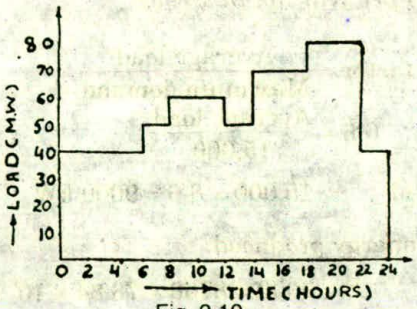


Fig. 2.19

(*b*) Now the standby equipment supplies

10 MW (70 – 60 = 10) for 4 hours

and 20 MW (80 – 60 = 20) for 4 hours.

∴ Energy generated by standby equipment

$$= (10 \times 4 + 20 \times 4) \times 10^3 = 120 \times 10^3 \text{ kWh}$$

Time for which standby equipment remains in operation (from the load curve) = 8 hours

$$\text{Average load} = \frac{120 \times 10^3}{8} = 15 \times 10^3 \text{ kW.}$$

$$\text{Load factor} = \frac{15 \times 10^3}{20 \times 10^3} = \mathbf{0.75.}\ \textbf{Ans.}$$

$$\text{Use factor} = \frac{E}{C \times t_1}$$

where E = Energy generated

C = Capacity of the standby equipment.

t_1 = Number of hours the plant has been in operation.

$$\therefore \text{ Use factor} = \frac{120 \times 10^3}{25 \times 10^3 \times 8} = \mathbf{0.6.}\ \textbf{Ans.}$$

Example 2.2. *A central power station has annual factors as follows :*

Load factor = 60% ; *Capacity factor* = 40%

Use factor = 45%

Power station has a maximum demand of 15,000 kW.

Determine :

(a) Annual energy production

(b) Reserve capacity over and above peak load

(c) Hours per year not in service.

Solution.

(a) Load factor $= \dfrac{\text{Average load}}{\text{Maximum demand}}$

$$0.6 = \frac{\text{Average load}}{15{,}000}$$

Average load $= 15{,}000 \times 0.6 = 9000$ kW.

$\therefore$ Annual energy produced

$$E = 9000 \times 8760 = 78.84 \times 10^6 \text{ kWh.}$$

(b) Capacity factor $= \dfrac{E}{C \times t}$

where C = capacity of the plant

t = time in hours in one year = 8760 hours

$$0.4 = \frac{78.84 \times 10^6}{C \times 8760}$$

$$C = \frac{78.84 \times 10^6}{0.4 \times 8760} = 22{,}500 \text{ kW}$$

$\therefore$ Reserved capacity = 22,500 – 15,000 = 7500 kW.

(c) Use factor $= \dfrac{E}{C \times t_1}$

where t_1 = Actual number of hours of the year for which the plant remains in operation.

$$0.45 = \frac{78.84 \times 10^6}{22{,}500 \times t_1}$$

$$t_1 = \frac{78.84 \times 10^6}{22{,}500 \times 0.45} = 7786 \text{ hours.}$$

$\therefore$ Hours per year not in service = 8760 – 7786 = 974 hours.

Example 2.3. *Find the diversity factor of power station which supplies the following loads :*

Load A : Motor load of 100 kW working between 10 A.M. and 6 P.M.

Load B : Lighting load of 60 kW between 6 P.M. and 10 A.M.

Load C : Pumping load of 40 kW between 4 P.M. and 10 A.M.

Solution. In this case sum of maximum demands = 100 + 60 + 40 = 200 kW and the simultaneous maximum demand is found as follows :

Time	*Load (kW)*	*Total load (kW)*
10 A.M. to 4 P.M.	100 (motor)	100
4 P.M. to 6 P.M.	100 (motor)	
+	40 (pumping)	140
6 P.M. to 10 P.M.	60 (lighting)	
+	40 (pumping)	100
10 P.M. to 10 A.M.	40 (pumping)	40

The above values show that simultaneous maximum demand on the power station is 140 kW.

$$\therefore \text{ Diversity factor} = \frac{200}{140} = 1.43.$$

Example 2.4. *The annual peak load on a 30 MW power station is 25 MW. The power station supplies loads having maximum demands of 10 MW, 8.5 MW, 5 MW and 4.5 MW. The annual load factor is 45%.*

Find :

(a) Average load,
(b) Energy supplied per year,
(c) Diversity factor,
(d) Demand factor.

Solution. Capacity of power station = 30 MW

Maximum demand on power station = 25 MW

(a) $\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$

$\therefore$ Average load = $0.45 \times 25 = 11.25$ MW.

(b) Energy supplied per year

= Average load × Number of hours in one year

$= (11.25 \times 1000) \times 8760 = 98.55 \times 10^6$ kWh.

(c) Diversity factor

$$= \frac{\text{Sum of individuals maximum demands}}{\text{Simultaneous maximum demand}}$$

$$= \frac{10 + 8.5 + 5 + 4.5}{25} = \frac{28}{25} = 1.12$$

(d) Demand factor of power station

$$= \frac{\text{Maximum demand}}{\text{Connected load}} = \frac{25}{10 + 8.5 + 5 + 4.5} = \frac{25}{28} = 0.89.$$

Example 2.5. *For a power station the yearly load duration curve is a straight line from 30,000 to 4,000 kW. To meet the load three turbo-generator are installed. The capacity of two generators is 15,000 kW each and the third is rated at 5,000 kW. Determine the following :*

(a) Load factor,

(b) Capacity factor or plant factor,

(c) Maximum demand.

Solution. As shown in Fig. 2.20 the load curve is a straight line from 30,000 to 4,000 kW

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

From the given load duration curve.

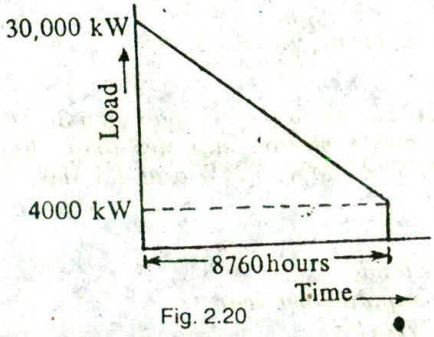


Fig. 2.20

Energy generated per year

= Area under the curve

$$= 4000 \times 8760 + \frac{1}{2} \times 8760 \times 2600$$

$$= 8760\,(4000 + 13{,}000) = 8760 \times 17{,}000 \text{ kWh}$$

$$= \frac{\text{Energy generated per year}}{8760}$$

$$\text{Average load} = \frac{8760 \times 17000}{8760} = 17{,}000 \text{ kW}$$

Maximum demand = 30,000 kW.

$$\text{Load factor} = \frac{17{,}000}{30{,}000} = 0.57 = 57\%$$

$$\text{Capacity factor} = \frac{\text{Energy produced}}{\text{Capacity of plant} \times \text{Time}}$$

Capacity of plant = 15,000 + 15,000 + 5,000 = 35,000 kW

$$\text{Capacity factor} = \frac{8760 \times 17{,}000}{35{,}000 \times 8760} = \frac{17{,}000}{35{,}000} = 0.49 = 49\%.$$

Example 2.6. *A power station has two 60 MW units each running for 7000 hours a year and one 30 MW unit running for 1500 hours a year. The energy produced per year is 700×10^6 kWh. Calculate the following :*

(a) Plant load factor

(b) Plant use factor or utilisation factor.

Solution. (a) Total capacity of power plant,

$$C = 60 + 60 + 30 = 150 \text{ MW} = (150 \times 1000) \text{ kW}.$$

$$\text{Average load} = \frac{700 \times 10^6}{8760} \text{ kW}.$$

(8760 being the number of hours in one year)

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

(Assuming power stations capacity equal to maximum demand)

$$= \frac{700 \times 10^6}{8760 \times 150 \times 1000} = 0.53 = 53\%. \quad \textbf{Ans.}$$

(b) Actual energy generated = 700×10^6 kWh.

Energy that could be generated by two 60 MW units and one 30 MW units .

$$= 2 \times 60 \times 7000 + 30 \times 1500 = 84 \times 10^4 + 45 \times 10^3$$

$$= 88.5 \times 10^4 \text{ MWh} = 88.5 \times 10^4 \times 10^3 \text{ kWh}$$

$$= 885 \times 10^6 \text{ kWh}$$

$$\therefore \text{ Plant use factor} = \frac{700 \times 10^6}{885 \times 10^6} = 0.79 = 79\%. \quad \textbf{Ans.}$$

Example 2.7. *A base load power station and standby power station share a common load as follows :*

Base load station annual output	$= 150 \times 10^6$ *kWh*
Base load station capacity	$= 35$ *MW*
Maximum demand on base load station	$= 30$ *MW*
Standby station capacity	$= 18$ *MW*
Standby station annual output	$= 14 \times 10^6$ *kWh*

Maximum demand (peak load) on standby station = 15 MW.

Determine the following for both power station :

(a) Load factor

(b) Capacity factor (Plant factor).

Solution. (*a*) **Base load station**

$$\text{Average load} = \frac{150 \times 10^6}{8760} = 17{,}100 \text{ kW.}$$

$$\therefore \text{ Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$= \frac{17{,}100}{30 \times 1000} = \frac{170}{300} = 0.57$$

$$\text{Capacity factors} = \frac{\text{Energy generated}}{\text{Capacity of plant} \times 8760}$$

$$= \frac{150 \times 10^6}{35 \times 8760} = 0.49 = 49\%.$$

(*b*) **Standby power station**

$$\text{Annual average load} = \frac{14 \times 10^6}{8760} = 1600 \text{ kW.}$$

$$\text{Annual load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$= \frac{1600}{15{,}000} = \frac{16}{150} \times 100 = 10.7\%$$

$$\text{Capacity factor} = \frac{\text{Energy generated}}{\text{Capacity} \times 8760} = \frac{14 \times 10^6}{18 \times 1000 \times 8760}$$

$$= 0.09 = 9\%. \quad \textbf{Ans.}$$

Example 2.8. *A power station is to supply three region of load whose peak loads are 20 MW, 15 MW and 25 MW. The annual load factor is 50% and the diversity factor of the load at the station is 1.5. Determine the following :*

(*a*) *Maximum demand on the station,*
(*b*) *Installed capacity suggesting number of unit,*
(*c*) *Annual energy supplied.*

Solution. (*a*) Diversity factor

$$= \frac{\text{Sum of individual maximum demand}}{\text{Simultaneous maximum demand}}$$

$$\therefore \text{ Simultaneous maximum demand}$$

$$= \frac{\text{Sum of individual maximum demand}}{\text{Diversity factor}}$$

$$= \frac{20 + 15 + 25}{15} = 40 \text{ MW.}$$

Hence maximum demand on station = 40 MW.

(*b*) Installed capacity of the plant can be taken equal to sum of individual maximum demand.

$\therefore$ Installed capacity = 20 + 15 + 25 = 60 **MW.**

Two units each of capacity 30 **MW** can be installed.

(*c*) Load factor = $\frac{\text{Average load}}{\text{Maximum demand}}$.

Average load = Load factor × Maximum demand

$= 0.5 \times 40 \times 1000 = 20 \times 1000$ kW.

$\therefore$ Energy produced per year

$= 20 \times 1000 \times 8760 = 175.2 \times 10^6$ kWh.

Example 2.9. *A power station is said to have a use factor of 47% and capacity factor of 40%. How many hours did it operate during the year.*

Solution. Let E = Energy produced

C = Capacity of plant

t_1 = Number of hours the plant has been in operation

t = 8760 hours (number of hours in an year)

$$0.47 = \frac{E}{C \times t_1} \quad \ldots(i)$$

$$0.40 = \frac{E}{C \times 8760} \quad \ldots(ii)$$

Dividing (*ii*) by (*i*), we get

$$\frac{0.40}{0.47} = \frac{E}{C \times 8760} \times \frac{C \times t_1}{E} = \frac{t_1}{8760}$$

$$t_1 = \frac{0.40 \times 8760}{0.47} = 7455 \text{ hours.}$$

Example 2.10. *Determine the generating cost per unit of 8 MW power station with the following data :*

Capital cost = *Rs.* 40×10^5
Annual cost of fuel = *Rs. 80,000*
Annual wages and taxes = *Rs. 90,000*
Interest and depreciation = *10%*
Annual load factor = *45%*

Solution. Interest and depreciation

$$= \frac{10}{100} \times 4 \times 10^5 = \text{Rs. } 4 \times 10^5$$

Cost of fuel + Cost of wages and taxes = 80,000 + 90,000

$$= \text{Rs. } 170{,}000 = \text{Rs. } 1.7 \times 10^5$$

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$\therefore$ Average load = Load factor × Maximum demand

$$= 0.45 \times 8 = 3.6 \text{ MW} = 3600 \text{ kW}$$

Energy produced per year

$$= 3600 \times 8760 \text{ kWh} = 31 \times 10^6 \text{ kWh.}$$

Total cost $= (4 \times 10^5 + 1.7 \times 10^5) = \text{Rs. } 5.7 \times 10^5$

$\therefore$ Energy cost per kWh

$$= \frac{5.7 \times 10^5}{31 \times 10^6} \times 100 = 1.84 \text{ paise.}$$

Example 2.11. *In a 60 MW steam power station working at 40% load factor the energy cost is found to be 1.5 paise / kWh. Calculate the cost of energy if the power station load factor is improved to 50%. Due to increased energy generation the fuel cost increases the annual, generation cost by 6%.*

Solution. Load factor $= \dfrac{\text{Average load}}{\text{Maximum demand}}$

Average load = (0.4 × 60,000) kW

Annual energy generated

$$= 0.4 \times 60{,}000 \times 8760 \text{ kWh} = 210 \times 10^6 \text{ kWh}$$

$$\text{Total annual cost} = 210 \times 10^6 \times \frac{1.5}{100} = \text{Rs. } 315 \times 10^4$$

Now when the load factor is 50%.

Annual energy generated

$$= 0.5 \times 60{,}000 \times 8760 = 262 \times 10^6 \text{ kWh.}$$

Annual cost at 50% load factor

$$= 315 \times 10^4 \times 1.06 = \text{Rs. } 333 \times 10^4$$

$$\therefore \text{ Cost per kWh} = \frac{333 \times 10^4}{262 \times 10^6} = 1.23 \text{ paise.} \quad \textbf{Ans.}$$

Example 2.12. *A 150 H.P. motor is required to operate at full load for 800 hours per year, at half load for 1800 hours per year and to be shut down for the remainder of the time. The motors available are :*

Motor M : *Cost = Rs. 11,000*
Efficiency at full load = 88%
Efficiency at half load = 85%

Motor N : *Efficiency at full load = 90%*
Efficiency at half load = 87%

Determine the maximum price which could economically be paid for motor N if the energy rate is 8 paise per kWh. Interest and depreciation cost may be taken as 12% per year.

Solution. *Motor M* : Output at full load

$$= 150 \times 0.735 \times 0.88 = 96 \text{ kW}.$$

(Assuming 1 H.P. = 735 watts)

Output at half load $= 75 \times 0.735 \times 0.85 = 47$ kW.

Energy consumed per year

$$= 96 \times 800 + 47 \times 1800 = 161{,}400 \text{ kWh}$$

Cost of energy $= 161{,}400 \times \frac{8}{100} = \text{Rs. } 12{,}912$

Interest and depreciation $= \frac{12}{100} \times 11{,}000 = \text{Rs. } 1320.$

Total cost $= 12{,}912 + 1320 = \text{Rs. } 14{,}232$

Motor N : Output at full load

$$= 150 \times 0.735 \times 0.9 = 99 \text{ kW}.$$

Output at half load $= 75 \times 0.735 \times 0.87 = 48$ kW.

Energy consumed per year

$$= 99 \times 800 + 48 \times 1800 = 166{,}600 \text{ kW}.$$

Cost of Energy $= 166{,}600 \times \frac{8}{100} = \text{Rs. } 13{,}328.$

Let the cost of motor = C

Interest and depreciation $= \frac{12}{100} \times C$

Total cost $= \text{Rs.} \left[13{,}328 + \frac{12}{100} \times C \right]$

Assuming annual cost of motor M and motor N to be equal

$$14{,}232 = 13{,}328 + \frac{12}{100} \times C$$

$$C = \text{Rs. } 7533. \quad \textbf{Ans.}$$

Example 2.13. *The load of a residential consumer for a day was found to be as follows :*

From 12.00 midnight to 6 A.M.	*No load*
From 6 A.M. to 8 A.M.	*120 W*
From 6 A.M. to 9.30 A.M.	*540 W*
From 9.30 A.M. to 11.30 A.M.	*No load*
From 11.30 A.M. to 2 P.M.	*480 W*
From 2 P.M. to 3.30 P.M.	*No load*
From 3.30 P.M. to 5 P.M.	*120 W*
From 5 P.M. to 6.30 P.M.	*360 W*
From 6.30 A.M. to 9 A.M.	*480 W*
From 9 P.M. to 12 mid night	*120 W*

Calculate :

(a) Energy consumed

(b) Load factor.

Solution. Energy consumed during the day

$$= 120 \times 3 + 540 \times 1.5 + 480 \times 2.5 + 120 \times 1.5 + 360 \times 1.5 + 480 \times 2.5 + 120 \times 3$$

$$= 4470 \text{ Wh} = 4.470 \text{ kWh.}$$

$$\text{Average load} = \frac{4470}{24} = 186 \text{ W.}$$

$$\text{Maximum demand} = 540 \text{ W.}$$

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$= \frac{186}{540} = 0.34 \quad \textbf{Ans.}$$

Example 2.14. *In a steam power station having a maximum demand of 20 MW the boiler efficiency and turbine efficiency are 80% and 90% respectively.*

If the coal consumption is 1 kg per unit of energy generated and cost of coal Rs. 40 per tonne ; determine :

(a) The thermal efficiency of power station,

(b) Cost of coal per year.

Annual load factor is 50%.

Solution. (a) Thermal efficiency

$$= \text{Boiler efficiency} \times \text{Turbine efficiency}$$

$$= 0.8 \times 0.9 = 0.72 \text{ or } 72\%$$

(*b*) Load factor = $\frac{\text{Average load}}{\text{Maximum demand}}$

$\therefore$ Average load = $0.5 \times 20 = 10$ MW

Energy generated per year

$$= (10 \times 1000) \times 8760 = 87.6 \times 10^6 \text{ kWh.}$$

$$\text{Coal consumption} = \frac{87.6 \times 10^6 \times 1}{1000}$$

$$= (87.6 \times 10^3) \text{ tonnes.}$$

Annual cost of coal = $(87.6 \times 10^3) \times 40$ = Rs. 3,504,000.

Example 2.15. *Determine the annual cost of a feed water softener from the following data :*

Cost	= *Rs. 80,000*
Salvage value	= *5%*
Life	= *10 years.*
Annual repair and maintenance cost	= *Rs. 2500*
Annual cost of chemicals	= *Rs. 5,000*
Labour cost per month	= *Rs. 300*
Interest on sinking fund	= *5%.*

Solution. Capital cost,

$$P = \text{Rs. } 80{,}000$$

$$\text{Salvage value, } S = \text{Rs. } \frac{5}{100} \times 80{,}000$$

$$n = \text{Life} = 10 \text{ years.}$$

Rate of interest on sinking fund, $r = 5\%$.

$\therefore$ Annual sinking fund payment

$$= (P - S)\left[\frac{r}{(1+r)^n - 1}\right]$$

$$= 0.95 \times 80{,}000 \times \left[\frac{0.05}{(1+0.5)^{10} - 1}\right]$$

$$= \text{Rs. } 0.95 \times 8 \times 10^4 \left(\frac{0.05}{1.63 - 1}\right) = \text{Rs. } 6040$$

Total cost per year

Annual sinking fund	= Rs. 6040
Annual repair and maintenance cost	= Rs. 2500

Annual cost of chemicals = Rs. 5000
Annual labour cost = Rs. 3600
$\therefore$ Total cost = Rs. 17,140.

Example 2.16. *A 500 kW electric power station cost Rs. 800 per kW installed. The plant supplies 150 kW for 5000 hours of the year, 400 kW for 1000 hours and 25 kW for the remaining period. Determine the cost of production per unit of electric energy. The fixed charges are 10% and operating charges 7 paise per kWh.*

Solution. Energy supplied

$$= 5000 \times 150 + 1000 \times 400 + 2760 \times 25$$

$$= 1{,}219{,}000 \text{ kWh}$$

$$\text{Fixed cost} = \frac{10}{100} \times (800 \times 500) = \text{Rs. } 40{,}000$$

$$\text{Cost per kWh} = \left(7 + \frac{40{,}000}{1{,}219{,}000}\right) = 10.3 \text{ paise.}$$

Example 2.17. *(a) Compute the monthly bill and unit energy cost for a total consumption of 1600 kWh and a maximum demand of 10 kW using Hopkinson demand rate quoted as follows :*

Demand Rates

First kilo-watts of maximum demand Rs. 15 per kW per month.

Next 5 kW of maximum demand at Rs. 12 per kW per month.

Excess over 6 kW of maximum demand at Rs. 10 per kW per month.

Energy Rates

First 50 kWh at 15 paise per kWh.

Next 50 kWh at 12 paise per kWh.

Next 300 kWh at 8 paise per kWh.

Next 500 kWh at 6 paise per kWh.

Excess over 900 kWh at 4 paise per kWh.

(b) Also find the lowest possible bill for a month for 3 days and the unit energy cost on the given energy consumption.

Solution. (a) Demand charge = $15 + 5 \times 12 + 4 \times 10$

$$= 15 + 60 + 40 = \text{Rs. } 115.$$

Energy charges = $50 \times 0.15 + 50 \times 0.12 + 300 \times 0.08$
$+ 500 \times 0.06 + 700 \times 0.04$

$$= \text{Rs. } 95.50$$

$\because$ Monthly bill = 115 + 95.50 = 210.50

$$\text{Unit energy cost} = \frac{210{,}50}{1600}$$

$$= 13.15 \text{ paise per kWh.}$$

(*b*) The lowest bill occurs when the demand is maximum which is possible at 100% load factor.

$\therefore$ Maximum demand = Average load

$$= \frac{1600}{30 \times 24} = 2.2 \text{ kW.}$$

Demand charge $= 15 + 1.22 \times 12 = 15 + 14.64 = \text{Rs. } 29.64$

$\therefore$ Energy charge = Rs. 95.50

$\therefore$ Minimum monthly bill

$$= 29.64 + 95.50 = \text{Rs. } 125.14.$$

$$\text{Unit energy cost} = \frac{125.14}{1600} = 7.8 \text{ paise per kWh.}$$

Example 2.18. *The annual cost of operating a 15,000 kW thermal power station are as follows :*

Cost of plant	= *Rs. 900 per kW*
Interest, insurance taxes on plant	= *5%*
Depreciation	= *5%*
Cost of primary distribution system	= *Rs. 500,000*

Interest, insurance, taxes and depreciation on primary distribution system = 5%

Cost of secondary distribution system = Rs. 900,000

Interest, taxes, insurance and depreciation on secondary distribution system = 5%

Maintenance of secondary distribution system = 180,000.

Plant Maintenance cost	
(*i*) *Fixed cost*	= *Rs. 30,000*
(*ii*) *Variable cost*	= *Rs. 40,000*
Operating costs	= *Rs.* 600,000
Cost of coal	= *Rs. 60 per tonnes*
Consumption of coal	= *30,000 tonnes*
Dividend to stock-holders	= *Rs. 10,00,000*
Energy loss in transmission	= *10%*
Maximum demand	= *14,000 kW*
Diversity factor	= *1.5*

Load factor = 70%

Device a two part tariff.

Solution. Maximum demand = 14,000 kW

$$\text{Load factor} = 0.7 = \frac{\text{Average load}}{\text{Maximum demand}}$$

$\therefore$ Average load = $0.7 \times 14{,}000$

$\therefore$ Energy generated per year = $14{,}000 \times 0.7 \times 8760$

$= 85.8 \times 10^6$ kWh

Cost of plant = Capacity of plant × Cost per kW

$= 15{,}000 \times 900$ = Rs. 1,35,00,000

Interest, insurances, taxes on plant

$$= \frac{5}{100} \times 13{,}500{,}000 = \text{Rs. } 675{,}000$$

$$\text{Plant depreciation} = \frac{5}{100} \times 13{,}500{,}000 = \text{Rs. } 675{,}000$$

Interest, insurance, taxes, depreciation on primary distribution system

$$= \frac{5}{100} \times 500{,}000 = \text{Rs. } 25{,}000$$

Cost of secondary distribution system

= Rs. 900,000.

$\therefore$ Interest, insurance, taxes depreciation on secondary distribution system

$$= \frac{5}{100} \times 900{,}000 = \text{Rs. } 45{,}000$$

Cost of coal $= 60 \times 30{,}000$ = Rs. 18,00,000

Fixed Costs

Interest, taxes and insurance on plant	= Rs. 675,000
Plant depreciation	= Rs. 675,000
Interest, taxes, insurance and depreciation on primary distribution system	= Rs. 25,000
On secondary distribution system	= Rs. 45,000
Fixed part of plant maintenance	= Rs. 30,000
Dividend of stock-holder	= Rs. 10,00,000
$\therefore$ Total fixed cost	= Rs. 24,50,000

Sum of maximum demand of consumers

$$= \text{Diversity factor} \times \text{Maximum demand}$$

$$= 1.5 \times 14{,}000 = 21{,}000 \text{ kW}$$

$\therefore$ Charge per kW per year

$$= \frac{24{,}50{,}000}{21{,}000} = \text{Rs. } 116.6 \text{ per kW per year.}$$

Variable Costs

Cost of coal	= Rs. 18,00,000
Plant maintenance	= Rs. 40,000
Variable part of operating cost	= Rs. 600,000
Total variable cost	= Rs. 26,20,000
Energy loss in transmission	= 10%

$\therefore$ Net energy transmitted

$$= 0.9 \times 85.8 \times 10^6 = 77.2 \times 10^6 \text{ kWh.}$$

$\therefore$ Rate per kWh $= \frac{2{,}620{,}000}{72.2 \times 10^6} = 3.4$ paise per kWh.

Example 2.19. *The annual costs expected by a utility system in supplying certain residential suburb of 40,000 customers are as follows :*

Fixed charges	= *Rs. 2,40,00,000*
Energy charges	= *Rs. 17,86,000*
Customer charges	= *Rs. 210,000*
Profit	= *Rs. 168,000*
Maximum demand	= *5000 kW*
Energy registered on customer's metres	= 17×10^6 *kWh*
Diversity factor	= *4*

Form a three charge rate putting $\frac{1}{4}$ *of profit in fixed charges* $\frac{1}{2}$ *in energy charges and* $\frac{1}{4}$ *in customer charges.*

Solution. Sum of maximum demands of customers

$$= 5000 \times 4 = 20{,}000 \text{ kW}$$

Fixed cost $= 2{,}400{,}000 + \frac{1}{4} \times 168{,}000 = \text{Rs. } 2{,}42{,}000.$

$\therefore$ Cost per kW per year

$$= \frac{24{,}42{,}000}{20{,}000} = \text{Rs. } 122.10$$

Energy cost = $17,86,000 + \frac{1}{2} \times 1,68,000$ = Rs. 18,70,000

$\therefore$ Energy rate $= \frac{187,00,000}{17 \times 10^6}$ = 11 paise per kWh.

Customer charge = $210,000 + \frac{1}{4} \times 168,000$ = Rs. 252,000

Charges per customer per year

$$= \frac{252,000}{40,000} = \text{Rs. } 6.30.$$

Example 2.20. *An input-output curve of a 10 MW station is expressed as follows :*

$$I = 10^6 (10 + 8L + 0.4 L^2)$$

where I is in kcal per hour and L is in mega watts.

(a) *Without plotting any curve find the load at which the maximum efficiency occurs.*

(b) *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. (a) $I = 10^6 (10 + 8L + 0.4 L^2)$

$$\frac{I}{L} = 10^6 \left[\frac{10}{L} + 8 + 0.4L\right]$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{L}{I}.$$

$\therefore$ $$\eta = \frac{1}{10^6 \left(\frac{10}{L} + 8 + 0.4L\right)} \quad \ldots(1)$$

Now for maximum value efficiency

$$\frac{d\eta}{dL} = 0$$

Differentiating (1), we get

$$\frac{d\eta}{dL} = \frac{-10^6 \left(-\frac{10}{L_2} + 0.4\right)}{\left[10^6 \left(\frac{10}{L} + 8 + 0.4L\right)\right]} = 0$$

$$\therefore \quad -10^6\left[\frac{-10}{L^2}+0.4\right]=0$$

or $$\frac{10}{L^2}=0.4$$

$$10-0.4L^2=0$$

$$L^2=\frac{10}{0.4}=25$$

$$L=5 \text{ MW}.$$

(*b*) When load $L = 3$ MW

Input $I_3 = 10^6\,[10 + 8 \times 3 + 0.4 \times 3^2]$

$= 10^6\,[10 + 24 + 3.6] = 37.6 \times 10^6$ kcal/hour.

When load $L = 5$ MW

Input $I_5 = 10^6\,[10 + 8 \times 5 + 0.4 \times 5^2]$

$= 10^6\,[10 + 40 + 10]$

$= 60 \times 10^6$ kcal/hour.

Increase in input required $= I_5 - I_3$

$= (60 - 37.6) \times 10^6 = 22.4 \times 10^6$ kcal/hr.

From 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 a

$$\frac{3+5}{2}=4 \text{ MW}$$

$+ 8L + 0.4L^2)$

Increment rate, IR $8L) \times 10^6$

$\therefore$ $IR = (8 + 0.8 \times 4) \times 10^6$, when load = 4 MW

$= (8 + 3.2) \times 10^6 = (11.2) \times 10^6$

Hence total increase in input

$= (11.2 \times 2) \times 10^6 = 22.4 \times 10^6$ kcal/hour.

Thus increase in input needed to increase stations output from 3 to 5 MW in both cases is same. This shows that the incremental rate curve can be assumed to be straight line.

Example 2.21. *The incremental fuel costs for two generating units A and B of a power plant are given by the following questions:*

$$\frac{dF_A}{dP_A} = 0.06\,P_A + 11.4$$

$$\frac{dF_B}{dP_B} = 0.07\,P_B + 10$$

where P is in mega-watts and F is in rupees per hour.

(*a*) *Find the economic loading of the two units when the total load to be supplied by the power station is 150 MW.*

(*b*) *Find the loss in fuel cost per hour if load is equally shared by the two units.*

Solution. (*a*) Let P_A = Load supplied by unit *A*

P_B = Load supplied by unit *B*

$$\therefore \quad P_A + P_B = 150 \qquad ...(1)$$

For economic loading of the two units

$$\frac{dF_A}{dP_A} = \frac{dF_B}{dP_B}$$

$$0.06\,P_A + 11.14 = 0.07\,P_B + 10 \qquad ...(2)$$

Solving (1) and (2)

$$P_A = 70 \text{ MW}$$

$$P_B = 80 \text{ MW}.$$

(*b*) If the load is equally shared by the two units that is if each unit supplies 75 MW, then increase in cost for unit *A*

$$= \int_{70}^{75} (0.06\,P_A + 11.4)\,dP_A$$

$$= \left[0.03\,P_A^2 + 11.4\,P_A\right]_{70}^{75} = \text{Rs. } 78.75 \text{ per hour.}$$

Increase in cost for unit *B* will be

$$= \int_{80}^{75} (0.07\,P_B + 10)\,dP_B$$

$$= [0.035\,P_B^2 + 10\,P_B]_{80}^{75} = -\text{ Rs. } 77.12 \text{ per hour.}$$

This shows that in case of unit *B* there is decrease in cost.

Hence net increase in cost due departure from economic distribution = 78.75 – 77.12 = Rs. 1.63 per hour.

Example 2.22. *Any undertaking consumes 6×10^6 kWh per year and its maximum demand is 2000 kW. It is offered two tariffs.*

(a) Rs. 80 per kW of maximum demand plus 3 paise per kWh.

(b) A flat rate of 6 paise per kWh.

Calculate the annual cost of energy.

Solution. (a) (According to first tariff the cost of energy)

$$= 2000 \times 80 + \frac{3}{100} \times 6 \times 10^6$$

$$= 160{,}000 + 180{,}000 = \text{Rs. } 340{,}000$$

(b) Cost of energy according to flat rate

$$= \frac{6}{100} \times 6 \times 10^6 = \text{Rs. } 360{,}000.$$

Example 2.23. *Two lamps are to be compared :*

(a) Cost of first lamp is Re. 1 and it takes 100 watts.

(b) Cost of second lamp is Rs. 4 and it takes 60 watts.

Both lamps are of equal candle power and each has a useful life of 100 hours. Which lamp will prove economical if the energy is charged at Rs. 70 per kW of maximum demand per year plus 5 paise per KWh ?

At what load factor both the lamps will be equally advantageous?

Solution. (a) *First Lamp*

Cost of lamp per hour

$$= \frac{1 \times 100}{1000} = 0.1 \text{ paise}$$

Maximum demand per hour

$$= \frac{100}{1000} = 0.1 \text{ kW.}$$

Maximum demand charge per hour

$$= 0.1 \times \frac{70 \times 100}{7860} = 0.08 \text{ paise}$$

Energy consumed per hour

$$= 0.1 \times 1 = 0.1 \text{ kWh.}$$

Energy charge per hour

$$= 0.1 \times 5 = 0.5 \text{ paise}$$

Total cost per hour = 0.1 + 0.08 + 0.5 = 0.68 paise.

(b) *Second Lamp*

Cost of lamp per hour

$$= \frac{4 \times 100}{1000} = 0.4 \text{ paise}$$

Maximum demand per hour

$$= \frac{60}{1000} = 0.06 \text{ kW}$$

Maximum demand charge per hour

$$= 0.06 \times \frac{70 \times 100}{8760} = 0.048 \text{ paise.}$$

Energy consumed per hour = $0.06 \times 1 = 0.06$ kWh.

Energy charge per hour = $0.06 \times 5 = 0.30$ paise.

Total cost per hour = $0.4 + 0.048 + 0.3 = 0.748$ paise.

Therefore, first lamp is economical.

Let x be the load factor at which both lamps become equally advantageous. Only maximum demand charge changes with load factor.

$$\therefore \quad 0.1 + \frac{0.08}{x} + 0.5 = 0.4 + \frac{0.048}{x} + 0.3$$

$$x = 0.32 \qquad \text{or } 32\%.$$

Example 2.24. *A new factory having a minimum demand of 100 kW and a load factor of 25% is comparing two power supply agencies.*

(a) *Public supply tariff is Rs. 40 per kW of maximum demand plus 2 paise per kWh.*

Capital cost = *Rs. 70,000*
Interest and depreciation = *10%*

(b) *Private oil engine generating station.*

Capital Cost = *Rs. 250,000*
Fuel consumption = *0.3 kg per kWh*
Cost of fuel = *Rs. 70 per tonne*
Wages = *0.4 paise per kWh*
Maintenance cost = *0.3 paise per kWh*
Interest and depreciation = *15%.*

Solution.

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

Average load = Load factor × Maximum demand

$$= 0.25 \times 700 = 175 \text{ kW}.$$

Energy consumed per year

$$= 175 \times 8760 = 153.3 \times 10^4 \text{ kWh}.$$

(*a*) *Public Supply*

Maximum demand charges per year = 40×700 = Rs. 28,000.

Energy charge per year

$$= \frac{2}{100} \times 153.3 \times 10^4 = 30{,}660$$

Interest and depreciation

$$= \frac{10}{100} \times 70{,}000 = \text{Rs. } 7{,}000.$$

Total cost = Rs. [28,000 + 30,660 + 7,000]

= Rs. 65,660

$\therefore$ Energy cost per kWh

$$= \frac{65{,}660}{153.3 \times 10^4} \times 100 = 429 \text{ paise}$$

(*b*) *Private oil engine generating station*

$$\text{Fuel consumption} = \frac{0.3 \times 153.3 \times 10^4}{1000} = 460 \text{ tonnes}$$

Cost of fuel = 460×70 = Rs. 32,000

Cost of wages and maintenance

$$= \left(\frac{0.4 + 0.3}{100}\right) \times 153.3 \times 10^4 = \text{Rs. } 10{,}731.$$

Interest and depreciation

$$= \frac{15}{100} \times 250{,}000 = \text{Rs. } 37{,}500$$

Total cost = Rs. [33,203 + 10,731 + 37,500]

= Rs. 80,431

Energy cost per kWh

$$= \frac{80{,}431}{153.3 \times 10^4} \times 100 = 5.2 \text{ paise}.$$

Example 2.25. *A diesel engine power plant has one 700 kW and two 500 kW generating units. The fuel consumption is 0.28 kg. per kWh and the calorific value of fuel oil is 10,200 kcal per kg. Estimate*

the fuel acquired for a month and overall efficiency of the plant. Plant capacity factor = 40%.

Solution. Capacity factor $= \dfrac{E}{c \times t}$

where c = capacity of the plant

$= 700 + 2 \times 500 = 1700$ kW

t = time (hours) in the given period

$= 30 \times 24 = 720$ hours.

$$\therefore \quad 0.4 = \frac{E}{2700 \times 720}$$

$$E = 0.4 \times 1720 \times 720 = 48,96,000 \text{ kWh}.$$

Fuel oil consumption $= 48,96,000 \times 0.28 = 137,088$ kg.

$$\text{Overall efficiency} = \frac{\text{Output}}{\text{Input}}$$

Output = 48,96,000 kWh = (48,96,000 × 860) kcal

$$\text{Overall efficiency} = \frac{48,96,000 \times 860}{137,088 \times 10,200} = 0.3 \text{ or } 30\%. \quad \textbf{Ans.}$$

Example 2.26. *The incremental fuel costs of two generating units A and B of a power station are given by the following expressions :*

$$\frac{dF_A}{dP_A} = 0.01\, P_A + 2.25$$

$$\frac{dF_B}{dP_B} = 0.015\, P_B + 1.5$$

where F is in rupees per hour and P it is MW. Determine incremental fuel cost and loading schedule for minimum cost if the total load to be supplied is to be 50 MW, 175 MW and 200 MW. Both units operate at all times and maximum and minimum load on each unit is to be 100 MW and 15 MW respectively.

Solution. Let P = total load

P_A = load supplied by unit A

P_B = load supplied by unit B

$$\therefore \quad P = P_A + P_B$$

As the incremental fuel cost of unit A is higher than that of B so for a total load of 50 MW the unit A should supply 15 MW.

$\therefore$ $P_A = 15$ MW

$P_B = 35$ MW

$\frac{dF_A}{dP_A} = 0.01 \times 15 + 2.25 =$ Rs. 2.40 per MWh

$\frac{dF_B}{dP_B} = 0.015 \times 35 + 1.5 =$ Rs. 2.025 per MWh

when the load increases the unit B will continue to supply the additional load till $\frac{dF_B}{dP_B} = 2.40$.

$\therefore$ $2.40 = 0.015\, P_B + 1.5$

$\therefore$ $P_B = \frac{0.9}{0.015} = 60$ MW

$\therefore$ When $P = 75$ MW

$P_A = 15$ MW and $P_B = 60$ MW

For total load $P = 175$ MW

$P_A + P_B = 175$ ...(*i*)

and for economical loading

$\frac{dF_A}{dP_A} = \frac{dF_B}{dP_B}$

$0.01\, P_A + 2.25 = 0.015\, P_B + 1.5$ ...(*ii*)

Solving (*i*) and (*ii*), we get

$P_A = 75$ MW

$P_B = 100$ MW.

When the total load = 200 MW

$P_A = 100$ MW

$P_B = 100$ MW.

$\frac{dF_A}{dP_A} = 0.01 \times 100 = 2.25 =$ Rs. 3.25 per MWh

$\frac{dF_B}{dP_B} = 0.015 \times 100 + 1.5 =$ Rs. 3 per MWh.

Example 2.27. *A daily load curve which exhibited a 20 minute peak load of 6000 kW is drawn to scale.*

1 cm = 2 hour 1 cm = 400 kW. The area under the curve is found to be 75 square centimetres. Find the load factor.

Solution. 1 square cm $= 400 \times 2 = 800$ kWh.

$$\text{Average load} = \frac{800 \times 75}{24} = 2500 \text{ kW}$$

$$\text{Load factor} = \frac{\text{Average load}}{\text{Peak load}} = \frac{2500}{6000} = 0.41. \quad \textbf{Ans.}$$

Example 2.28. *In a power distribution system a certain feeder supplies three distribution transformers each one supplying a group of transformers whose connected loads are as follows :*

Transformer 1 Store lighting and Power	*Transformer 2 Residence Lighting*	*Transformer 3 General Power service and commercial lighting*
(i) 10 kW, 5 H.P. *(ii) 4 kW*	*(i) 0.5 kW* *(ii) 20 kW*	*(i) 10 H.P., 5 kW* *(ii) 15 H.P.*

Assuming motor efficiency 70% and suitable demand factor and diversity factor from Tables 2.2 and 2.3. Calculate maximum feeder load.

Solution. Demand factor

$$= \frac{\text{Individual Maximum Demand}}{\text{Connected Load}}$$

Individual Maximum Demand

= Demand factor × Connected load

Transformer 1

Sum of individual maximum demand

$$= 10 \times 0.70 + \frac{5 \times 0.746}{0.7} \times 0.75 + 4 \times 0.70$$

$$= 7 + 4 + 2.8 = 13.8 \text{ kW}$$

$$\text{Diversity factor} = \frac{\text{Sum of individual maximum demand}}{\text{Simultaneous maximum demand}}$$

$\therefore$ Simultaneous maximum demand on transformer 1

$$M_1 = \frac{\text{Sum of individual maximum demand}}{\text{Diversity factor}}$$

$$= \frac{13.8}{1.8} = 9.2 \text{ kW}.$$

Similarly simultaneous maximum demand on transformer 2 and transformer 3 is given by M_2 and M_3 as follows :

$$M_2 = \frac{0.5 \times 0.6 + 20 \times 0.5}{3.5} = \frac{10.3}{3.5}$$

$$= 2.94 \text{ kW}.$$

$$M_3 = \frac{1}{1.5}\left\{\frac{10 \times 0.746}{0.70} \times 0.75 + 5 \times 0.60 + \frac{15 \times 0.746 \times 0.65}{0.70}\right\}$$

$$= \frac{1}{1.5}[8 + 3 + 10.4] = \frac{21.4}{1.5} = 14.2 \text{ kW}.$$

Assuming a diversity factor of 1.3 between transformers.

Maximum feeder load

$$= \frac{M_1 + M_2 + M_3}{1.3}$$

$$= \frac{9.2 + 2.94 + 14.2}{1.3} = 20.8 \text{ kW}. \quad \textbf{Ans.}$$

Example 2.29. *A power station has to supply load as follows :*

Time (Hours)	*0—6*	*6—12*	*12—14*	*14—18*	*18—24*
Load (MW)	*30*	*90*	*60*	*100*	*50*

(*a*) *Draw the load curve.*
(*b*) *Draw load-duration curve.*
(*c*) *Choose suitable generating units to supply the load.*
(*d*) *Calculate load factor.*
(*e*) *Calculate plant capacity.*

Solution. The load curve is shown in Fig. 2.21 and the load duration curve is shown in Fig. 2.22.

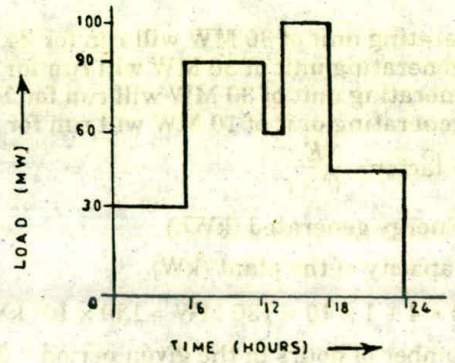


Fig. 2.21

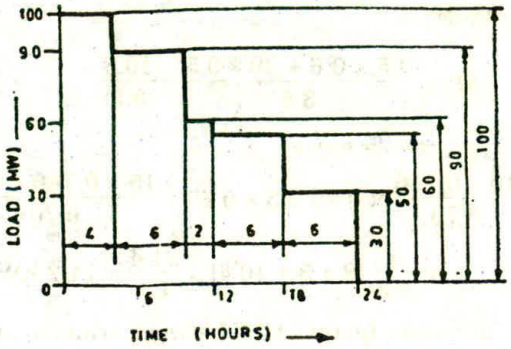


Fig. 2.22 Load duration curve.

Energy generated $= 30 \times 6 + 90 \times 6 + 60 \times 2 + 100 \times 4 + 50 \times 6$

$= 1540$ MWh $= 1540 \times 10^3$ kWh

Average Load $= \dfrac{1540 \times 10^3}{24}$ kW

Maximum demand $= 100 \times 10^3$ kW

$\therefore$ Load factor $= \dfrac{1540 \times 10^3}{24 \times 100 \times 10^3} = 0.64$ **Ans.**

To supply the load three generating units each of 30 MW capacity and one generating of 10 MW capacity should be selected. One additional unit should be kept as standby. Its capacity should be equal to the capacity of biggest set, *i.e.* 30 MW.

Load duration curve will indicate the operational schedule of different generating units. The operational schedule will be as follows :

(*i*) One generating unit of 30 MW will run for 24 hours.
(*ii*) Second generating unit of 30 MW will run for 18 hours.
(*iii*) Third generating unit of 30 MW will run for 10 hours.
(*iv*) Fourth generating unit of 10 MW will run for 4 hours.

Plant capacity factor $= \dfrac{E}{C \times t}$

where E = Energy generated (kWh)

C = Capacity of the plant (kW)

$= 30 \times 4 + 1 \times 10 = 130$ MW $= 130 \times 10^3$ kW.

t = Number of hours in the given period = 24 hours.

$\therefore$ Plant capacity factor

$$= \frac{1540 \times 10^3}{130 \times 10^3 \times 24} = 0.49. \quad \textbf{Ans.}$$

Example 2.30. *It is proposed to supply a load with a maximum demand of 100 MW and load factor of 40%. Choice is to be made from Nuclear power plant, Hydropower plant and steam power plant. Calculate the overall cost per kWh in case of each scheme.*

Cost	*Nuclear power plant*	*Hydro power plant*	*Steam power plant*
Capital cost per kW installed	*Rs. 2500*	*Rs. 1800*	*Rs. 900*
Interest	*5%*	*5%*	*6%*
Depreciation	*5%*	*4%*	*6%*
Operating cost / kWh	*4 paise*	*2 paise*	*7 paise*
Transmission and Distribution cost per kWh	*0.1 paise*	*0.4 paise*	*0.1 paise*

Solution.

Nuclear Power Plant

Capital cost $= 2500 \times 10^3 \times 100 = \text{Rs. } 25 \times 10^7$

Interest $= \text{Rs. } \frac{5}{100} \times 24 \times 10^7$

Depreciation $= \text{Rs. } \frac{5}{100} \times 25 \times 10^7$

$\therefore$ Annual fixed cost (Interest + Depreciation)

$= \text{Rs. } 2 \times 5/100 \times 25 \times 10^7 = \text{Rs. } 25 \times 10^6$

Energy generated per year

= Average load × 8760

= Load factor × Maximum demand × 8760

$= 0.4 \times 100 \times 10^3 \times 8760 = 350.4 \times 10^6$ kWh.

Running cost/kWh = Operating cost/kWh + Transmission and distribution cost/kWh

$= 4 + 0.1 = 4.1$ paise.

$\therefore$ Overall cost/kWh = Running cost/kWh + Fixed cost/kWh

$$= 4.1 + \frac{25 \times 10^6 \times 100}{350.4 \times 10^6}$$

$= 4.1 + 7.1 = 11.2$ paise.

Hydropower Plant

Capital cost $= 1800 \times 100 \times 10^3 = \text{Rs. } 18 \times 10^7$

Interest $= \frac{5}{100} \times 18 \times 10^7 = 9 \times 10^6$

Depreciation $= \frac{4}{100} \times 18 \times 10^7 = \text{Rs. } 7.2 \times 10^6$

Annual fixed cost $= 9 \times 10^6 + 7.2 \times 10^6 = 16.2 \times 10^6$

Running cost/kWh = 2 + 0.4 = 2.4 paise.

Overall cost/kWh $= 2.4 + \frac{16.2 \times 10^6 \times 10}{350.4 \times 10^6} = 2.4 + 4.6 = 7$ paise

Steam Power Plant

Capital cost $= \text{Rs. } 900 \times 100 \times 10^9 = \text{Rs. } 9 \times 10^7$

Interest $= \text{Rs. } \frac{6}{100} \times 9 \times 10^7$

Depreciation $= \text{Rs. } \frac{6}{100} \times 9 \times 10^7$

Annual fixed cost $= 2 \times \frac{6}{100} \times 9 \times 10^7 = \text{Rs. } 10.8 \times 10^6$

Running cost/kWh = 7 + 0.1 = 7.1 paise

Overall cost/kWh= Running cost/kWh + fixed cost/kWh

$$= 7.1 + \frac{10.8 \times 10^6}{350.4 \times 10^6} \times 100 = 10.2 \text{ paise}$$

Therefore, overall cost/kWh is minimum in case of hydropower plant.

Example 2.31. *Following data pertains to a power plant of 100 MW installed capacity.*

Capital cost = *Rs. 900 / kW installed*

Interest and depreciation = *12%*

Annual load factor = *60%*

Annual capacity factor = *50%*

Annual running charges = *Rs.* 15×10^6

Energy consumed by the power plant auxiliaries = 60%.

Calculate the following :

(a) Reserve capacity

(*b*) *Cost per kWh.*

Solution. (*a*) Load factor = $\frac{\text{Average load}}{\text{Maximum demand}}$

Capacity factor = $\frac{E}{C \times t}$

where E = Energy produced = Average load × Time

C = Capacity

t = Time

$\therefore$ Capacity factor = $\frac{\text{Average load}}{\text{Capacity}}$

$$\frac{\text{Load factor}}{\text{Capacity factor}} = \frac{\text{Average load}}{\text{Maximum demand}} \times \frac{\text{Capacity}}{\text{Average load}}$$

$$\frac{0.6}{0.5} = \frac{\text{Capacity}}{\text{Maximum demand}}$$

$\therefore$ Maximum demand

$$= \frac{0.5 \times \text{Capacity}}{0.6} = \frac{0.5 \times 150}{0.6} = 125 \text{ MW}$$

Reserve Capacity = 150 − 125 = 25 MW. **Ans.**

(*b*) Load factor = $\frac{\text{Average load}}{\text{Maximum demand}}$

Average load = Load factor × Maximum demand

$$= 0.6 \times 125 = 75 \text{ MW} = 75 \times 10^3 \text{ kW}.$$

Energy produced per year

$$= 75 \times 10^3 \times 8760 = 657 \times 10^6 \text{ kWh}$$

Energy used by auxiliaries

$$= \frac{6}{100} \times 657 \times 10^6$$

Net energy sent out = $657 \times 10^6 - \frac{6}{100} \times 657 \times 10^6$

$$= 617.6 \times 10^6 \text{ kWh}.$$

Annual Interest and depreciation (Fixed Cost)

$$= \frac{12}{100} \times 150 \times 10^3 \times 700 = \text{Rs. } 12.6 \times 10^5$$

Total annual cost = Fixed cost + Running cost

$$= 126 \times 10^5 + 15 \times 10^6 = \text{Rs. } 27.6 \times 10^6$$

$$\text{Cost of generation} = \frac{27.6 \times 10^6}{617 \times 10^6} \times 100 = 4.47 \text{ paise.} \quad \textbf{Ans.}$$

Example 2.32. *It is proposed to supply a load either by a hydro power plant or by a steam power plant. The following data may be assumed as shown below :*

Reserve capacity for hydropower plant is 30% and for steam power station is 20%. Determine the load factor at which the overall cost per kWh would be same for both the power plants.

Cost	*Hydropower plant*	*Steam power plant*
Capital cost per kW installed	*Rs. 1800*	*Rs. 1000*
Interest and depreciation	*10%*	*14%*
Operation cost per kWh	*3 paise*	*6 paise*

Solution. Let, Maximum demand

$= M$ kW

Load factor $= F$

Average load $= M \times F$

Energy generated per year = Average load × 8760

Energy generated per year = $M \times F \times 8760$ kWh.

Hydropower Plant

Reserve capacity = 30%

Installed capacity = 1.3 M kW

Capital cost = Rs. $1800 \times 1.3 M$ = Rs. $2340 M$.

Fixed cost per year (Interest and depreciation)

$$= \text{Rs. } \frac{10}{100} \times 2340 M = \text{Rs. } 234 M$$

Overall cost/kWh

= Running cost per kWh + Fixed cost per kWh

$$= \left(3 + \frac{234 M}{MF \times 8760} \times 100\right) \text{paise.}$$

Steam Power Plant

Reserve capacity = 20%

Installed capacity = 1.2 M kW

Capital cost = Rs. $1000 \times 1.2 M$ = Rs. $1200 M$

Fixed cost per year = (Interest + Depreciation)

$$= \text{Rs.}\ \frac{14}{100} \times 1200\,M = \text{Rs.}\ 168\,M$$

Overall cost per kWh = Running cost per kWh + Fixed cost per kWh

$$= \left(6 + \frac{168\,M}{MF \times 8760} \times 100\right) \text{paise.}$$

As the overall cost per kWh is same for both the power stations.

$$3 + \frac{234\,M}{MF \times 8760} \times 100 = 6 + \frac{168\,M \times 100}{MF \times 8760}$$

$$\frac{66\,M \times 1000}{MF \times 8760} = 3$$

$$\frac{600}{F \times 8760} = 3$$

$$F = 0.25$$

$\therefore$ % Load factor = 25%. **Ans.**

Example 2.33. *The input output curve of 100 MW power station is expressed as follows :*

$$I = 10^6\,(100 + 2L + 0.0004\,L^3)$$

where I is in kcal/hr and L is in MW.

Determine (a) Input, heat rate and efficiency when load is 40 MW.

(b) Load at which efficiency is maximum.

Solution.

(a) When L = Load = 40 MW

$$I = 10^6\,(100 + 2 \times 40 + 0.0004 \times 40^3)$$

$$= 10^6 \times 205.6 \text{ kcal/hr.}$$

Heat rate $\left(\frac{I}{L}\right) = 10^6\,(100 + 2 + 0.0004 \times L^2)$

$$= 10^6\,(100 + 2 \times .0004 \times 40^2)$$

$$= 102.64 \times 10^6 \text{ kcal/MWh.}$$

Efficiency $= \frac{\text{Output}}{\text{Input}} = \frac{40 \times 10^3 \times 860}{10^6 \times 205.6} = 0.17 = 17\%$

(As 1 kWh = 860 kcal)

(*b*) Efficiency will be maximum when heat rate is equal to incremental rate.

$$I = 10^6 (100 + 2L + 0.0004 \times L^3)$$

$$\text{H.R.} = \frac{I}{L} = 10^6 \left(\frac{100}{L} + 2 + 0.0004\, L^2 \right)$$

Incremental rate, $\frac{dI}{dL} = 10^6 (+ 2 + 0.00012\, L^2)$

$$10^6 \left(\frac{100}{L} + 2 + 0.0004\, L^2 \right) = 10^6 (2 + 0.0012\, L^2)$$

$$\therefore \frac{100}{L} + 0.0004\, L^2 = 0.00012\, L^2$$

$$\frac{100}{L} = 0.0008\, L^2$$

$$L^2 = \frac{100}{0.0008} = 125{,}000$$

$$L = 50 \text{ MW.} \quad \textbf{Ans.}$$

Example 2.34. *Calculate the cost of generation per kWh for a power station having the following data :*

Installed capacity of the plant = 120 MW.

Capital Cost = Rs. 96 × 10⁶

Rate of interest and depreciation = 14%

Annual cost of fuel oil, salaries and taxation = Rs. 12 × 10⁵

Local factor = 40%

Also find the saving in cost per kWh if the annual load factor is raised to 50%.

Solution. Load factor = $\frac{\text{Average load}}{\text{Maximum demand}}$

Assuming maximum demand equal to capacity of the power plant

$$0.4 = \frac{\text{Average load}}{120}$$

Average load = 120 × 0.4 = 48 MW.

Energy generated per annum

$$= 48 \times 10^3 \times 8760 = 420.38 \times 10^6 \text{ kWh}$$

Interest and depreciation (Fixed cost)

$$= \frac{14}{100} \times 96 \times 10^6 = \text{Rs. } 1344 \times 10^4$$

Running cost = Cost of fuel oil, salaries and taxation.

Total annual cost = Fixed cost + Running cost

$$= 1344 \times 10^4 + 12 \times 10^6 = \text{Rs. } 25.44 \times 10^6$$

$$\text{Cost per kWh} = \frac{25.44 \times 10^6 \times 100}{420.48 \times 10^6} = 6 \text{ paise.}$$ **Ans.**

When the load factor is raised to 50%

$$0.5 = \frac{\text{Average load}}{\text{Maximum demand}}$$

Average load = 0.5 × Maximum demand

$$= 0.5 \times 120 = 60 \text{ MW.}$$

Energy produced per year

$$= 60 \times 10^3 \times 8760 = 525.6 \times 10^6 \text{ kWh.}$$

Total annual cost will remain same.

Total annual cost = Rs. 25.44×10^6

$$\text{Cost per kWh} = \frac{25.44 \times 10^6 \times 100}{525.6 \times 10^6} = 4.82 \text{ paise.}$$

Saving in cost per kWh = 6 − 4.82 = 1.18 paise. **Ans.**

Example 2.35. *The input output curve of a 10 MW power station is expressed as follows :*

$$I = 10^6 (8 + L + 0.4 L^2)$$

where I is in kcal per hour and L is in MW.

Determine the average heat rate of the power station for a day if it operates at its full capacity for 12 hours and is kept running at zero load for remaining 12 hours. Also calculate the saving per kWh of energy produced if the energy is generated at a constant 24 hours load (100% load factor).

Solution. (*a*) Energy generated,

$$E = 10 \times 12 + 0 \times 12 = 120 \text{ MWh.}$$

Input $I = I_{10} + I_0$

where I_{10} = Input when load is 10 MW

I_0 = Input when load is zero MW

$$\therefore \quad I_{10} = 10^6 (8 + 8 \times 10 + 0.4 \times 10 \times 10) \times 12$$

$$= 10^6 \times 128 \times 12 \text{ kcal}$$

$$\therefore \quad I = I_{10} + I_0 = 136 \times 12 \times 10^6 \text{ kcal.}$$

$\therefore$ Average heat rate

$$= \frac{\text{Input}}{\text{Output}} = \frac{I}{E} = \frac{136 \times 12 \times 10^6}{120}$$

$$= 136 \times 10^6 \text{ kcal/MWh.}$$

(*b*) Total energy generated during 24 hours

$$= E = 120 \text{ MWh.}$$

$$\therefore \quad \text{Average load} = \frac{120}{24} = 5 \text{ MW}$$

$$\text{Input } I_5 = 10^6 (8 + 8 \times 5 + 0.4 \times 5^2)$$

$$= 10^6 (58) \text{ kcal per hour.}$$

$$\therefore \quad \text{Heat rate} = \frac{58}{5} \times 10^6 = 11.6 \times 10^6 \text{ kcal/MWh}$$

$$\therefore \quad \text{Saving} = (13.6 - 11.6)\, 10^6$$

$$= 2 \times 10 \text{ kcal/MWh.} \quad \textbf{Ans.}$$

Example 2.36. *A 20 H.P. condensate pump motor has been burnt beyond repair. Two alternatives have been proposed to replace it. Manufacturer A offers to replace the motor for Rs. 5000. The efficiency of this motor is 90% at full load and 80% at half load. Manufacturer B offers a motor for Rs. 4200. Its efficiencies are 80% and 84% at full load and half load respectively.*

The life of each motor is 20 years, salvage value 5%, interest on capital cost 5% and the motor operates 20% of time at full load and 75% at half load.

The annual maintenance cost of motor A is Rs. 400 and that of motor B is Rs. 500. If the energy rate 10 paise per kWh, find which motor is more economical to buy ? Also determine at what energy rate the two alternatives become equal.

Solution. Motor A

Capital cost, (P) = Rs. 5000

Salvage value, $(S) = \frac{5}{100} \times P$

Life, (n) = 20 years.

Depreciation per year

$$= \frac{P - S}{n} = \frac{0.95 \times 500}{20} = \text{Rs. } 237$$

Annual interest $= \frac{5}{100} \times 5000 = \text{Rs. } 250$

The motor operates at full load for $\left(\frac{1}{4} \times 8760\right)$ hours and a half load for $\left(\frac{3}{4} \times 8760\right)$ hours in one year.

$$\therefore \text{ Energy cost } = \left[25 \times 0.735 \times \frac{8760}{4} \times \frac{1}{0.9} \times \frac{10}{100}\right] + 25 \times 0.735 \times \frac{3}{4} \times 8760 \times \frac{1}{0.85} \times \frac{10}{100}\Bigg]$$

$$= \text{Rs. } (4471 + 14{,}203) = \text{Rs. } 18{,}674.$$

Annual maintenance cost = Rs. 400

Total cost = Rs. [237 + 250 + 18,674 + 400] = Rs. 19,561.

Motor B

Depreciation per year $= \frac{0.95 \times 4200}{20} = \text{Rs. } 199$

Interest $= \frac{5}{100} \times 4200 = \text{Rs. } 210$

$$\text{Energy cost} = \left[25 \times 0.735 \times \frac{1}{4} \times \frac{8760}{0.85} \times \frac{10}{100}\right] + \left[25 \times 0.735 \times \frac{3}{4} \times \frac{8760}{0.82} \times \frac{10}{100}\right]$$

$$= \text{Rs. } [4734 + 14{,}722] = \text{Rs. } 19{,}456.$$

Annual maintenance cost = Rs. 500

Total cost = Rs. [199 + 210 + 19,456 + 500]

= Rs. 20,365.

Hence motor *A* is economical.

(*b*) Let the energy rate = *r* paise/kWh

At this rate the two alternatives becomes equal.

Annual cost of motor *A*

$$C_A = \text{Rs.} \left[237 + 250 + 25 \times 0.735 \times \frac{8760}{4} \times \frac{1}{0.9}\right.$$

$$\times \frac{r}{100} + 25 \times 0.735 \times 8760 \times \frac{3}{4} \times \frac{1}{0.85} \times \frac{r}{100} + 400\Bigg]$$

Annual cost of motor B

$$C_B = \text{Rs.}\Bigg[199 + 210 \times 25 \times 0.735 \times \frac{1}{4} \times 8760 \times \frac{1}{0.85} \times \frac{r}{100} + 25 \times 0.735 \times 8760 \times \frac{3}{4} \times \frac{1}{0.82} \times \frac{r}{100} \times 500\Bigg]$$

Equating $C_A = C_B$, we get

$r = 28$ paise. **Ans.**

Example 2.37. *A diesel power station has ful consumption 0.2 kg per kWh. If the calorific value of the oil is 11,000 kcal per kg determine the overall efficiency of the power station.*

Solution. For 1 kWh output

Heat input = $11,000 \times 0.2 = 2200$ kcal.

Now 1 kWh = 862 kcal.

$$\therefore \text{Overall efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{862}{2200} = 39.2\%. \quad \textbf{Ans.}$$

Example 2.38. *A steam power station has an installed ca, of 120 MW and a maximum demand of 100 MW. The coal consu tion is 0.4 kg per kWh and cost of coal is Rs. 80 per tonne. The annua expenses on salary bill of staff and other overhead charges excluding cost of coal is Rs. 50×10^5. The power station works at a load factor of 0.5 and the capital cost of the power station is Rs. 4×10^5. If the rate of interest and depreciation is 10% determine the cost of generating per kWh.*

Solution. Maximum demand = 100 MW

Load factor = 0.5

Average load = $100 \times 0.5 = 50$ MW.

$= 50 \times 1000 = 50,000$ kW.

Energy produced per year

$= 50,000 \times 8760 = 438 \times 10^6$ kWh.

Coal consumption $= 438 \times 10^6 \times \frac{0.4}{1000} = 1752 \times 10^6$ tonnes.

Annual Cost

(*i*) Cost of coal $= 1752 \times 10^2 \times 80 = \text{Rs. } 14,016 \times 10^2$

(*ii*) Salaries = Rs. 50×10^5

(*iii*) Interest and depreciation

$$= \frac{10}{100} \times 4 \times 10^5 = \text{Rs. } 4 \times 10^4$$

$$\text{Total cost} = \text{Rs. } 14{,}016 \times 10^3 + \text{Rs. } 50 \times 10^5 + \text{Rs. } 4 \times 10^4 = \text{Rs. } 19{,}056 \times 10^3$$

Cost of generation per kWh

$$= \frac{19{,}056 \times 10^3}{438 \times 10^6} \times 100 = 4.35 \text{ paise.} \quad \textbf{Ans.}$$

Example 2.39. *A 200 MW thermal power station is to supply power to a system having maximum and minimum demand 140 MW and 40 MW respectively during the year. Assuming load duration curve to be a straight line, determine the following :*

(*i*) *Load factor*

(*ii*) *Capacity factor (Plant factor).*

Solution. C = Capacity of power plant = 200 MW

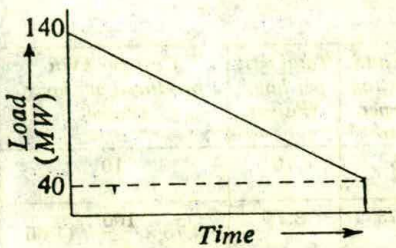


Fig. 2.23

Maximum demand = 140 MW

Minimum demand = 40 MW

t = Time per year

= 8760 hours

Load duration curve is shown in Fig. 2.23.

Energy supplied per year (E)

$$= 8760 \times 40 + \frac{8760 \times 100}{2}$$

$$= 8760 \times 90 \text{ MWh}$$

$$\text{Average load} = \frac{8760 \times 90}{8760} = 90 \text{ MW}$$

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} = \frac{90}{140} = 0.64$$

$$\text{Capacity factor} = \frac{E}{C \times t} = \frac{8760 \times 90}{200 \times 8760} = 0.45.$$

Example 2.40. *Calculate the cost of electrical energy generated per kWh at 100% load factor, 75% load factor, 50% load factor and at 25% load factor for a steam power plant. The fixed cost is Rs. 438 per kW of installed capacity per year and the fuel and operating costs*

are 5 paise per kWh generated. Plot the curve between cost of energy per kWh and load factor.

Solution.

Load factor = 100%

$$C_1 = \text{Fixed cost per hour} = \frac{43{,}800}{8760} = 5 \text{ paise.}$$

$\therefore$ 1 kW plant is available at a cost of 5 paise per hour.

E = Energy generated per hour at 100% load factor

$= 1 \times 1 = 1$ kWh.

C_2 = Fuel and operating cost per hour

$= E \times 5 = 1 \times 5 = 5$ paise

C = Total cost per kWh produced per hour.

$= C_1 + C_2 = 5 + 5 = 10$ paise.

Similarly the total costs per kWh at other load factors are as follows :

Load factor %	*Energy Produced per hour (kWh)*	*Fixed cost (Paise)*	*Fuel and operating cost per hour*	*Total cost per hour (Paise)*	*Cost per kWh produced per hour (Paise)*
100	1	5	5	10	10
75	0.75	5	3.75	8.75	$8.75 \times \frac{100}{75} = 11.66$
50	0.5	5	2.5	7.5	$7.5 \times \frac{100}{50} = 15$
25	0.25	5	1.25	6.25	$6.25 \times \frac{100}{25} = 25$

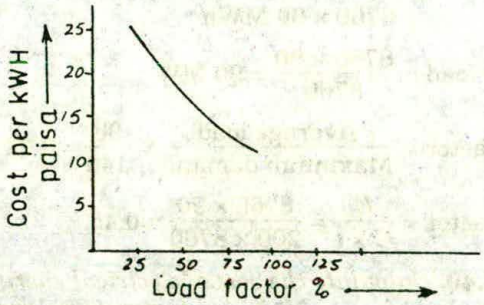


Fig. 2.24

Fig. 2.24 shows the variation of cost of energy per kWh generated with respect to load factor.

This shows that cost per kWh increases with decrease in load factor.

Example 2.41. *In a steam power plant the capital cost of power generation equipment is Rs. 25×10^5. The useful life of the plant is 30 years and salvage value of the plant to Rs. 1×10^5. Determine by sinking fund method the amount to be saved annually for replacement if the rate of annual compound interest is 6%.*

Solution. P = Capital cost = Rs. 20×10^5

S = Salvage value = Rs. 1×10^5

n = Useful life = 30 years

r = Compound interest

A = Amount to be saved per year for replacement

$$A = \frac{(P - S)\, r}{(1 + r)^n - 1} = \frac{(20 \times 10^5 - 1 \times 10^5) \times 0.06}{(1 + 0.06)^{30} - 1}$$

= Rs. 24,000. **Ans.**

Example 2.42. *A hydro power plant is to be used as peak load plant at an annual load factor of 30%. The electrical energy obtained during the year is 750 × 105 kWh. Determine the maximum demand.*

If the plant capacity factor is 24% find reserve capacity of the plant.

Solution. E = Energy generated = 750×10^5 kWh

$$\text{Average load} = \frac{750 \times 10^5}{8760} = 8560 \text{ kW}$$

where 8760 is the number of hours in year.

Load factor = 30%

M = Maximum demand

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$M = \frac{85{,}600}{0.3} = 28.530 \text{ kW}$$

C = Capacity of plant

$$\text{Capacity factor} = \frac{E}{C \times 8760}$$

$$0.24 = \frac{750 \times 10^5}{C \times 8760}$$

$$C = 35{,}667 \text{ kW}$$

Reserve capacity = $C - M$ = 35,667 – 28,530 = 7137 kW.

Example 2.43. *A power supply system has a hydro-power plant of 12 MW capacity and a diesel power plant of 30 MW capacity. The hydro power plant has a pondage provision and can store water to generate 20 MWh. For the coming week the estimated power in river flow is 3 MW and expected load to be supplied is as follows :*

Load (MW)	*Time (Hours)*
42	*20*
30	*60*
25	*50*
15	*20*
8	*18*
	Total = 168 hours

(*a*) *Calculate total energy that can be generated by hydro power plant.*

(*b*) *How the load shall be shared by the two power plants ?*

Solution.

(*a*) E_1 = Energy which can be generated in coming week.

$$= 3 \times 168 = 504 \text{ MWh}$$

As the hydro power plant has a provision to store 120 MWh.

E_2 = Total energy that the hydro power plant can generate

$$= E_1 + 120 = 504 + 120 = 624 \text{ MWh.}$$

(*b*) The hydro power plant will be started when the load exceeds 30 MW.

E = Energy generated by diesel engine

$$= 8 \times 18 + 15 \times 20 + 25 \times 50 + 30 \times 60$$

$$= 144 + 300 + 1250 + 1800 = 3494 \text{ MWh.}$$

The hydro power plant will run at its full capacity of 12 MW for 20 hours. Energy generated by hydro power plant

$$= 12 \times 20 = 240 \text{ MWh.}$$

Example 2.44. *A steam power plant is to supply load for 24 hours as follows :*

Time	*5 A.M. to 10 A.M.*	*10 A.M. to 5 P.M.*	*5 P.M. to 11 P.M.*	*11 P.M. to 5 A.M.*
Load (MW)	*50*	*100*	*35*	*15*

(a) *The energy rate is 14 paise per kWh and cost of input is 15 N.P. per 6000 kcal. The thermal efficiency of the plant is 35% at 100 MW, 30% at 59 MW, 28% at 35 MW and 20% at 15 MW.*

Determine the net revenue earned.

(b) *If the above load is supplied by a combination of steam power plant and pump storage plant and steam power plant runs at constant load with 35% efficiency. Calculate the capacity of steam power plant and percentage increase in revenue earned.*

The overall efficiency of pump storage plant is 79% and cost of energy input and cost of selling power is same as mentioned above.

Solution.

(a) E = Energy generated by steam power plant in 24 hours.

$$= 40 \times 5 + 100 \times 7 + 35 \times 6 + 15 \times 6$$

$$= 250 + 700 + 210 + 90 = 1250 \text{ MWh}$$

$$= 1250 \times 10^3 \text{ kWh}$$

r = Energy rate = 14 paise per kWh

C_1 = Cost of selling power = $E \times r$

$$= 1250 \times 10^3 \times \frac{14}{100} = 175 \times 10^3 \text{ rupees}$$

C_2 = Input to steam plant in 24 hours

$$= \frac{100 \times 7}{0.35} + \frac{50 \times 5}{0.3} + \frac{35 \times 6}{0.28} + \frac{15 \times 6}{0.2}$$

$$= 2000 + 833 + 750 + 450 = 4033 \text{ MWh.}$$

$$= 4033 \times 10^3 \text{ kWh} = 4033 \times 10^3 \times 860 \text{ kcal.}$$

$$= 3468 \times 10^6 \text{ kcal.}$$

(as 1 kWh = 860 kcal.)

S = Input rate = 15 paise per 6000 kcal.

C_2 = Cost of input energy

$$= \frac{3468 \times 10^6}{6000} \times \frac{15}{100} = 86.7 \times 10^3 \text{ rupees}$$

New revenue earned from steam power plant = $C_1 - C_2$

$$= 175 \times 10^3 - 86.7 \times 10^3$$

$$= 88.3 \times 10^3 \text{ rupees per day.}$$

(*b*) Let x = Capacity of steam power plant when it works in combination with pumps storage plant.

E_1 = Energy used from thermal plant to pump water of pump storage plant during off-peak period.

$= (100 - x) \times 7$

E_2 = Energy supplied by pump storage plant during off-speak period.

$= [(x - 50) \times 5 + (x - 35) \times 6 + (x - 15) \times 6] \times 0.7$

But $E_1 = E_2$

$$(100 - x) \times 7 = [(x - 50) \times 5 + (x - 35) \times 6 + (x - 15) \times 6] \times 0.7$$

$$x = 57 \text{ MW}$$

Thus the base load of 57 MW should be taken by steam power plant

C_1 = Cost of selling power

$= 175 \times 10^3$ rupees (as already found)

E_2 = Energy input to steam plant in 24 hours

$$= \frac{x \times 24}{0.35} = \frac{57 \times 24}{0.35}$$

$= 3902$ MWh $= 3908 \times 10^3$ kWh

$= 3908 \times 10^3 \times 860$ kcal $= 3360 \times 10^6$ kcal.

C_2 = Cost of input energy

$$= \frac{3360 \times 10^6}{6000} \times \frac{15}{100} = 84 \times 10^3 \text{ rupees}$$

Net revenue earned $= C_1 - C_2 = 175 \times 10^3 - 84 \times 10^3$

$= 91 \times 10^2$ rupees per day

% increase in revenue earned

$$= \frac{91 \times 10^3 - 88.3 \times 10^3}{88.3} \times 100$$

$= 3.05\%$.

Example 2.45. *The following data is supplied for a power plant:*

Annual load factor = 65%

Capacity factor = 55%

Installed capacity of the plant = 200 MW

Capital cost of the plant = Rs. 140 × 10^6

Annual cost of coal, oil, taxes and salaries = Rs. 21 × 10^6

Rate of Interest = 5% of the capital

Rate of depreciation = 6% of the capital

Units of energy used in running the plant auxiliaries = 4% of total units generated.

Determine :

(a) Reserve capacity

(b) Generating cost.

Solution. C = Capital of the plant

L = Average load

M = Maximum demand

t = Hours in one year = 8760

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$0.65 = \frac{L}{M}$$

$$L = 0.65 \times M$$

E = Energy generated in one year

$$= L \times 8760 = 0.65 \times M \times 8760$$

$$\text{Capacity factor} = \frac{E}{C \times t}$$

$$0.55 = \frac{0.65 \times M \times 8760}{200 \times 8760}$$

$$M = 169 \text{ MW}$$

$$\text{Reserve capacity} = C - M = 200 - 169$$

$$= 31 \text{ MW}$$

$$\therefore \quad E = 0.69 \times 169 \times 8760$$

$$= 962 \times 10^3 \text{ kWh} = 962 \times 10^6 \text{ kWh.}$$

Now 4% of E is required to run the plant auxiliaries.

$$\therefore \quad E_1 = \text{Total energy generated}$$

$$= \left(1 + \frac{4}{100}\right) \times E$$

$$= \left(1 + \left(\frac{4}{100}\right)\right) \times 962 \times 10^6$$

$$= 1001 \times 10^6 \text{ kWh}$$

C_1 = Interest per year

$$= \frac{5}{100} \times 130 \times 10^6 = \text{Rs. } 7 \times 10^6.$$

C_2 = Depreciation per year

$$= \frac{6}{100} \times 140 \times 10^6 = \text{Rs. } 8.4 \times 10^6$$

C_3 = Running cost per year

$$= \text{Rs. } 21 \times 10^6$$

C = Total cost = $C_1 + C_2 + C_3$

$$= (7 + 8.4 + 21)\ 10^6 = \text{Rs. } 36.4 \times 10^6$$

$$\text{Cost of generation} = \frac{C}{E_1} = \frac{36.4 \times 10^6}{1001 \times 10^6} \times 100$$

$$= 3.64 \text{ paise per kWh.}$$

Example 2.46. *The estimated costs of two power stations A and B running parallel are*

Rs. (130 × kW + 0.028 kWh) and

Rs. (125 × kW + 0.032 kWh) respectively. The power stations supply power to a system whose maximum load is 120 MW and minimum load is 20 MW during the year. The load varies as straight line. Determine for minimum cost of generation.

(a) Installed capacity of each station.

(b) Annual load factor and capacity factor of each station.

(c) Cost of generation.

Solution.

(a) C_A = Cost of power station A

$$= 130 \times \text{kW} + 0.028 \text{ kWh}$$

Let $A_1 = 130$

$B_1 = 0.028$

C_B = Cost of power station B

$$= 125 \text{ kW} + 0.032 \text{ kWh.}$$

Let $A_2 = 125$

$B_2 = 0.032$

H—Time in hours for which base load power plant is to be operated for minimum overall cost

$$= \frac{A_1 - A_2}{B_2 - B_1}$$

$$= \frac{130 - 125}{0.032 - 0.028} = 1250 \text{ hours}$$

Now as shown in Fig. 2.25

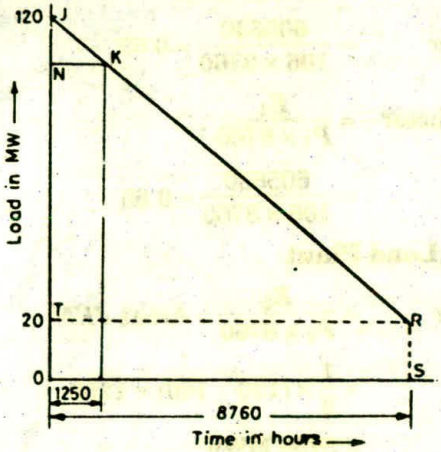


Fig. 2.25

Let P_1 = Peak load on base load plant

P_2 = Peak load on peak load plant

From triangles JRT and JKN.

$$\frac{NK}{TR} = \frac{JN}{JT}$$

$$\frac{1250}{8760} = \frac{120 - P_1}{120 - 20}$$

$$P_1 = 10^6 \text{ MW}$$

$$P_2 = 120 - 106 = 14 \text{ MW}$$

(*b*) For base load plant

Load factor $= \dfrac{E_1}{P_1 \times 8760}$

where E_1 = Actual units generated

$= \text{Area } NKRSON$

$= \text{Area } NKRT + \text{Area } TRSO$

$= \frac{1}{2}(NK + RT) \times NT + RT \times RS$

$= \frac{1}{2}(1250 + 8760) \times (106 - 20) + 8760 \times 20$

$= 605630 \text{ MWh.}$

Load factor $= \frac{605630}{106 \times 8760} = 0.65$

Capacity factor $= \frac{E_1}{P_1 \times 8760}$

$= \frac{605630}{106 \times 8760} = 0.65$

For Peak Load Plant

Load factor $= \frac{E_2}{P_2 \times 8760} = \text{Areas } JKN$

$= \frac{1}{2} \times (120 - 160) \times 1250$

$= 8750 \text{ MWh}$

Load factor $= \frac{8750}{14 \times 8760}$

$= 0.07 = 7\%$

Capacity factor $= \frac{E_2}{P_2 \times 8760}$

$= 0.07 = 7\%$

Since there is no reserve capacity.

(*c*) For base load plant

E_1 = Total energy generated

$= 605630 \text{ MWh} = 605.630 \times 10^6 \text{ kWh}$

C_1 = Cost

$= 130 \times 10^3 \times 106 + 0.028 \times 605.630 \times 10^6$

$= \text{Rs. } 30 \times 10^6$

For peak load plant

E_2 = Total energy generated

= 8750 MWh = 8.750×10^6 kWh

C_2 = Cost

= $125 \times 14 \times 10^3 + 0.032 \times 8.750 \times 10^6$

= Rs. 2×10^6

E = Total energy generated

$E = E_1 + E_2 = (605.630 + 8.750) \times 10^6$

= 614.38×10^6

C = Total Cost

= $C_1 + C_2 = 30 \times 10^6 + 2 \times 10^6$

= Rs. 32×10^6

$$\text{Cost per kWh} = \frac{C}{E}$$

$$= \frac{32 \times 10^6 \times 100}{614.38 \times 10^6} = 5.2 \text{ paise.}$$

Example 2.47. *A common load is to be shared by two power plants. One power plant is a base load plant with 30 MW installed capacity and other power plant is a standby plant with 20 MW capacity. The yearly output of the base load plant is 130×10^6 kWh and that of standby plant is 9×10^6 kWh. The peak load taken by the standby plant is 15 MW and this plant works for 2800 hours during the year. The base load plant takes a peak of 25 MW. Determine the following for both plants :*

(a) *Annual load factor*

(b) *Plant use factor*

(c) *Capacity factor.*

Solution.

Standby Power Plant

C = Capacity of plant

= 20 MW

E = Energy generated per year

= 9×10^6 kWh

t = Hours of working per year

= 2800 hours

T = Hours in year = 8760

M = Maximum demand

= 15 MW

(*a*) Annual load factor

$$= \frac{E}{M \times T} = \frac{9 \times 10^6}{15 \times 1000 \times 8760}$$

= 0.068 or 6.8%.

(*b*) Plant use factor $= \frac{M}{C} = \frac{15}{20}$

= 0.75 or 75%.

(*c*) Capacity factor $= \frac{E}{C \times t}$

$$= \frac{9 \times 10^6}{20000 \times 2800} = 0.16 \text{ or } 16\%.$$

Base Load Power Plant

C = Capacity of plant

= 30 MW

E = Energy generated per year

= 130×10^6 kWh

M = Maximum demand

= 25 MW.

(*a*) Annual load factor

$$= \frac{E}{M \times T} = \frac{130 \times 10^6}{25 \times 1000 \times 8760}$$

= 0.593 or 59.3%.

(*b*) Plant use factor $= \frac{M}{C} = \frac{25}{30}$

= 0.83 or 83%.

(*c*) Capacity factor $= \frac{E}{C \times t}$

$$= \frac{130 \times 10^6}{30000 \times 8760} = 0.494 \text{ or } 49.4\%.$$

Example 2.48. *An electric supply company has the following annual expenses :*

Generation	*Rs.* 80×10^4
Transmission	*Rs.* 25×10^4
Distribution	*Rs.* 20×10^5
Fuel	*Rs.* 30×10^5
Repair etc.	*Rs.* 3.5×10^5

The number of units generated per year are 430×10^6 kWh. The consumers have an aggregate maximum demand of 80 MW. The fixed charges for generation, transmission, distribution, fuel, repair etc. are 80%, 90%, 95%, 15% and 50% respectively. Losses in transmission and distribution are 10%.

Determine a two part tariff to be charged from the consumers.

Solution. M = Maximum demand

$= 80 \text{ MW} = 80 \times 10^3 \text{ kW}$

E = Energy generated per year

$= 430 \times 10^6$ kWh.

The fixed and running charges are calculated as follows :

Item	*Total charges (Rs.)*	*Fixed charges*		*Running charges*	
		%	*Amount (Rs.)*	*%*	*Amount (Rs.)*
Generation	80×10^4	80	64×10^4	20	16×10^4
Transmission	25×10^4	90	22.5×10^4	10	2.5×10^4
Distribution	20×10^5	95	19×10^5	5	1×10^5
Fuel	30×10^5	15	4.5×10^5	85	25.5×10^5
Repairs etc.	3.5×10^5	50	1.75×10^5	50	1.75×10^5
Total			339×10^4		301×10^4

C_1 = Fixed charges

$= \text{Rs. } 339 \times 10^4$

Fixed charges per kV of maximum demand

$$= \frac{C_1}{M} = \frac{339 \times 10^4}{80 \times 10^3}$$

$= \text{Rs. } 42.37$

C_2 = Running charges = Rs. 301×10^4

Transmission losses = 10%

Net energy supplied (E)

$= 430 \times 10^6 \times 0.9$

Running charges per unit

$$= \frac{C_2}{E} = \frac{301 \times 10^4 \times 100}{430 \times 10^6 \times 0.9}$$

$= 0.77$ paise.

Therefore the two part tariff is Rs. 42.37 per kW of maximum demand plus 0.77 paise per kWh.

Example 2.49. *Determine the thermal efficiency of a steam power plant and its coal bill per annum using the following data.*

Maximum demand = *24000 kW*
Load factor = *40%*
Boiler efficiency = *90%*
Turbine efficiency = *92%*
Coal consumption = *0.87 kg / Unit*
Price of coal = *Rs. 280 per tonne.*

Solution. η = Thermal efficiency

= Boiler efficiency × Turbing efficiency

$= 0.9 \times 0.92$

$= 0.83$

$$\text{Load factor} = \frac{\text{Average Load}}{\text{Maximum Demand}}$$

Average Load $= 0.4 \times 24000$

$= 9600$ kW

E = Energy generated in a year

$= 9600 \times 8760$

$= 841 \times 10^5$ kWh

$$\text{Cost of coal per year} = \frac{E \times 0.87 \times 280}{1000}$$

$$= \frac{841 \times 10^5 \times 0.87 \times 280}{1000}$$

$= \text{Rs. } 205 \times 10^5$.

Example 2.50. *The following data relates to a steam power plant.*

Capacity of the plant = 100 MW

Capital Cost = Rs. 1800 per kW installed

Maximum demand = 80 MW

Interest and depreciation = 10% on capital

Fuel cost = Rs. 80 per tonne

Fuel consumption = 1.3 kg / kwh

Salaries, wages and maintenance = Rs. 8×10^5 per year

Load factor = 50%

Determine the cost of generation per kwh.

Solution.

C = Capacity of the power plant

= 100 MW = 100 × 1000 kW

Capital investment

$$= 100 \times 1000 \times 1800 = \text{Rs. } 18 \times 10^7$$

C_1 = Interest and depreciation

$$= \frac{10}{100} \times 18 \times 10^7 = \text{Rs. } 18 \times 10^6$$

Average load = Maximum Demand × Load factor

$$= 80 \times 0.5 = 40 \text{ MW} = 40 \times 1000 \text{ kW}$$

E = Energy generated per year = Average load × Time in hours

$$= 40 \times 1000 \times 8760$$

$$= 3504 \times 10^5 \text{ kWh}$$

W = Weight of fuel consumed

$$= 1.3 \times E$$

$$= 1.3 \times 3504 \times 10^5$$

$$= 4555 \times 10^5 \text{ kg}$$

$$= 4555 \times 10^2 \text{ tonne}$$

C_2 = Cost of fuel

$$= W \times 80$$

$$= 4555 \times 10^2 \times 80 = \text{Rs. } 3644 \times 10^4$$

C_3 = Salaries, wages and maintenance

$$= \text{Rs. } 8 \times 10^5$$

S = Total investment

$$= C_1 + C_2 + C_3$$

$$= 18 \times 10^6 + 3644 \times 10^4 + 8 \times 10^5$$

$$= \text{Rs. } 55.24 \times 10^6$$

Cost of generation = $\frac{S}{E}$

$$= \frac{55.24 \times 10^6}{3504 \times 10^5}$$

$$= 15.76 \text{ paise per kWh.}$$

Example 2.51. *Two electrical units are used for same purpose.*

Cost of first unit = Rs. 7000 and it takes 90 kW.

Cost of second unit = Rs. 18000 and it takes 50 kW.

Useful life of each unit = 38×10^3 hours.

Energy rate = Rs. 100 per kW of maximum demand per year and 8 paise per kWh.

Find which unit will be economical if both units run at full load.

Solution. *First Unit.*

C_1 = Capital cost per hour

$$= \frac{7000}{38 \times 10^3} = \text{Rs. } 0.184$$

Maximum demand = 90 kW

Rate for maximum demand = Rs. 100 per kW

C_2 = Charge for maximum demand per hour

$$= \frac{90 \times 100}{8760} = \text{Rs. } 1.028$$

E_1 = Energy produced per hour = $90 \times 1 = 90$ kWh.

C_3 = Energy charges per hour

$= E_1 \times$ Rate

$$= 90 \times \frac{8}{100} = \text{Rs. } 7.20$$

C = Total charge per hour for the operation of the unit

$= 0.184 + 1.028 + 7.20 = \text{Rs. } 8.412$

Second unit

$$C_1 = \text{Capital cost per hour} = \frac{18000}{38 \times 10^3} = 0.47$$

C_2 = Charge for maximum demand per hour

$$= \frac{50 \times 100}{8760} = \text{Rs. } 0.57$$

C_3 = Energy charge per hour

$$= (50 \times 1) \times \frac{8}{100}$$

= Rs. 4.0

C = Total charges per hour

$= C_1 + C_2 + C_3$

$= 0.47 + 0.57 + 4.0$ = Rs. 5.04

Hence second unit is economical.

Example 2.52. *The maximum (peak) load on a thermal power plant of 60 MW capacity is 50 MW at an annual load factor of 50%. The loads having maximum demands of 25 MW, 20 MW, 8 MW and 5 MW are connected to the power station.*

Determine : (a) Average load on power station (b) Energy generated per year (c) Demand factor (d) Diversity factor.

Solution.

(a) Load factor = $\frac{\text{Average load}}{\text{Maximum demand}}$

Average load = $0.5 \times 50 = 25$ MW

(b) E = Energy generated per year

= Average load × 8760

$= 25 \times 1000 \times 8760$

$= 219 \times 10^6$ kWh.

(c) Demand factor = $\frac{\text{Maximum demand}}{\text{Connected load}}$

$$= \frac{50}{25 + 20 + 8 + 5}$$

$$= \frac{50}{58} = 0.86$$

(d) Diversity factor = $\frac{M_1}{M_2}$

where M_1 = Sum of individual maximum demands

$= 25 + 20 + 8 + 5 = 58$ MW

M_2 = Simultaneous maximum demand = 50 MW

Diversity factor = $\frac{58}{50} = 1.16$

PROBLEMS

2.1. Explain the following terms as applied to power system :

(*i*) Demand factor,
(*ii*) Connected load,
(*iii*) Maximum Demand,
(*iv*) Use factor,
(*v*) Capacity factor.

2.2. (*a*) What is meant by load curve ? What is its significance in power generation ?
(*b*) Explain the difference between load curve and load duration curve.

2.3. What is meant by load factor and diversity factor ? Prove that an increase in diversity of load improves the load factor of a power system.

2.4. What do you understand by power plant economics ? Explain the fixed costs and operating cost of a power station.

2.5. What is meant by depreciation of a power station ? Explain the straight line method and sinking fund method of calculating depreciation ?

2.6. What is meant by tariff ? What are the various types of tariffs in common use ? Explain the two part tariff.

2.7. Explain the terms (*i*) heat rate, (*ii*) incremental rate of a power plant. What is the significance of incremental rate curve ?

2.8. Explain how economical load division is obtained between the two alternators of a power stations ?
Prove that for economical load sharing the incremental rates of the two are equal.

2.9. Power stations *A* and *B* are of equal capacities. State which power station is running economical if the two power stations are working at load factor of 70% and 60% respectively.
[Ans. Power Station *A*]

2.10. Write short notes on the following :
(*a*) Types of loads
(*b*) Types of power plants
(*c*) Base load power plant
(*d*) Peak load power plant.

2.11. The input-output curve of a 150 MW station is expressed by the formula,

$$I = 10^6 (250 + 5L + 0.03L^3) + L^4$$

where I is in kcal per hour and L is in mega-watts. Find the load at which minimum heat rate occurs and check with the plot.
[Ans. 73.8 MW]

2.12. The input-output curves of three generating units are given by the following formulae :

Units	*Input-Output Curve*
A	$I = 10^6 (10 + 0.04 L^2 + 0.02 L^3)$
B	$I = 10^6 (8 + 8 L + 0.4 L^2)$
C	$I = 10^6 (10 - 6L)$

where I is in kcal per hour and L in the MW.

The capacity of unit A, B, C and 10, 10 and 6 MW respectively. Plot the individual and combined incremental rate curves on a common graph and devise a combined loading schedule for the three units when total loads to be supplied are 6 MW, 18 MW, 12 MW, 24 MW and 26 MW.

2.13. Calculate the unit cost of production of electric energy for a power station for which data are supplied as follows :

Capacity	= 50 MW
Cost per kW	= Rs. 600
Load factor	= 40%
Interest and depreciation	= 10%

Cost of fuel, taxation and salaries = Rs. 36×10^5.

[**Ans.** 3.71 paise]

2.14. Estimate the generating cost per unit supplied from a power plant having the following data :

Plant capacity	= 120 MW
Capital cost	= Rs. 600×10^6
Annual load factor	= 40%
Annual cost of fuel, taxation, oil and salaries	= Rs. 600,000
Interest and depreciation	= 10%

[**Ans.** 1.33 paise]

2.15. Prove that for maximum efficiency of a power plant the incremental rate is equal to heat rate.

2.16. Estimate the generating cost per unit supplied from a power plant having data :

Output per year	= 4×10^8 kWh
Load factor	= 50%
Annual fixed charges	= Rs. 40 per kW
Annual running charges	= 4 paise per kWh.

2.17. A 50 MW generating station has the following data :

Capital cost	= Rs. 15×10^5
Annual taxation	= Rs. 0.4×10^5
Annual salaries and wages	= Rs. 1.2×10^6
Cost of coal	= Rs. 65 per tonne
Calorific value of coal	= 5500 kcal/kg.
Rate of interest and depreciation	= 12%
Plant heat rate	= 33,000 kcal/kWh

at 100% capacity and 40000 kcal/kWh at 60%.

Calculate the generating cost/kWh at 100% and 60% capacity factor.

(A.M.I.E. 1979)

2.18. Write short notes on the following :

(*a*) Economics in plant selection

(*b*) Power plant capacity

(*c*) E.H.V. lines.

2.19. A system with a maximum demand of 100,000 kW and load factor of 30% is to be supplied by either (*a*) 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 40,000 kW. The capital cost of the steam and storage station are Rs. 1200 per kW and Rs. 1050 per kW respectively. The corresponding operating cost 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. *(A.M.I.E. 1976)*

2.20. Discuss the factors which affect choice of power station.

2.21. Find the cost of generation per kWh from the following data :

Capacity of a plant	= 120 MW
Capital cost	= Rs. 1,200 per kW installed
Interest and depreciation	= 10% on capital
Fuel consumption	= 1.2 kg/kWh
Fuel cost	= Rs. 40 per tonne.

Salaries, wages, repair and maintenance = Rs. 600,000 per year.

The maximum demand is 80 MW, and load factor is 40%.

(A.M.I.E. 1981)

2.22. A power plant has the following annual factor :

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.

(A.M.I.E. 1981)

2.23. The following data is supplied for a power plant :

Capacity	= 150 MW
Capital cost	= Rs. 1800 per kW
Interest and depreciation	= 8% of the capital cost
Annual running charges	= Rs. 18×10^6
Profit	= 70% of the capital
Energy consumed to run power plant auxiliaries	= 5% of energy generated
Annual capacity factor	= 0.5
Annual load factor	= 0.55

Determine the following ;

(*a*) Reserve capacity

(*b*) Cost of generation per kWh.

2.24. Why is it necessary to predict the future load demand. What are the methods of load forecasting ?

2.25. Explain the effect of variable load on power plant operation and design.

2.26. (*a*) An Electric Supply undertaking has the following data.

Power generated	= 500×10^6 kWh
Maximum demand	= 150×10^3 kW

Cost of generation = Rs. 32×10^5
Cost of transmission line = Rs. 650×10^4
Cost of line of distribution = Rs. 280×10^4
Cost of fuel = Rs. 550×10^4

Out of these 10% and 8%, 6% and 90% are running charges and remaining is a fixed charge. The transmission and distribution loss is 10%. Calculate two part tariff.

(*b*) If the load factor of the plant is raised to 55% for the same maximum demand, calculate the percentage saving in overall cost per kWh.

2.27. The cost of an electric motor is Rs. 5000. It is to be overhauled two times during life of 10 years. On each overhauling a sum of Rs. 1000 is spent. Calculate depreciation cost per year if residual cost of motor after 10 years is Rs. 800. [**Ans.** Rs. 620]

2.28. A power plant supplies power to four regions of loads of 10 MW, 20 MW, 15 MW and 18 MW. Find maximum demand if diversity factor is 1.3.

Steam Power Plant

3.0 Introduction

Steam is an important medium of producing mechanical energy. Steam has the advantage that it can be raised from water which is available in abundance it does not react much with the materials of the equipment of power plant and is stable at the temperature required in the plant. Steam is used to drive steam engines, steam turbines etc. Steam power station is most suitable where coal is available in abundance. Thermal electrical power generation is one of the major method. Out of total power developed in India about 60% is thermal. For a thermal power plant the range of pressure may vary from 10 kg/cm^2 to super critical pressures and the range of temperature may be from 250° C to 650°C.

The average all India Plant load factor (P.L.F.) of thermal power plants in 1987-88 has been worked out to be 56.4% which is the highest P.L.F. recorded by thermal sector so far.

3.1. Essentials of Steam Power Plant Equipment

A steam power plant must have following equipments :

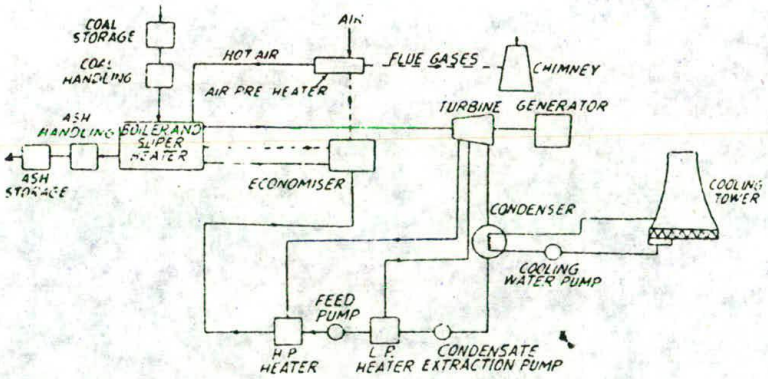


Fig. 3.1

(*i*) A furnace to burn the fuel.
(*ii*) Steam generator or boiler containing water. Heat generated in the furnace is utilized to convert water in steam.
(*iii*) Main power unit such as an engine or turbine to use the heat energy of steam and perform work.
(*iv*) Piping system to convey steam and water.

In addition to the above equipment the plant requires various auxiliaries and accessories depending upon the availability of water, fuel and the service for which the plant is intended.

The flow sheet of a thermal power plant consists of the following four main circuits :

(*i*) Feed water and steam flow circuit
(*ii*) Coal and ash circuit
(*iii*) Air and gas circuit
(*iv*) Cooling water circuit.

A steam power plant using steam as working substance works basically on Rankine cycle.

Steam is generated in a boiler, expanded in the prime mover and condensed in the condenser and fed into the boiler again.

The different types of systems and components used in steam power plant are as follows :

(*i*) High pressure boiler
(*ii*) Prime mover
(*iii*) Condensers and cooling towers
(*iv*) Coal handling system
(*v*) Ash and dust handling system
(*vi*) Draught system
(*vii*) Feed water purification plant
(*viii*) Pumping system
(*ix*) Air preheater, economiser; super heater, feed heaters.

Fig. 3.1 shows a schematic arrangement of equipment of a steam power station. Coal received in coal storage yard of power station is transferred in the furnace by coal handling unit. Heat produced due to burning of coal is utilised in converting water contained in boiler drum into steam at suitable pressure and temperature. The steam generated is passed through the superheater. Superheated steam then flows through the turbine. After doing work in the turbine the pressure of steam is reduced. Steam leaving the turbine passes through the condenser which maintain the low pressure of steam at the exhaust of turbine. Steam pressure in the condenser depends upon flow rate and temperature of cooling water and on effectiveness of air removal equipment. Water circulating through the condenser may be taken from the various sources such as river, lake or sea. If sufficient quantity of water is not available the hot water

coming out of the condenser may be cooled in cooling towers and circulated again through the condenser.

Bled steam taken from the turbine at suitable extraction points is sent to low pressure and high pressure water heaters.

Air taken from the atmosphere is first passed through the air pre-heater, where it is heated by flue gases. The hot air then passes through the furnace. The flue gases after passing over boiler and superheater tubes, flow through the dust collector and then through economiser, air pre-heater and finally they are exhausted to the atmosphere through the chimney.

Steam condensing system consists of the following :

(*i*) Condenser (*ii*) Cooling water
(*iii*) Cooling tower (*iv*) Hot well
(*v*) Condenser cooling water pump
(*vi*) Condensate air extraction pump
(*vii*) Air extraction pump (*viii*) Boiler feed pump
(*ix*) Make up water pump.

3.1.1. Power Station Design

Power station design requires wide experience. A satisfactory design consists of the following steps :

(*i*) Selection of site.
(*ii*) Estimation of capacity of power station.
(*iii*) Selection of turbines and their auxiliaries.
(*iv*) Selection of boilers, and their auxiliaries.
(*v*) Design of fuel handling system.
(*vi*) Selection of condensers.
(*vii*) Design of cooling system.
(*viii*) Design of piping system to carry steam and water.
(*ix*) Selection of electrical generator.
(*x*) Design and control of instruments.
(*xi*) Design of layout of power station.

Quality of coal used in steam power station plays an important role in the design of power plant. The various factors to be considered while designing the boilers and coal handling units are as follows :

(*i*) Slagging and erosion properties of ash.
(*ii*) Moisture in the coal. Excessive moisture creates additional problems particularly in case of pulverised fuel power plants.
(*iii*) Burning characteristic of coal.
(*iv*) Corrosive nature of ash.

3.1.2. Characteristics of Steam Power Plant

The desirable characteristic for a steam power plant are as follows :

(*i*) Higher efficiency. (*ii*) Lower cost.
(*iii*) Ability to burn coal especially of high ash content, and inferior coals.
(*iv*) Reduced environmental impact in terms of air pollution.
(*v*) Reduced water requirement.
(*vi*) Higher reliability and availability.

3.2 Coal Handling

Coal delivery equipment is one of the major components of plant cost. The various steps involved in coal handling are as follows :

(See Fig. 3.2)
(*i*) Coal delivery (*ii*) Unloading
(*iii*) Preparation (*iv*) Transfer
(*v*) Outdoor storage (*vi*) Covered storage
(*vii*) In plant handling (*viii*) Weighing and measuring
(*ix*) Feeding the coal into furnace.

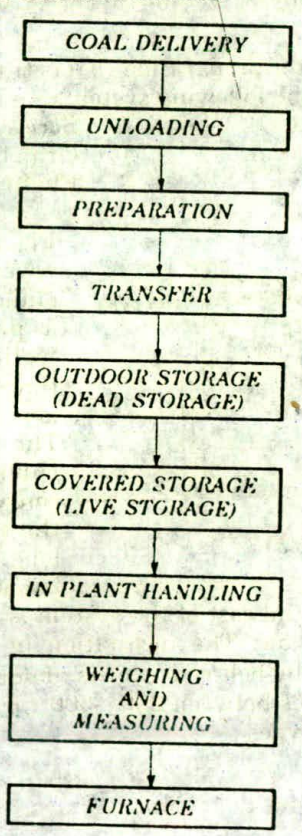


Fig. 3.2.

(*i*) **Coal Delivery.** The coal from supply points is delivered by ships or boats to power stations situated near to sea or river whereas coal is supplied by rail or trucks to the power stations which are situated away from sea or river. The transportation of coal by trucks is used if the railway facilities are not available.

(*ii*) **Unloading.** The type of equipment to be used for unloading the coal received at the power station depends on how coal is received at the power station. 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. In case the coal is brought by railway wagons, ships or boats, the unloading may be done by car shakes, rotary car dumpers, cranes, grab buckets and coal accelerators. Rotary car dumpers although costly are quite efficient for unloading closed wagons.

(*iii*) **Preparation.** When the coal delivered is in the form of big lumps and it is not of proper size, the preparation (sizing) of coal can be achieved by crushers, breakers, sizers driers and magnetic separators.

(*iv*) **Transfer.** After preparation coal is transferred to the dead storage by means of the following systems :

1. Belt conveyors.
2. Screw conveyors.
3. Bucket elevators.
4. Grab bucket elevators.
5. Skip hoists.
6. Flight conveyor.

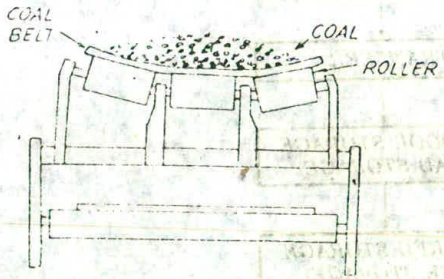


Fig. 3.3.

1. **Belt conveyor.** Fig. 3.3 shows a belt conveyor. It consists of an endless belt moving over a pair of end drums (rollers). At some distance a supporting roller is provided at the centre. The belt is made up of rubber or canvas. Belt conveyor is suitable for the transfer of coal over long distances. It is used in medium and large power plants. The initial cost of the system is not high and power consumption is also low. The inclination at which coal can be successfully elevated by belt conveyor is about 20 . Average speed of belt conveyors varies between 200—300 r.p.m. This conveyor is preferred than other types.

Advantages of belt conveyor

1. Its operation is smooth and clean.
2. It requires less power as compared to other types of systems.
3. Large quantities of coal can be discharged quickly and continuously.
4. Material can be transported on moderates inclines.

2. **Screw conveyor.** It consists of an endless helicoid screw fitted to a shaft (Fig. 3.4). The screw while rotating in a trough transfers the coal from feeding end to the discharge end.

This system is suitable, where coal is to be transferred over shorter distance and space limitations exist. The initial cost of the system is low. It suffers from the drawbacks that the power consumption is high and there is considerable wear of screw. Rotation of screw varies between 75—125 r.p.m.

3. **Bucket elevator.** It consists of buckets fixed to a chain (Fig. 3.6). The chain moves over two wheels. The coal is carried by the buckets from bottom and discharged at the top.

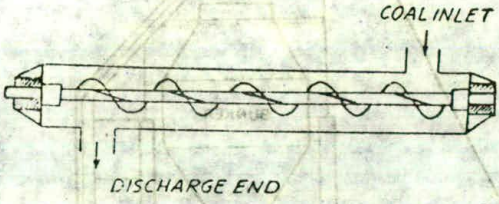


Fig. 3.4 Screw conveyor.

4. **Grab bucket elevator.** It lifts and transfers coal on a single rail or track from one point to the other. The coal lifted by grab buckets is transferred to overhead bunker or storage. This system requires less power for operation and requires minimum maintenance.

The grab bucket conveyor can be used with crane or tower as shown in Fig. 3.4 (*a*). Although the initial cost of this system is high but operating cost is less.

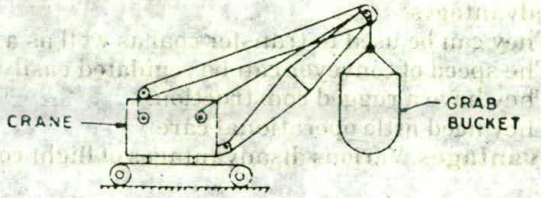


Fig. 3.4 (a).

5. **Skip hoist.** It consists of a vertical or inclined hoistway a bucket or a car guided by a frame and a cable for hoisting the bucket. The bucket is held in up right position. It is simple and compact method of elevating coal or ash. Fig. 3.5 shows a skip hoist.

6. **Flight conveyor.** It consists of one or two strands of chain to which steel scraper or flights are attached which scrap the coal through a trough having identical shape. This coal is discharged in the bottom of trough. It is low in first cost but has large energy consumption. There is considerable wear.

Skip hoist and bucket elevators lift the coal vertically while Belts and flight conveyors move the coal horizontally or on inclines.

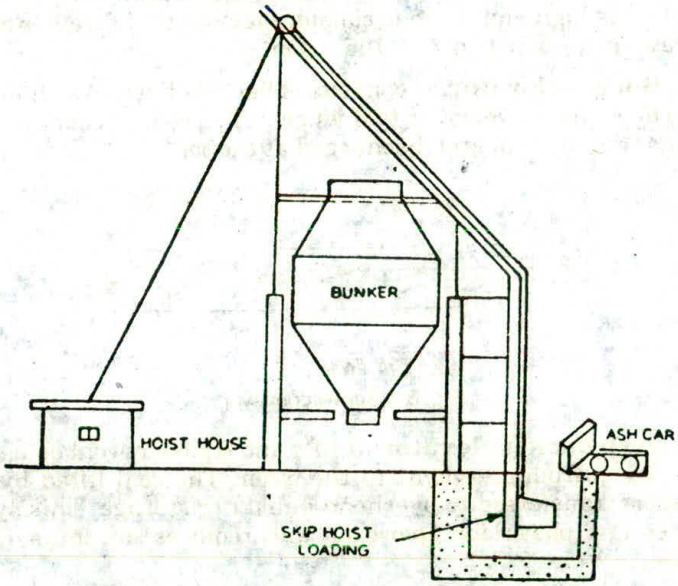


Fig. 3.5

Fig. 3.5 (*a*) shows a flight conveyor. Flight conveyors possess the following advantages :

(*i*) They can be used to transfer coal as well as ash.
(*ii*) The speed of conveyor can be regulated easily.
(*iii*) They have a rugged construction.
(*iv*) They need little operational care.

Disadvantages. Various disadvantages of flight conveyors are as follows :

(*i*) There is more wear due to dragging action.
(*ii*) Power consumption is more.

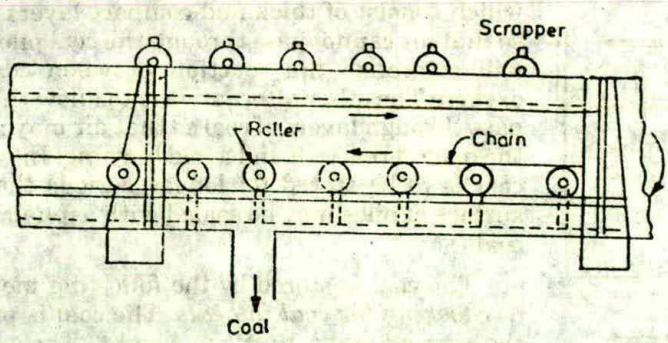


Fig. 3.5 (*a*).

(*iii*) Maintenance cost is high.

(*iv*) Due to abrasive nature of material handled the speed of conveyors is low (10 to 30 m/min).

(*v*) **Storage of coal.** It is desirable that sufficient 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. Also when the prices are low, the coal can be purchased and stored for future use. The amount of coal to be stored depends on the availability of space for storage, transportation facilities, the amount of coal that will whether away and nearness to coal mines of the power station.

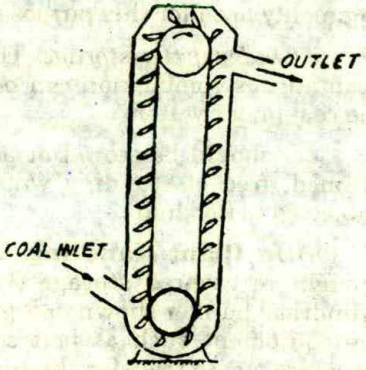


Fig. 3.6

Usually coal required for one month operation of power plant is stored in case of power stations situated at longer distance from the collieries whereas coal need for about 15 days is stored in case of power station situated near to collieries. Storage of coal for longer periods is not advantageous because it blocks the capital and results in deterioration of the quality of coal.

The coal received at the power station is stored in dead storage in the form of piles laid directly on the ground.

The coal stored has the tendency to whether (to combine with oxygen of air) and during this process coal loss some of its heating value and ignition quality. Due to low oxidation the coal may ignite spontaneously. This is avoided by storing coal in the form of piles

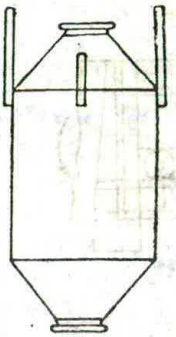


Fig. 3.7

which consist of thick and compact layers of coal so that air cannot pass through the coal piles. This will minimise the reaction between coal and oxygen. The other alternative is to allow the air to pass through layers of coal so that air may remove the heat of reaction and avoid burning. In case the coal is to be stored for longer periods the outer surface of piles may be sealed with asphalt or fine coal.

The coal is stored by the following methods : (*i*) *Stocking the coal in heats.* The coal is piled on the ground upto 10–12 m height. The pile top should be given a slope in the direction in which the rain may be drained off. The sealing of stored pile is desirable in order to avoid the oxidation of coal after packing in air tight layer of coal.

Asphalt, fine coal dust and bituminous coating are the materials commonly used for this purpose.

(*ii*) *Under water storage.* The possibility of slow oxidation and spontaneous combustion can be completely eliminated by storing the coal under water.

Coal should be stored at a site located on solid ground, well drained, free of standing water preferably on high ground not subjected to flooding.

(*vi*) **In Plant Handling.** From the dead storage the coal is brought to covered storage (Live storage) (bins or bunkers). A cylindrical bunker shown in Fig. 3.7. In plant 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.

(*vii*) **Coal weighing methods.** Weigh lorries, hoppers and automatic scales are used to weigh the quantity coal. The commonly used methods to weigh the coal are as follows :

(*i*) Mechanical (*ii*) Pneumatic (*iii*) Electronic.

The Mechanical method works on a suitable lever system mounted on knife edges and bearings connected to a resistance in the form of a spring of pendulum. The pneumatic weighters use a pneumatic transmitter weight head and the corresponding air pressure determined by the load applied. The electronic weighing machines make use of load cells that produce voltage signals proportional to the load applied.

The important factor considered in selecting fuel handling systems are as follows :

(*i*) Plant flue rate, (*ii*) Plant location in respect to fuel shipping, (*iii*) Storage area available.

3.2.1 Dewatering of Coal

Excessive surface moisture of coal reduces and heating value of coal and creates handling problems. The coal should therefore be dewatered to produce clean coal. Cleaning of coal has the following advantages :

(*i*) Improved heating value.
(*ii*) Easier crushing and pulverising.
(*iii*) Improved boiler performance.
(*iv*) Less ash to handle.
(*v*) Easier handling.
(*vi*) Reduced transportation cost.

3.3 Fuel Burning Furnaces

Fuel is burnt in a confined space called furnace. The furnace provides supports and enclosure for burning equipment. Solid fuels such as coal, coke, wood etc. are burnt by means of stokers where as burners are used to burn powdered (Pulverised) c[illegible]nd liquid fuels. Solid fuels require a grate in the furnace to hold the bed of fuel.

3.3.1 Types of Furnaces. According to the method of firing fuel furnaces are classified into two categories :

(*i*) Grate fired furnaces (*ii*) Chamber fired furnaces.

Grate fired furnaces. They are used to burn solid fuels. They may have a stationary or a movable bed of fuel.

These furnaces are classified as under depending upon the method used to fire the fuel and remove ash and slag.

(*i*) Hand fired (*ii*) Semi-mechanized
(*iii*) Stocker fired.

Hand fired and semi-mechanised furnaces are designed with stationary fire grates and stoker furnaces with travelling grates or stokers.

Chamber fired furnaces. They are used to burn pulverised fuel, liquid and gaseous fuels.

Furnace shape and size depends upon the following factors :

(*i*) Type of fuel to be burnt.
(*ii*) Type of firing to be used.
(*iii*) Amount of heat to be recovered.
(*iv*) Amount of steam to be produced and its conditions.
(*v*) Pressure and temperature desired.
(*vi*) Grate area required.

(*vii*) Ash fusion temperature.
(*viii*) Flame length.
(*ix*) Amount of excess air to be used.

Simply furnace walls consists of an interior face of refractory material such as fireclay, silica, alumina, kaolin and diaspore, an intermediate layer of insulating materials such as magnesia with the exterior casing made up of steel sheet. Insulating materials reduce the heat loss from furnace but raise the refractory temperature. Smaller boilers used solid refractory walls but they are air cooled. In larger units, bigger boilers use water cooled furnaces.

To burn fuels completely, the burning equipment should fulfil the following conditions :

1. The flame temperature in the furnace should be high enough to ignite the incoming fuel and air. Continuous and reliable ignition of fuel is desirable.
2. For complete combustion the fuel and air should be thoroughly mixed by it.
3. The fuel burning equipment should be capable to regulate the rate of fuel feed.
4. To complete the burning process the fuel should remain in the furnace for sufficient time.
5. The fuel and air supply should be regulated to ach. optimum air fuel ratios.
6. Coal firing equipment should have means to hold . discharge the ash.

Following factors should be considered while selecting a suitable combustion equipment for a particular type of fuel :

(*i*) Grate area required over which the fuel burns.
(*ii*) Mixing arrangement for air and fuel.
(*iii*) Amount of primary and secondary air required.
(*iv*) Arrangement to counter the effects of caping in fuel or of low ash fusion temperature.
(*v*) Dependability and easier operation.
(*vi*) Operating and maintenance cost.

3.4 Method of Fuel Firing

The solid fuels are fired into the furnace by the following methods :

1. Hand firing.
2. Mechanical firing.

3.4.1 Hand Firing

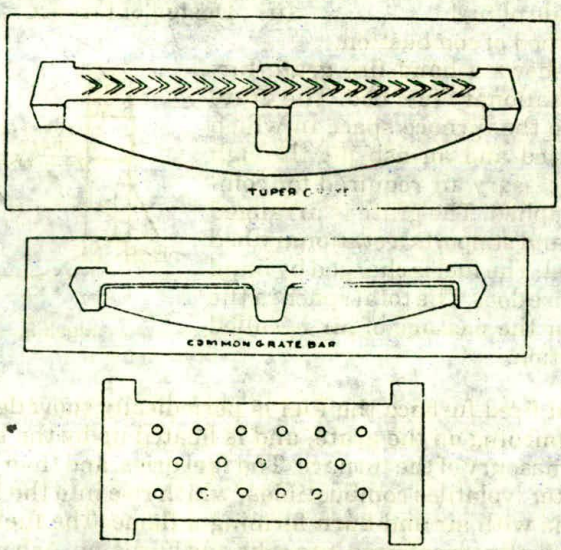
This is a simple method of firing coal into the furnace. It requires no capital investment. It is used for smaller plants. This method of fuel firing is discontinuous process, and there is a limit to the size of furnace which can be efficiently fired by this method. Adjustments

are to be made every time for the supply of air when fresh coal is fed into furnace.

Hand Fired Grates. A hand fired grate is used to support the fuel bed and admit air for combustion. While burning coal the total area of air openings varies from 30 to 50% of the total grate area. The grate area required for an installation depends upon various factors such as its heating surface, the rating at which it is to be operated and the type of fuel burnt by it. The width of air openings varies from 3 to 12 mm.

The construction of the grate should be such that it is kept uniformly cool by incoming air. It should allow ash to pass freely.

Hand fired grates are made up of cast iron. The various types of hand fired grates are shown in Fig. 3.8. In large furnaces vertical shaking grates of circular type are used.



SAWDUST GRATE
Fig. 3.8

The main characteristic of a grate fired furnaces are the heat liberation per unit of grate area and per unit of volume. The heat liberation per unit area of fire grate area is calculated as follows :

$$H = \frac{W \times C}{A}$$

where H = Heat liberation per unit of fire grate area

W = Rate of fuel consumption (kg/sec)

C = Lower heating value of fuel (kcal/kg)

A = Fire grate area (m^2)

The heat liberation per unit of furnace volume is given by the following expression :

$$H = \frac{W \times C}{V}$$

where H = Heat liberation per unit volume

W = Rate of fuel consumption (kg/sec)

C = Lower heating value of fuel (kcal/kg)

V = Volume of furnace (m^3).

These two characteristics depend on the following factors :

(*i*) Grade of fuel (*ii*) Design of furnace

(*iii*) Method of combustion.

Fig. 3.9 shows a hand fire grate furnace with a stationary fuel bed. The grate divides it into the furnace space in which the fuel is fired and an ash pit through which the necessary air required for combustion is supplied. The grate is arranged horizontally and supports a stationary bed of burning fuel. The fuel is charged by hand through the fire door. The total space in the grate used for the passage of air is called its useful section.

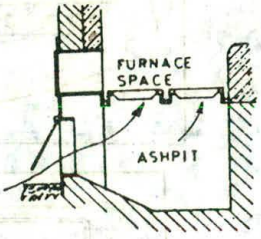


Fig. 3.9

In a hand fired furnace the fuel is periodically shovelled on to the fuel bed burning on the grate, and is heated up by the burning fuel and hot masonry of the furnace. The fuel dries, and then evolves gaseous matter (volatiles combustibles) which rise into the furnace space and mix with air and burn forming a flame. The fuel left on the grate gradually transforms into coke and burns-up. Ash remains on the grate which drops through it into ash pit from which it is removed at regular intervals. Hand fired furnaces are simple in design and can burn the fuel successfully but they have some disadvantages also mentioned below :

(*i*) The efficiency of a hand fired furnace is low.

(*ii*) Attending to furnace requires hard manual labour.

(*iii*) Study process of fuel feed is not maintained.

Cleaning of hand fired furnaces may be mechanised by use of rocking grate bars as shown in Fig. 3.9 (*a*). The grate bars loosen the slag and cause some of it to drop together with the ash into the bunker without disturbing the process of combustion.

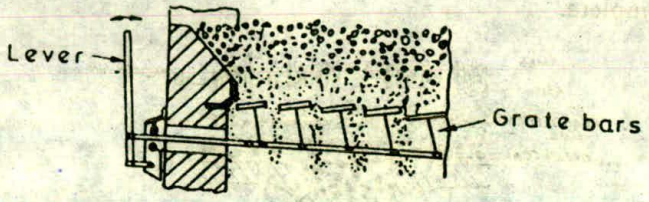


Fig. 3.9 (*a*)

3.4.2 Mechanical Firing (*Stokers*)

Mechanical stokers are commonly used to feed solid fuels into the furnace in medium and large size power plants.

The various advantages of stoker firing are as follows :

(*i*) Large quantities of fuel can be fed into the furnace. Thus greater combustion capacity is achieved.

(*ii*) Poorer grades of fuel can be burnt easily.

(*iii*) Stoker save labour of handling ash and are self-cleaning.

(*iv*) By using stokers better furnace conditions can be maintained by feeding coal at a uniform rate.

(*v*) Stokers save coal and increase the efficiency of coal firing.

The main disadvantages of stokers are their more costs of operation and repairing resulting from high furnace temperatures.

Principles of Stokers. The working of various types of stokers is based on the following two principles :

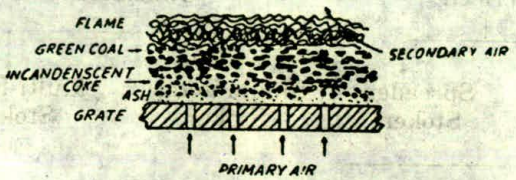


Fig. 3.10

1. *Overfeed Principle.* According to this principle (Fig. 3.10) the primary air enters the grate from the bottom. The air while moving through the grate openings gets heated up and air while moving through the grate openings gets heated up and the grate is cooled. The hot air that moves through a layer of ash and picks up additional energy. The air then passes through a layer of incandescent coke where oxygen reacts with coke to form-CO_2 and water vapours accompanying the air react with incandescent coke to form CO_2, CO and free H_2. The gases leaving the surface of fuel bed contain volatile matter of raw fuel and gases like CO_2, CO, H_2, N_2 and H_2O. Then additional air known as secondary air is supplied to burn the combustible gases. The combustion gases entering the

boiler consist of N_2, CO_2, O_2 and H_2O and also CO if the combustion is not complete.

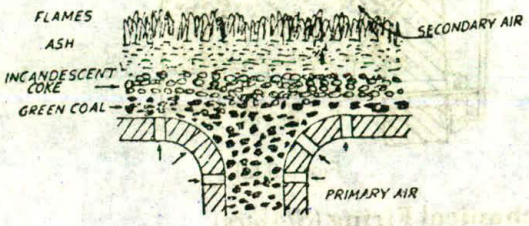
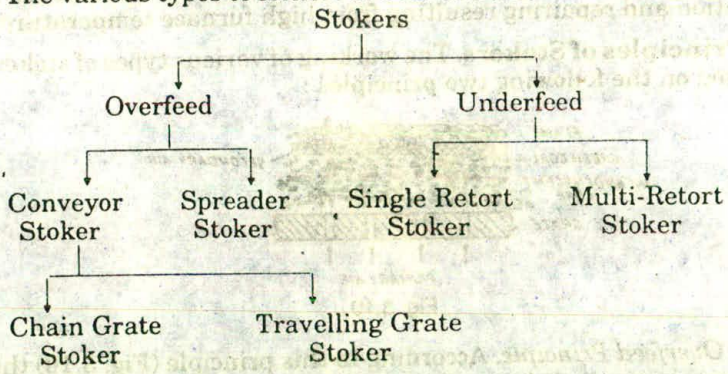


Fig. 3.11

2. *Underfeed Principle.* Fig. 3.11 shows underfeed principle. In underfeed principle 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 passes through a layer of ash. The secondary air is supplied to burn the combustible gases. Underfeed principle is suitable for burning the semi-bituminous and bituminous coals.

3.4.3 Types of Stokers

The various types of stokers are as follows :



Charging of fuel into the furnace is mechanised by means of stokers of various types. They are installed above the fire doors underneath the bunkers which supply the fuel. The bunkers receive the fuel from a conveyor.

(*i*) **Chain Grate Stoker.** Chain grate stoker and travelling grate stoker differ only in grate construction. A chain grate stoker (Fig. 3.12) consists of an endless chain which forms a support for the fuel bed.

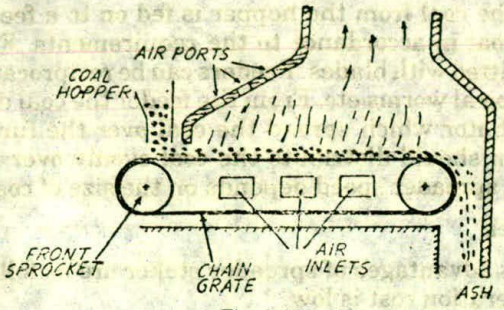


Fig. 3.12.

The chain travels over two sprocket wheels, one at the front and one at the rear of furnace. The travelling chain receives coal at its front end through a hopper and carries it into the furnace. The ash is tipped from the rear end of chain. The speed of grate (chain) can be adjusted to suit the firing condition. The air required for combustion enters through the air inlets situated below the grate. Stokers are used for burning non-coking free burning high volatile high ash coals. Although initial cost of this stoker is high but operation and maintenance cost is low.

The travelling grate stoker also uses an endless chain but differs in that it carries small grate bars which actually support the fuel fed. It is used to burn lignite, very small sizes of anthracites coke breeze etc.

The stokers are suitable for low ratings because the fuel must be burnt before it reaches the rear of the furnace. With forced draught, rate of combustion is nearly 30 to 50 lb of coal per square foot of grate area per hour, for bituminous 20 to 35 pounds per square foot per hour for anthracite.

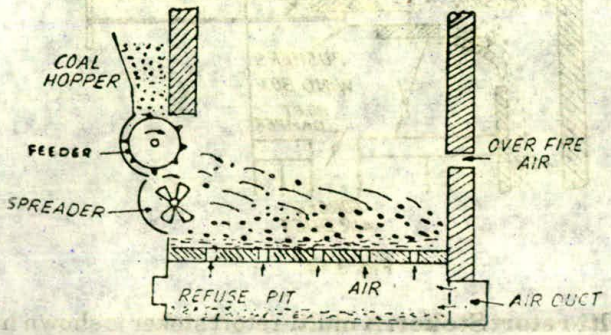


Fig. 3.13.

(*ii*) **Spreader Stoker.** A spreader stoker is shown in Fig. 3.13. In this stoker the coal from the hopper is fed on to a feeder which measures the coal in accordance to the requirements. Feeder is a rotating drum fitted with blades. Feeders can be reciprocating rams, endless belts, spiral worms etc. From the feeder the coal drops on to spreader distributor which spread the coal over the furnace. The spreader system should distribute the coal evenly over the entire grate area. The spreader speed depends on the size of coal.

Advantages

The various advantages of spreader stoker are as follows :

1. Its operation cost is low.
2. A wide variety of coal can be burnt easily by this stoker.
3. A thin fuel bed on the grate is helpful in meeting the fluctuating loads.
4. Ash under the fire is cooled by the incoming air and this minimises clinkering.
5. The fuel burns rapidly and there is little coking with coking fuels.

Disadvantages

1. The spreader does not work satisfactorily with varying size of coal.
2. In this stoker the coal burns in suspension and due to this fly ash is discharged with flue gases which requires an efficient dust collecting equipment.

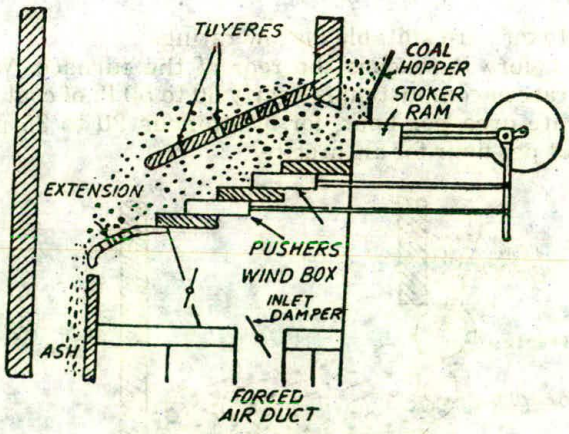


Fig. 3.14.

(*iii*) **Multi-retort Stoker.** A multi-retort stoker is shown in Fig. 3.14. The coal falling from the hopper is pushed forward during the inward stroke of stoker ram. The distributing rams (pushers) then

slowly move the entire coal bed down the length of stoker. The length of stroke of pushers can be varied as desired. The slope of stroke helps in moving the fuel bed and this fuel bed movement keeps it slightly agitated to break up clinker formation. The primary air enters the fuel bed from main wind box situated below the stoker. Partly burnt coal moves on to the extension grate. A thinner fuel bed on the extension grate requires lower air pressure under it. The air entering from the main wind box into the extension grate wind box is regulated by an air damper.

As sufficient amount of coal always remains on the grate, this stoker can be used under large boilers (upto 500,000 lb per hr capacity) to obtain high rates of combustion. Due to thick fuel bed the air supplied from the main wind box should be at higher pressure.

Example 3.1. *A chain grate stoker is used to burn bituminous cool having 10% moisture and 10% ash. The higher calorific value of coal is 7000 kcal/kg. The steam generator produces steam at the rate of 10,000 kg per hour. It uses 600 kcal to evaporate 1 kg of feed water entering the boiler and super heat it to the final temperature, calculate the following :*

(a) Hourly coal supply

(b) Grate area

(c) Grate length if grate width is 5 metres.

Assume overall steam generator efficiency 80%. This stoker can burn the coal at the rate of 15×10^5 kcal per sq. metre hour.

Solution. Heat absorbed by water and steam

$$= 100{,}000 \times 600 = 60 \times 10^6 \text{ kcal per hr.}$$

As the steam generator efficiency = 80%.

$\therefore$ Heat to be produced

$$= \frac{60 \times 10^6}{0.8} = 75 \times 10^6 \text{ kcal per hour.}$$

$\therefore$ Amount of coal required

$$= \frac{75 \times 10^6}{7000 \times 1000} = 10.71 \text{ tonnes.}$$

$$\text{Grate area} = \frac{75 \times 10^6}{15 \times 10^5} = 50 \text{ sq. metres.}$$

Grate width = 5 metres.

$\therefore$ Grate length $= \frac{50}{5} = 10$ metres.

3.5 Automatic Boiler Control

By means of automatic combustion control it becomes easy to maintain a constant steam pressure and uniform furnace draught and supply of air or fuel can be regulated to meet the changes in steam demand. The boiler operation becomes more flexible and better efficiency of combustion is achieved. This saves manual labour also.

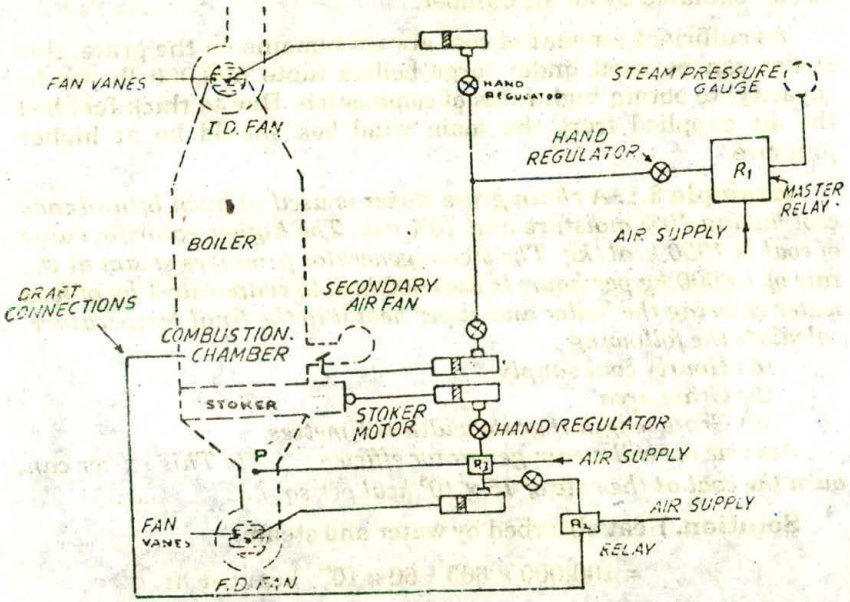


Fig. 3.15.

Hagan system of automatic combustion control is shown in Fig. 3.15. Master relay R_1, is sensitive to small vanations in steam pressure and is connected to steam pressure gauge. A fall in pressure operates the master relay R_1 which in turn operates the servo-motor coupled to the vanes of the induced draught (*I.D.*) fan to open them slightly and simultaneously the secondary air fan damper gets opened proportionately. By this readjustment of induced draught takes place and stabilised conditions in the combustion chamber get changed. These changes operate relay R_2 to alter the position of forced draught fan servo-motor to adjust the position of forced draught fan vanes so that stable conditions in combustion chamber are maintained. This change causes more air to flow through passage which in turn operates relay R_3. This causes stoker motor to supply extra fuel into the furnace. In case of an increase of pressure

of steam the above process is reversed. Hand regulators are provided to servo motors and master relay for manual control of system.

3.6 Pulverised Coal

Coal is pulverised (powdered) to increase its surface exposure thus permitting rapid combustion. Efficient use of coal depends greatly on the combustion process employed.

For large scale generation of energy the efficient method of burning coal is confined still to pulverised coal combustion. The pulverised coal is obtained by grinding the raw coal in pulverising mills. The various pulverising mills used are as follows :

(*i*) Ball mill (*ii*) Hammer mill
(*iii*) Ball and race mill (*iv*) Bowl mill.

The essential functions of pulverising mills are as follows :

(*i*) Drying of the coal (*ii*) Grinding
(*iii*) Separation of particles of the desired size.

Proper drying of raw coal which may contain moisture is necessary for effective grinding.

The coal pulverising mills reduce coal to powder form by three actions as follows :

(*i*) Impact (*ii*) Attrition (abrasion)
(*iii*) Crushing.

Most of the mills use all the above mentioned all the three actions in varying degrees. In impact type mills hammers break the coal into smaller pieces whereas in attrition type the coal pieces which rub against each other or metal surfaces to disintegrate. In crushing type mills coal caught between metal rolling faces gets broken into pieces. The crushing mills use steel balls in a container. These balls act as crushing elements.

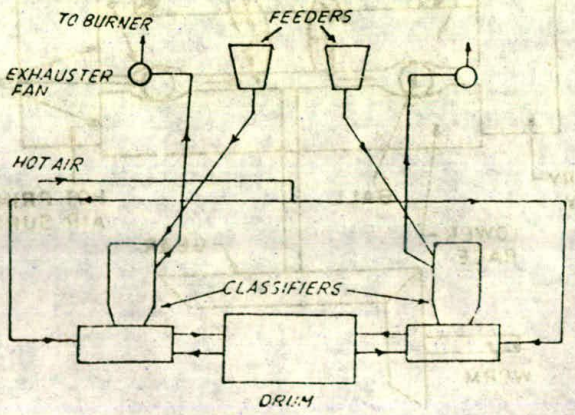


Fig. 3.16.

3.6.1 Ball mill

A line diagram of ball mill using two classifiers is shown in Fig. 3.16. It consists of a slowly rotating drum which is partly filled with steel balls. Raw coal from feeders is supplied to the classifiers from where it moves to the drum by means of a screw conveyor. As the drum rotates the coal gets pulverised due to the combined impact between coal and steel balls. Hot air is introduced into the drum. The powdered coal is picked up by the air and the coal air mixture enters the classifiers, where sharp changes in the direction of the mixture throw out the oversized coal particles. The over-sized particles are returned to the drum. The coal air mixture from the classifier moves to the exhauster fan and then it is supplied to the burners.

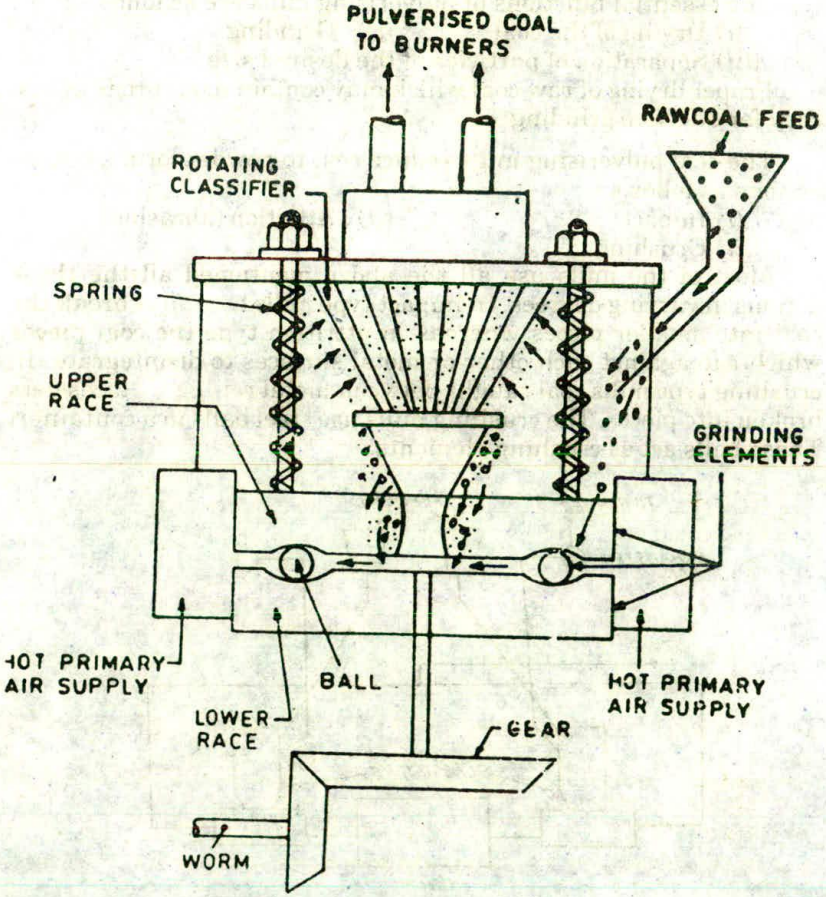


Fig. 3.16 (*a*)

3.6.2 Ball and race mill

Fig. 3.16 (*a*) shows a ball and race mill. In this mill the coal passes between the rotating elements again and again until it has been pulverised to desired degree of fineness. The coal is crushed between two moving surfaces namely balls and races. The upper stationary race and lower rotating race driven by a worm and gear hold the balls between them. The raw coal supplied falls on the inner side of the races. The moving balls and races catch coal between them to crush it to a powder. The necessary force needed for crushing is applied with the help of springs. The hot air supplied picks up the coal dust as it flows between the balls and races, and then enters the classifier. Where oversized coal particles are returned for further grinding, where as the coal particles of required size are discharged from the top of classifier.

In this mill coal is pulverised by a combination of crushing, impact and attrition between the grinding surfaces. The advantages of this mill are as follows :

(*i*) Lower capital cost (*ii*) Lower power consumption
(*iii*) Lower space required (*iv*) Lower weight.

However in this mill there is greater wear as compared to other pulverisers.

The use of pulverised coal has now become the standard method of firing in the large boilers. The pulverised coal burns with some advantages that result in economic and flexible operation of steam boilers.

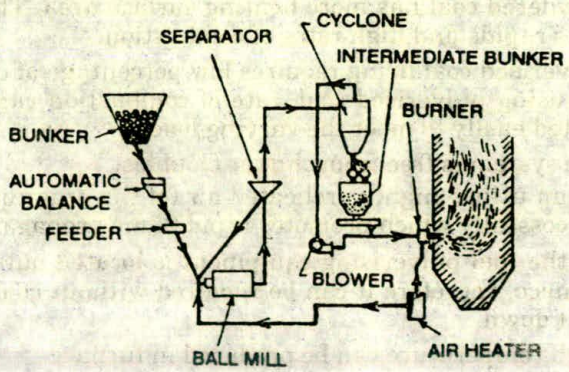


Fig. 3.17 (*a*).

Preparation of pulverised fuel with an intermediate bunker is shown in Fig. 3.17 (*a*). The fuel moves to the automatic balance and then to the feeder and ball mill through which hot air is blown. It dries the pulverised coal and carries it from the mill to the separator.

The air fed to the ball mill is heated in the air heater. In the separator dust (fine pulverised coal) is separated from large coal particles which are returned to the ball mill for regrinding. The dust moves to the cyclone. Most of the dust (about 90%) from cyclone moves to bunker. The remaining dust is mixed with air and fed to the burner.

Coal is generally ground in low speed ball tube mill. It is filled to 20—35% of its volume. With steel balls having diameter varying from 30—60 mm. The steel balls crush and ground the lumps of coal. The average speed of rotation of tube or drum is about 18—20 R.P.M. [Fig. 3.17 (*b*)].

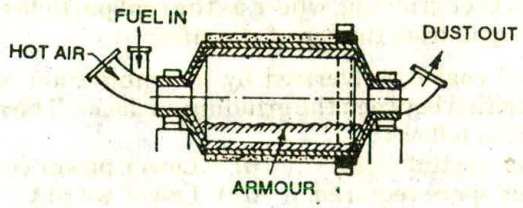


Fig. 3.17 (*b*) Ball tube mill.

Advantages

The advantages of using pulverised coal are as follows :

1. It becomes easy to burn wide variety of coal. Low grade coal can be burnt easily.
2. Powdered coal has more heating surface area. They permits rapids and high rates of combustion.
3. Pulverised coal firing requires low percentage of excess air.
4. By using pulverised coal, rate of combustion can be adjusted easily to meet the varying load.
5. The system is free from clinker troubles.
6. It can utilise highly preheated air (of the order of 700°F) successfully which promotes rapid flame propagation.
7. As the fuel pulverising equipment is located outside the furnace, therefore it can be repaired without cooling the unit down.
8. High temperature can be produced in furnace.

Disadvantages

1. It requires additional equipment to pulverise the coal. The initial and maintenance cost of the equipment is high.

2. Pulverised coal firing produces fly ash (fine dust) which requires a separate fly ash removal equipment.
3. The furnace for this type of firing has to be carefully designed to withstand for burning the pulverised fuel because combustion takes place while the fuel is in suspension.
4. The flame temperatures are high and conventional types of refractory lined furnaces are inadequate. It is desirable to provide water cooled walls for the safety of the furnaces.
5. There are more chances of explosion as coal burns like a gas.
6. Pulverised fuel fired furnaces designed to burn a particular type of coal can not be used to any other type of coal with same efficiency.
7. The size of coal is limited. The particle size of coal used in pulverised coal furnace is limited to 70 to 100 microns.

3.6.3 Shaft Mill

Fig. 3.17 (*a*) shows fuel pulverisation with a shaft mill. The fuel from bunker is moved to feeder via automatic balance. Then from duct fuel goes to mill where it is crushed by beaters secured on the spindle of the mill rotor.

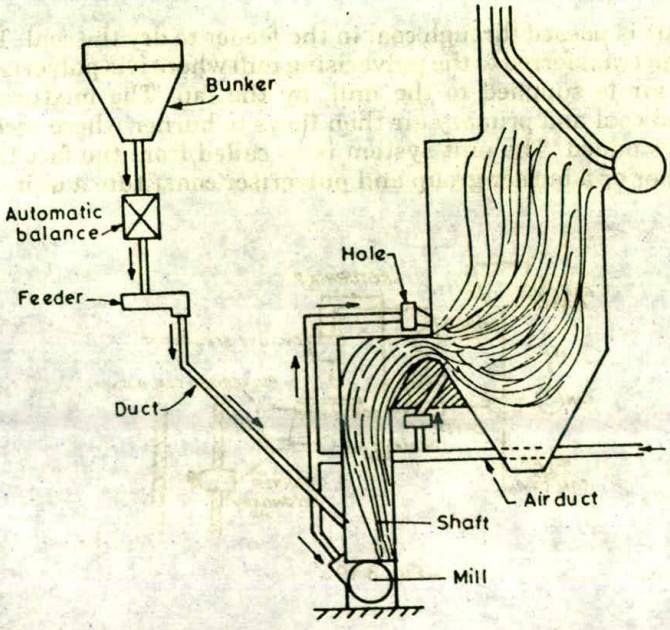


Fig. 3.17 (*b*)

The pulverised fuel is dried up and then blown into shaft by hot air. Secondary air is delivered into the furnace through holes to burn the fuel completely.

3.7 Pulverised Coal Firing

Pulverised coal firing is done by two system :

(*i*) Unit System or Direct System.

(*ii*) Bin or Central System.

Unit System. In this system (Fig. 3.18) the raw coal from the coal bunker drops on to the feeder.

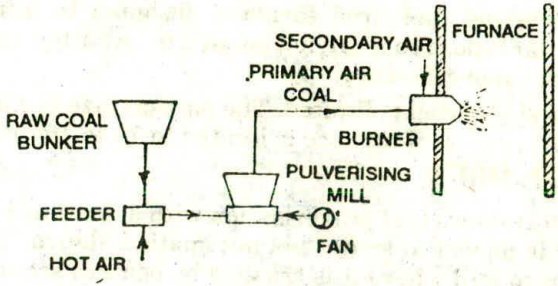


Fig. 3.18

Hot air is passed through coal in the feeder to dry the coal. The coal is then transferred to the pulverising mill where it is pulverised. Primary air is supplied to the mill, by the fan. The mixture of pulverised coal and primary air then flows to burner where secondary air is added. The unit system is so called from the fact that each burner or a burner group and pulveriser constitute a unit.

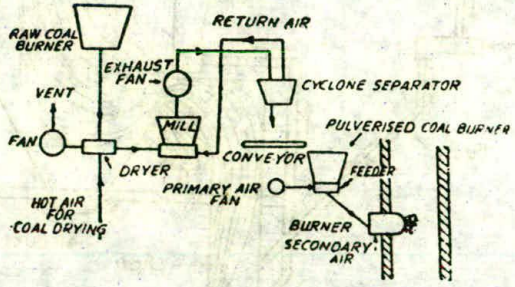


Fig. 3.19.

Advantages

1. The system is simple and cheaper than the central system.
2. There is direct control of combustion from the pulverising mill.
3. Coal transportation system is simple.

Bin or Central System. It is shown in Fig. 3.19. Crushed coal from the raw coal bunker is fed by gravity to a dryer where hot air is passed through the coal to dry it. The dryer may use waste flue gases, preheated air or bleeder steam as drying agent. The dry coal is then transferred to the pulverising mill. The pulverised coal obtained is transferred to the pulverised coal bunker (bin). The transporting air is separated from the coal in the cyclone separator. The primary air is mixed with the coal at the feeder and the mixture is supplied to the burner.

Advantages

1. The pulverising mill grinds the coal at a steady rate irrespective of boiler feed.
2. There is always some coal in reserve. Thus any occasional breakdown in the coal supply will not effect the coal feed to the burner.
3. For a given boiler capacity pulverising mill of small capacity will be required as compared to unit system.

Disadvantages

1. The initial cost of the system is high.
2. Coal transportation system is quite complicated.
3. The system requires more space.

To a large extent the performance of pulverised fuel system depends upon the mill performance. The pulverised mill should satisfy the following requirements :

1. It should deliver the rated tonnage of coal.
2. Pulverised coal produced by it should be of satisfactory fineness over a wide range of capacities.
3. It should be quiet in operation.
4. Its power consumption should be low.
5. Maintenance cost of the mill should be low.

Fig. 3.19 (*a*) shows the equipments for unit and central system of pulverised coal handling plant.

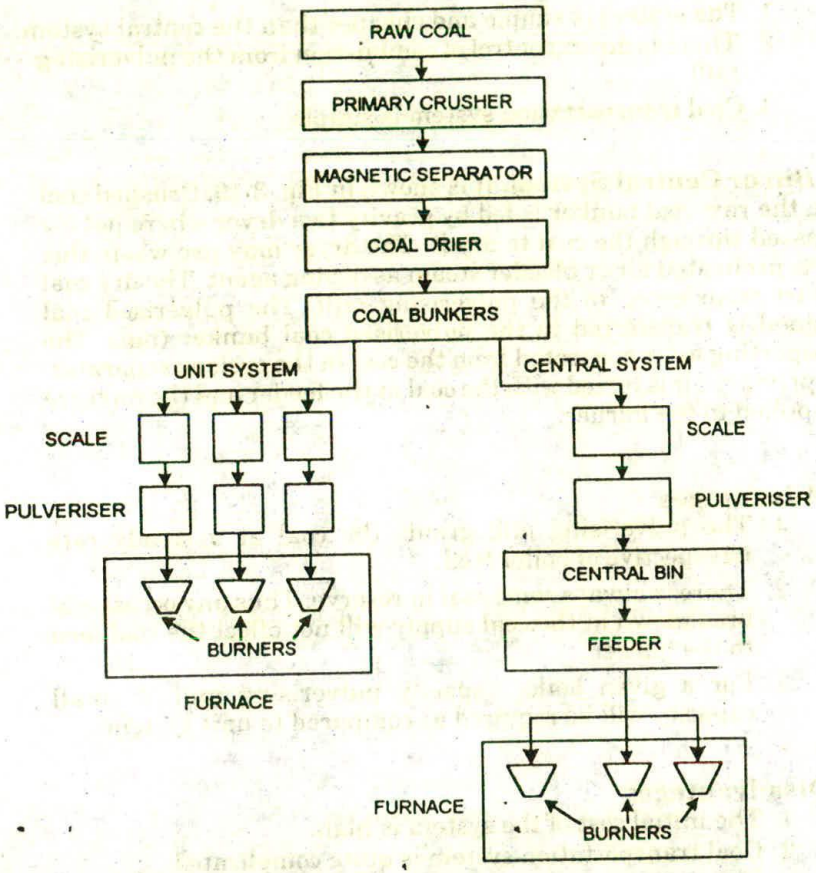


Fig. 3.19 (*a*)

3.8 Pulverised Coal Burners

Burners are used to burn the pulverised coal. The main difference between the various burners lies in the rapidity of air-coal mixing *i.e.*, turbulence. For bituminous coals the turbulent type of burner is used whereas for low volatile coals the burners with long flame should be used. A pulverised coal burner should satisfy the following requirements :

(*i*) It should mix the coal and primary air thoroughly and should bring this mixture before it enters the furnace in contact with additional air known as secondary air to create sufficient turbulence.

(*ii*) It should deliver and air to the furnace in right proportions and should maintain stable ignition of coal air mixture

and control flame shape and travel in the furnace. The flame shape is controlled by the secondary air vanes and other control adjustments incorporated into the burner. Secondary air if supplied in too much quantity may cool the mixture and prevent its heating to ignition temperature.

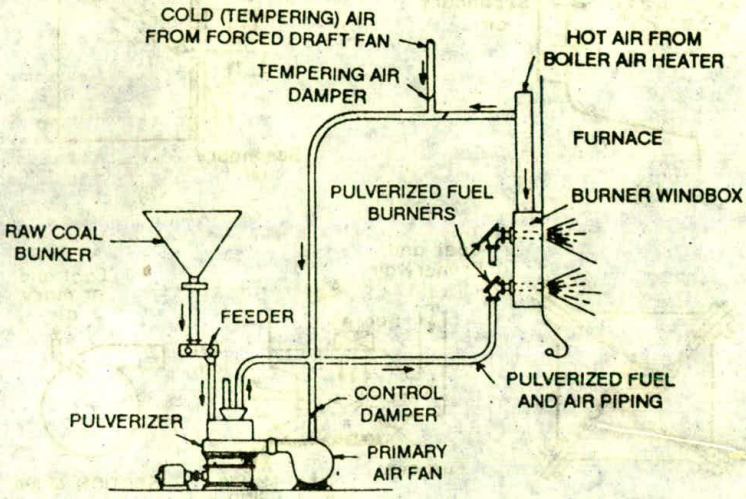


Fig. 3.19 (*b*) Shows typical firing system in pulverised coal.

(*iii*) Coal air mixture should move away from the burner at a rate equal to flame front travel in order to avoid flash back into the burner.

The various types of burners are as follows :

1. **Long Flame Burner (U-Flame Burner).** In this burner air and coal mixture travels a considerable distance thus providing sufficient time for complete combustion [Fig. 3.20 (*a*)].

2. **Short Flame Burner (Turbulent Burner).** It is shown in Fig. 3.20 (*b*). The burner is fitted in the furnace will and the flame enters the furnace horizontally.

3. **Tangential Burner.** A tangential burner is shown in Fig. 3.20 (*c*). In this system one burner is fitted attach corner of the furnace. The inclination of the burner is so made that the flame produced are tangential to an imaginary circle at the centre.

4. **Cyclone Burner.** It is shown in Fig. 3.20 (*d*). This burner uses crushed coal intend of pulverised coal. Its advantages are as follows :

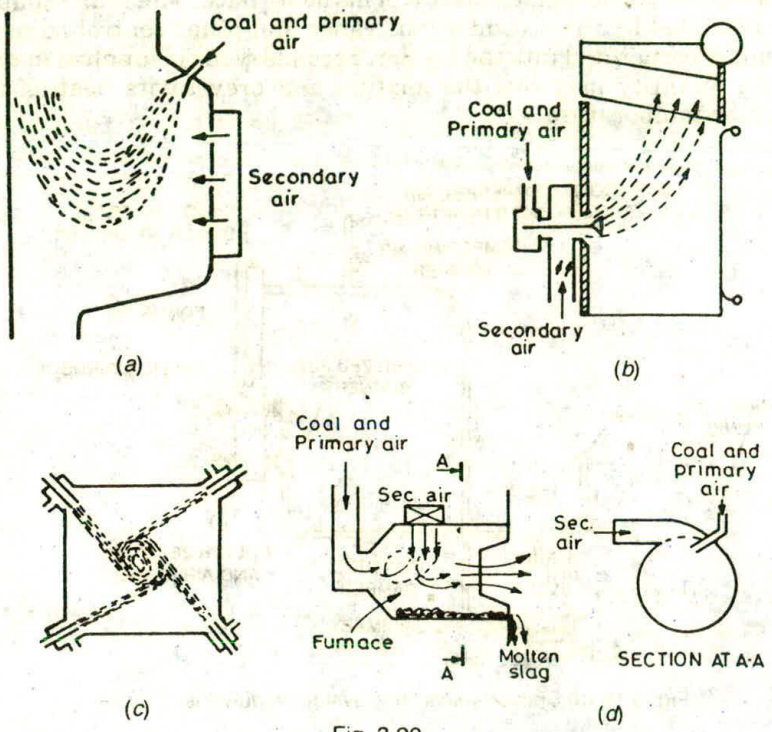
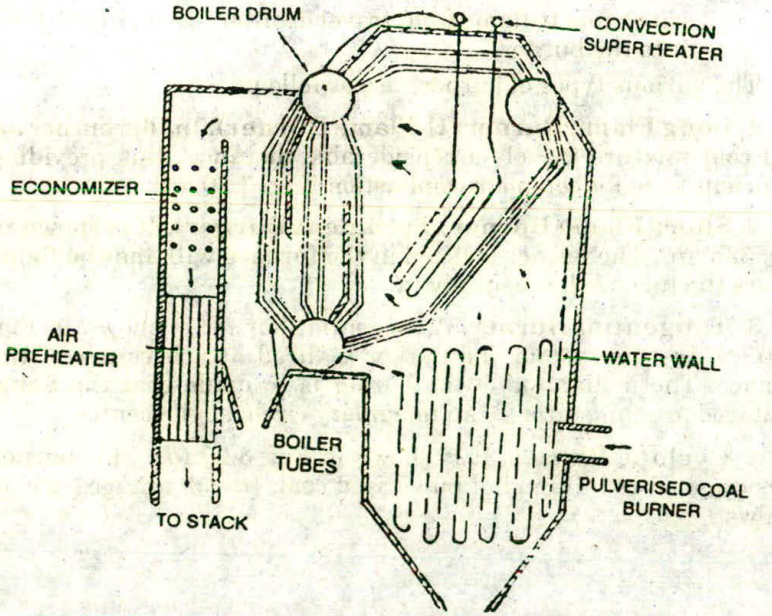

Coal and primary air
Secondary air
(a)
Coal and Primary air
Secondary air
(b)
(c)
Coal and Primary air
A
Sec. air
Furnace
A
Molten slag
Coal and primary air
Sec. air
SECTION AT A-A
(d)

Fig. 3.20


BOILER DRUM
CONVECTION SUPER HEATER
ECONOMIZER
AIR PREHEATER
WATER WALL
BOILER TUBES
PULVERISED COAL BURNER
TO STACK

(*i*) It saves the cost of pulverisation because of a crusher needs less power than a pulveriser.

(*ii*) Problem of fly ash is reduced. Ash produced is in the molten form and due to inclination of furnace it flows to an appropriate disposal system.

Fig. 3.21 (*a*) shows a pulverised coal-fired boiler.

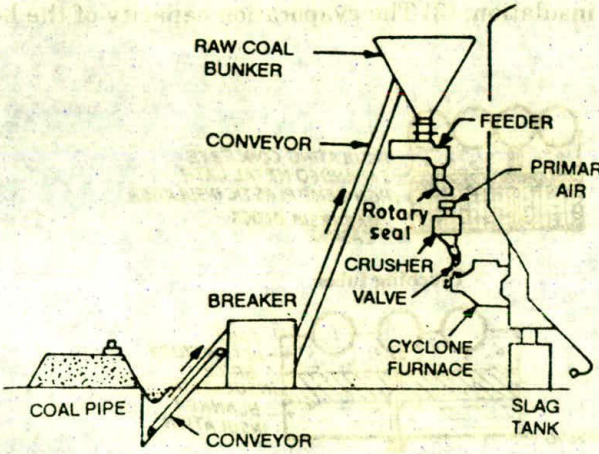


Fig. 3.21 (*b*) Shows a typical firing system for cyclone furnace.

3.8.1 Cyclone Fired Boilers. In cyclone fired boilers the furnace is arranged as a horizontal cylinder. The pulverised fuel is bed along the periphery of the cylinder. The hot gases travel axially into the water tube section having a tight helix path. The temperature generated in the combustion zone is quite high and because of this the tubes are coated with fused ash which goes on collecting the ash particles going in the flue gases. The out going gases contain particles less than 20 microns.

The cyclone furnaces can successfully burn coals having low ash fusion temperature. The cyclone furnace is operated under combustion air pressure of 700 to 1000 mm of water gauge.

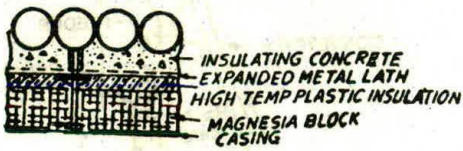
Cyclone fired boilers have the following advantages : (*i*) Quick load variations can be easily handled. (*ii*) Nearly 85% of ash in coal is burnt in the form of liquid slag. The ash can be removed in the molten form. (*iii*) The slag can be used as a building material. (*iv*) Fly-ash problem is reduced to much lower limits.

3.9 Water Walls

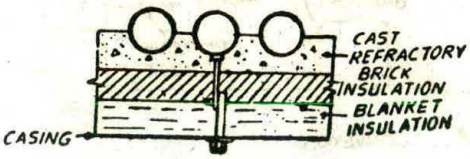
Larger central station type boilers have water cooled furnaces. The combustion space of a furnace is shielded wholly or partially by small diameter tubes placed side by side. Water from the boiler is

made to circulate through these tubes which connect lower and upper headers of boiler.

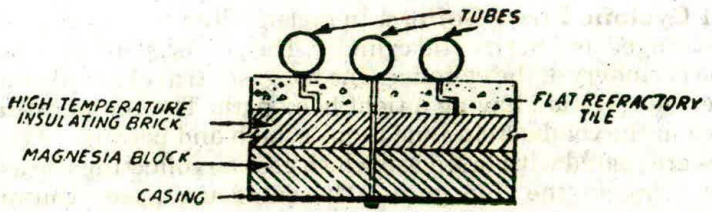
The provision of water walls is advantageous due to following reasons : (1) These walls provide a protection to the furnace against high temperatures. (2) They avoid the crosion of the refractory material and insulation. (3) The evaporation capacity of the boiler is increased.



Touching tubes.



Half radiant cast refactory.



Tangent tubes-flat files.
Fig. 3.22

The tubes are attached with the refractory materials on the inside or partially embedded into it. Fig. 3.22 shows the various water walls arrangement.

3.10 Ash Disposal

A large quantity of ash is, produced in steam power plants using coal. Ash produced in about 10 to 20% of the total coal burnt in the furnace. 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 gases. It is desirable to quench the ash before handling due to following reasons : (1) Quenching reduces the temperature of ash. (2) It reduces the corrosive action of ash. (3) Ash forms clinkers by fusing in large lumps and by quenching

clinkers will disintegrate. (4) Quenching reduces the dust accompanying the ash.

Handling of ash includes its removal from the furnace, loading on the conveyors and delivered to the fill from where it can be disposed off.

3.10.1 Ash Handling equipment

Mechanical means are required for the disposal of ash. The handling equipment should perform the following functions : (1) Capital investment, operating and maintenance charges of the equipment should be low. (2) It should be able to handle large quantities of ash. (3) Clinkers, soot, dust etc. create troubles, the equipment should be able to handle them smoothly. (4) The equipment used should remove the ash from the furnace, load it to the conveying system to deliver the ash to a dumping site or storage and finally it should have means to dispose of the stored ash. (5) The equipment should be corrosion and wear resistant.

Fig. 3.23 shows a general layout of ash handling and dust collection system. The commonly used ash handling systems are as follows :

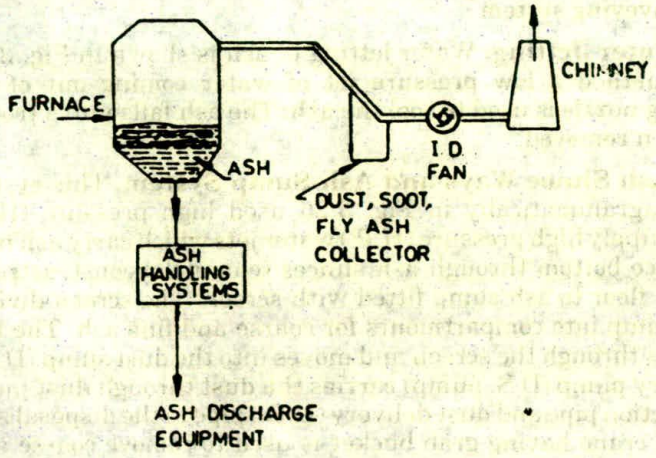


Fig. 3.23

(*i*) Hydraulic system (*ii*) Pneumatic system
(*iii*) Mechanical system.

The commonly used ash discharge equipment is as follows :

(*i*) Rail road cars (*ii*) Motor truck
(*iii*) Barge.

The various methods used for the disposal of ash are as follows :

(*i*) **Hydraulic System.** In this system, ash from the furnace grate falls into a system of water possessing high velocity and is carried to the sumps. It is generally used in large power plants. Hydraulic system is of two types namely low pressure hydraulic system used for continuous removal of ash and high pressure system which is used for intermittent ash disposal. Fig. 3.24 shows hydraulic system.

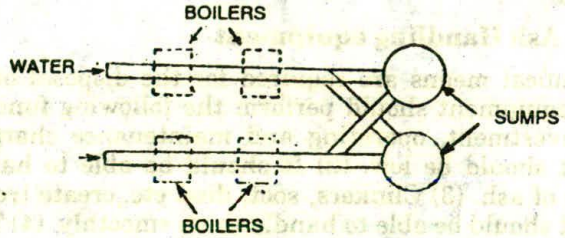


Fig. 3.24

In this method water at sufficient pressure is used to take away the ash to sump. Where water and ash are separated. The ash is then transferred to the dump site in wagons, rail cars or trucks. The loading of ash may be through a belt conveyor, grab buckets. If there is an ash basement with ash hopper the ash can fall, directly in ash car or conveying system.

(*ii*) **Water Jetting.** Water jetting of ash is shown in Fig. 3.25. In this method a low pressure jet of water coming out of the quenching nozzle is used to cool the ash. The ash falls into a trough and is then removed.

(*iii*) **Ash Sluice Ways and Ash Sump System.** This system shown diagrammatically in Fig. 3.26 used high pressure (H.P.) pump to supply high pressure (H.P.) water jets which carry ash from the furnace bottom through ash sluices (channels) constructed in basement floor to ash sump fitted with screen. The screen divides the ash sump into compartments for coarse and fine ash. The fine ash passes through the screen and moves into the dust sump (D.S.). Dust slurry pump (D.S. pump) carries the dust through dust pump (D.P.), suction pipe and dust delivery (D.D.) pipe to the disposal site. Overhead crane having grab bucket is used to remove coarse ash. A.F.N. represents ash feeding nozzle and S.B.N. represents sub way booster nozzle and D.A. means draining apron.

(*iv*) **Pneumatic system.** In this system (Fig. 3.27) ash from the boiler furnace outlet falls into a crusher where larger ash particles are crushed to small sizes. The ash is then carried by a high velocity air or steam to the point of delivery. Air leaving the ash separator

is passed through filter to remove dust etc. so that the exhauster handles clean air which will protect the blades of the exhauster.

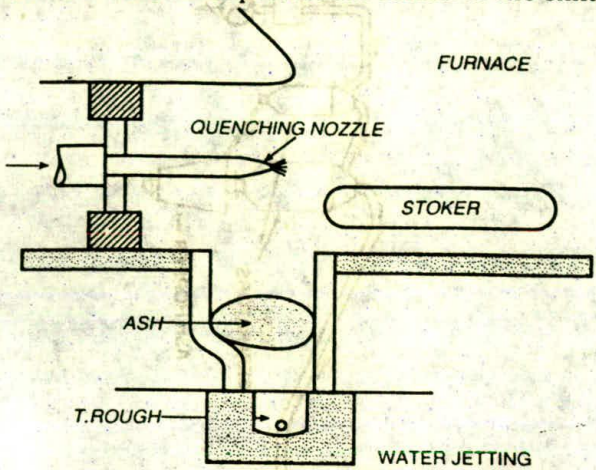


Fig. 3.25

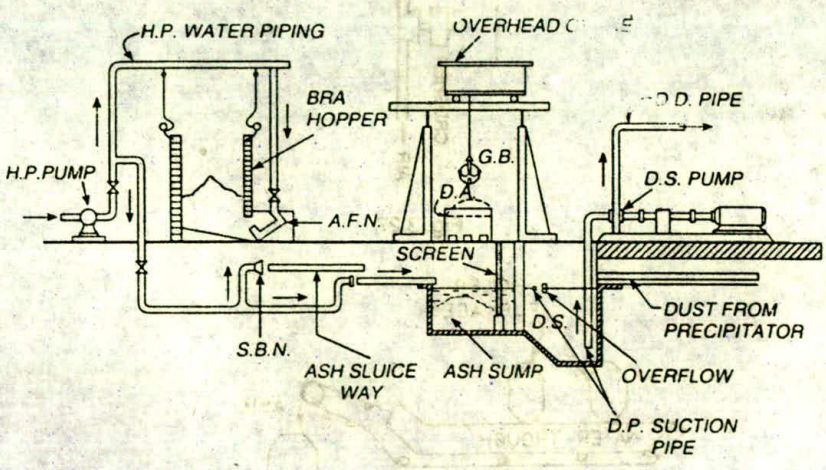


Fig. 3.26

(*v*) **Mechanical ash handling system.** Fig. 3.27 (*a*) shows a mechanical ash handling system. In this system ash cooled by water seal falls on the belt conveyor and is carried out continuously to the bunker. The ash is then removed to the dumping site from the ash bunker with the help of trucks.

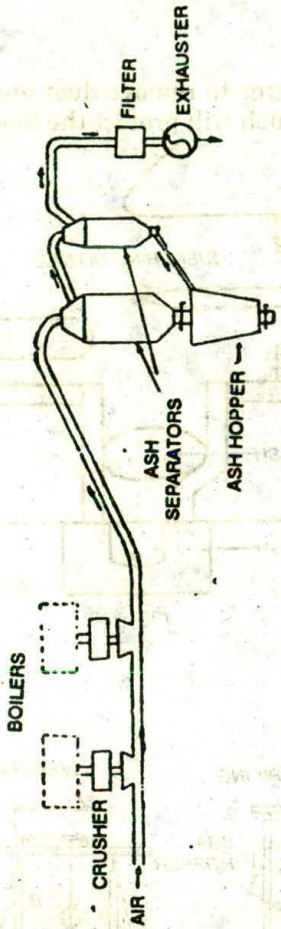


Fig. 3.27

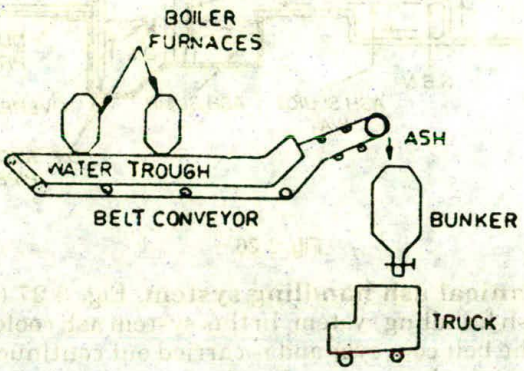


Fig. 3.27 (*a*)

Efficient Combustion of Coal

The factors which affect the efficient combustion of coal are as follows :

1. **Type of coal.** The important factors which are considered for the selection of coal are as follows :

(*i*) Sizing (*ii*) Caking (*iii*) Swelling properties (*iv*) Ash fusion temperature.

The characteristics which control the selection of coal for a particular combustion equipment are as follows :

(*i*) Size of coal
(*ii*) Ultimate and proximate analysis
(*iii*) Resistance of degradation
(*iv*) Grindability
(*v*) Caking characteristics
(*vi*) Slagging characteristics
(*vii*) Deterioration during storage
(*viii*) Corrosive characteristics
(*ix*) Ash Content.

The average ash content in Indian coal is about 20%. It is therefore desirable to design the furnace in such a way as to burn the coal of high ash content. The high ash content in coal has the following :

(*i*) It reduces thermal efficiency of the boiler as loss of heat through unburnt carbon, excessive clinker formation and heat in ashes in considerably high.

(*ii*) There is difficulty of hot ash disposal.

(*iii*) It increases size of plant.

(*iv*) It increases transportation cost of fuel per unit of heat produced.

(*v*) It makes the control difficult due to irregular combustion. High as content fuels can be used more economically in pulverised form. Pulverised fuel burning increases the thermal efficiency as high as 90% and controls can be simplified by just adjusting the position of burners in pulverised fuel boilers. The recent steam power plants in India are generally designed to use the pulverised coal.

2. **Type of Combustion equipment.** It includes the following:

(*i*) Type of furnace

(*ii*) Method of coal firing such as : (*a*) Hand firing (*b*) Stoker firing (*c*) Pulverised fuel firing.

(*iii*) Method of air supply to the furnace. It is necessary to provide adequate quantity of secondary air with sufficient turbulence.

(*iv*) Type of burners used.

(*v*) Mixing arrangement of fuel and air.

The flames over the bed are duel to the burning of volatile gases, lower the volatile content in the coal, shorter will be the flame. If the volatiles burn up intensely high temperature is generated over the furnace bed and helps to burn the carbon completely and *vice versa*.

For complete burning of volatiles and prevent unburnt carbon going with ash adequate quantity of secondary air with sufficient turbulence should be provided.

3.11 Smoke and Dust Removal

In coal fed furnaces the products of combustion contain particles of solid matter floating in suspension. This may be smoke or dust. The production of smoke indicates that combustion conditions are faulty and amount of smoke produced can be reduced by improving the furnace design.

In spreader stokers and pulverised coal fired furnaces the coal is burnt in suspension and due to this dust in the form of fly ash is produced. The size of dust particles is designated in microns (1 μ = 0.001 mm). Dust particles are mainly ash particles called fly ash intermixed with some quantity of carbon ash material called cinders. Gas borne particles larger than 1 μ in diameter are called dust and when such particles become greater in size than 100μ they are called cinders.

Smoke is produced due to the incomplete combustion of fuels, smoke particles are less than 10μ in size.

The disposal smoke to the atmosphere is not desirable due to the following reasons :

1. A smoky atmosphere is less healthful than smoke free air.
2. Smoke is produced due to incomplete combustion of coal. This will create a big economic loss due to loss of heating value of coal.
3. In a smoky atmosphere lower standards of cleanliness are prevalent. Buildings, clothings, furniture etc. becomes dirty due to smoke. Smoke corrodes the metals and darkens the paints.

To avoid smoke nuisance 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. A small amount of smoke leaving chimney shows good furnace conditions whereas smokeless chimney does not necessarily mean a better efficiency in the boiler room.

To avoid the atmospheric pollution the fly ash must be removed from the gaseous products of combustion before they leaves the chimney.

The removal of dust and cinders from the flue gas is usually effected by commercial dust collectors which are installed between the boiler outlet and chimney usually in the chimney side of air preheater.

3.12 Types of Dust Collectors

The various types of dust collectors are as follows :

1. Mechanical dust collectors.
2. Electrical dust collectors.

Mechanical dust collectors. Mechanical dust collectors are sub-divided into wet and dry types. In wet type collectors also known as scrubbers water sprays are used to wash dust from the air. The basic principles of mechanical dust collectors are shown in Fig. 3.28. As shown in Fig. 3.28 (*a*) by increasing the cross-sectional area of duct through which dust laden gases are passing, the velocity of gases is reduced and causes heavier dust particles to fall down. Changing the direction of flow [Fig. 3.28 (*b*)] of flue gases causes the heavier particles of settle out. Sometime baffles are provided as shown in Fig. 3.28 (*c*) to separate the heavier particles.

Mechanical dust collectors may be wet type or dry type. Wet type dust collectors called scrubbers make use of water sprays to wash the dust from flue gases.

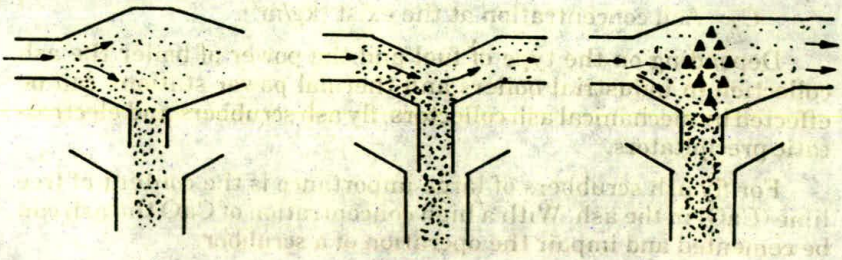


Fig. 3.28

Dry type dust collectors include gravitational, cyclone, louvred and baffle dust collectors.

A cyclone dust collector is shown in Fig. 3.29. This collector uses a downward flowing vortex for dust laden gases along the inner walls. The clean gas leaves from an inner upward flowing vortex. The dust particles fall to the bottom due to centrifuging action.

Electrostatic Precipitators. It has two sets of electrodes, insulated from each other, that maintain an electrostatic field

between them at high voltage (Fig. 3.30). The flue gases are made to pass between these two sets of electrodes. The electric field ionises the dust particles that pass through it attracting them to the electrode of opposite charge. The other electrode is maintained at a negative potential of 30,000 to 60,000 volts. The dust particles are removed from the collecting electrode by rapping the electrode periodically. The electrostatic precipitator is costly but has low maintenance cost and is frequently employed with pulverised coal fired power stations for its effectiveness on very fine ash particles and is superior to that of any other type.

The principal characteristics of an ash collector is the degree of collection.

$$\eta = \text{Degree of collection}$$

$$= \frac{G_1 - G_2}{G_1}$$

$$= \frac{C_1 - C_2}{C_1}$$

where G_1 = Quantity of ash entering an ash collector per unit time (kg/s)

G_2 = Quantity of uncollected ash passing through the collector per unit time (kg/s)

C_1 = Concentration of ash in the gases at the inlet to the ash collector (kg/m^3)

C_2 = Ash concentration at the exist (kg/m^3).

Depending on the type of fuel and the power of boiler the ash collection in industrial boilers and thermal power stations can be effected by mechanical ash collectors, fly ash scrubbers and electrostatic precipitators.

For fly ash scrubbers of large importance is the content of free lime (CaO) in the ash. With a high concentration of CaO the ash can be cemented and impair the operation of a scrubber.

The efficiency of operation of gas cleaning devices depends largely on the physico-chemical properties of the collected ash and of the entering waste gases.

Following are the principal characteristics of the fly ash :

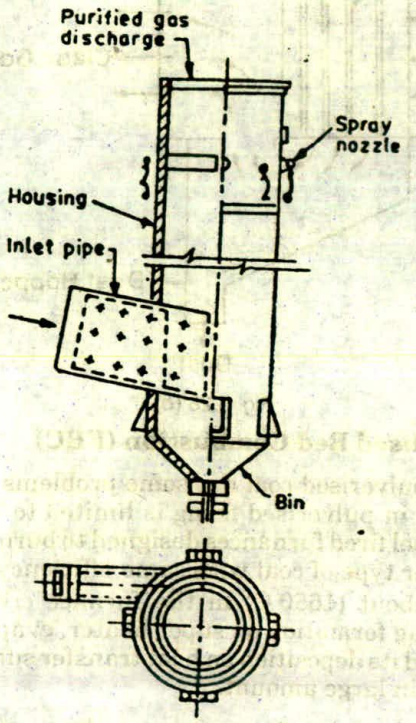
(*i*) Density
(*ii*) Dispersity (Particle size)
(*iii*) Electric resistance (For electrostatic precipitators)
(*iv*) Coalescence of ash particles.

Due to increasing boiler size and low sulphur high ash content coal the problem of collecting fly ash is becoming increasingly complex. Fly ash can range from very fine to very coarse size depending on the source. Particles colour varies from light tan to grey to black. Tan colour indicates presence of ion oxide while dark shades indicate presence of unburnt carbon. Fly ash particles size varies between 1 micron (1μ) to 300μ. Fly ash concentration in flue gases depends upon mainly the following factors :

(*i*) Coal composition.

(*ii*) Boiler design and capacity.

Percentage of ash in coal directly contributes to fly ash emission while boiler design and operation determine the percentage retained in the furnace as bottom ash and fly ash carried away by flue gas. Fly ash concentration widely varies around 20-90 g/mm^3 depending on coal and boiler design. Fly ash particle size distribution depends primarily on the type of boiler such as pulverised coal fired boiler typically produces coarser particles then cyclone type boilers. Electrostatic precipitator (ESP) is quite commonly used for removal of fly ash from flue gases.



3.12.1 Fly Ash Scrubber

Fig. 3.28 (*a*) shows a fly wash centrifugal scrubber. It is similar to a mechanical ash collector but has a flowing water film on its inner walls. Due to this film, the collected ash is removed more rapidly from the apparatus to the bin and there is less possibility for secondary. Capture of collected dust particles by the gas flow. The degree of ash collection in scrubbers varies from 0.82 to 0.90. The dust laden gas enters through the inlet pipe.

Cinder Catcher. Cinder catcher [Fig. 3.28 (*b*)] is used to remove dust and cinders from the gas. In this catcher the dust laden gas is made to strike a series of vertical baffles that change its direction and reduce its velocity. The separated dust and cinders fall to the hopper for removal. Cinder catchers are ordinarily used with stoker firing.

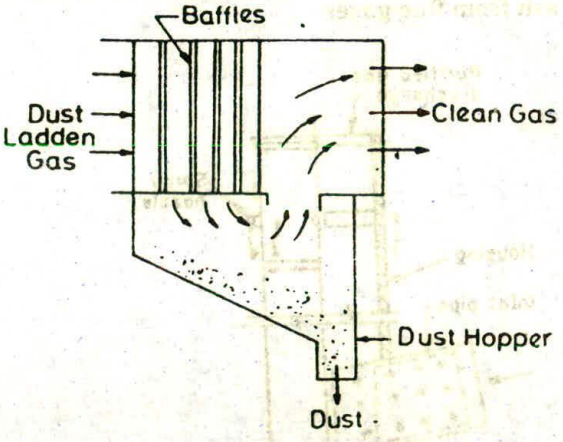


Fig. 3.28 (*b*).

3.12.2 Fluidised Bed Combustion (FBC)

Burning of pulverised coal has some problems such as particle size of coal used in pulverised firing is limited to 70–100 microns, the pulverised fuel fired furnances designed to burn a particular can not be used other type of coal with same efficiency, the generation of high temp. about (1650°C) in the furnace creates number of problems like slag formation on super heater, evaporation of alkali metals in ash and its deposition on heat transfer surfaces, formation of SO_2 and NO_x in large amount.

Fluidised Bed combustion system can burn any fuel including low grade coals (even containing 70% ash), oil, gas or municipal waste. Improved desulphurisation and low NO_x emission are its main characteristics. Fig. 3.28 (*c*) shows basic principle of Fluidised

bed combustion (FBC) system. The fuel and inert material dolomite are fed on a distribution plate and air is supplied from the bottom of distribution plate. The air is supplied at high velocity so that solid feed material remains in suspension condition during burning. The heat produced is used to heat water flowing through the tube and convert water into steam. During burning SO_2 formed is absorbed by the dolomite and thus prevents its escape with the exhaust gases. The molten slag is tapped from the top surface of the bed. The bed temperature is nearly 800–900°C which is ideal for sulphur retention addition of limestone or dolomite to the bed brings down SO_2 emission level to about 15% of that in conventional firing methods.

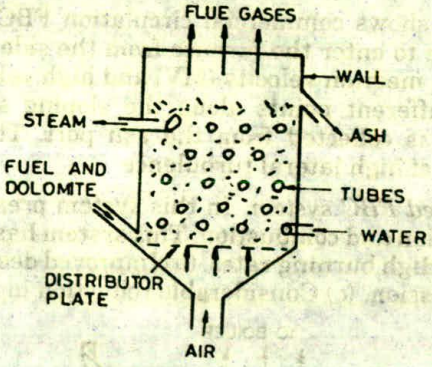


Fig. 3.28 (*c*)

The amount of NO_x is produced is also reduced because of low temperature of bed and low excess air as compared to pulverised fuel firing.

The inert material should be resistant to heat and disintegration and should have similar density as that of coal. Limestone, or dolomite, fused alumina, sintered ash are commonly used as inert materials.

Various advantages of FBC system are as follows :

(*i*) FBC system can use any type of low grade fuel including municipal wastes and therefore is a cheaper method of power generation.

(*ii*) It is easier to control the amount of SO_2 and NO_x formed during burning. Low emission of SO_2 and NO_x will help in controlling the undesirable effects of SO_2 and NO_x during combustion. SO_2 emission is nearly 15% of that in conventional firing methods.

(*iii*) There is a saving of about 10% in operating cost and 15% in the capital cost of the power plant.

(*iv*) The size of coal used has pronounced effect on the operation and performance of FBC system. The particle size preferred is 6 to 13 mm but even 50 mm size coal can also be used in this system.

3.12.3 Types of FBC systems

FBC systems are of following types : (*i*) Atmospheric FBC system : (*a*) Over feed system (*b*) Under feed system.

In this system the pressure inside the bed is atmospheric.

Fig. 3.28 (*d*) shows commercial circulation FBC system. The solid fuel is made to enter the furnace from the side of walls. The low velocity (LV), medium velocity (MV) and high velocity (HV) air is supplied at different points along the sloping surface of the distribution ash is collected from the ash port. The burning is efficient because of high lateral turbulence.

(*ii*) *Pressurised FBC system.* In this system pressurised air is used for fluidisation and combustion. This system has the following advantages : (*a*) High burning rates. (*b*) Improved desulphurisation and low NO_x emission. (*c*) Considerable reduction in cost.

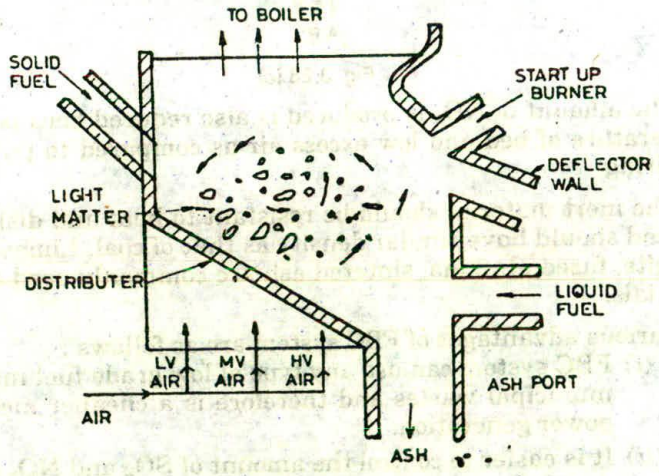


Fig. 3.28 (*d*)

3.13 Draught

The purpose of draught is as follows :

(*i*) To supply required amount of air to the furnace for the combustion of fuel. The amount of fuel that can be burnt per square foot of grate area depends upon the quantity of air circulated through fuel bed.

(*ii*) To remove the gaseous products of combustion.

Draught is defined as the difference between absolute gas pressure at any point in a gas flow passage and the ambient (same elevation) atmospheric pressure. Draught is plus if $P_{atm} < P_{gas}$ and it is minus $P_{atm} > P_{gas}$. Draught is achieved by small pressure difference which causes the flow of air or gas to take place. It is measured in millimetre (mm) of water.

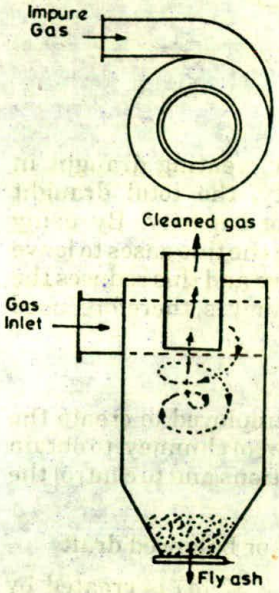


Fig. 3.29.

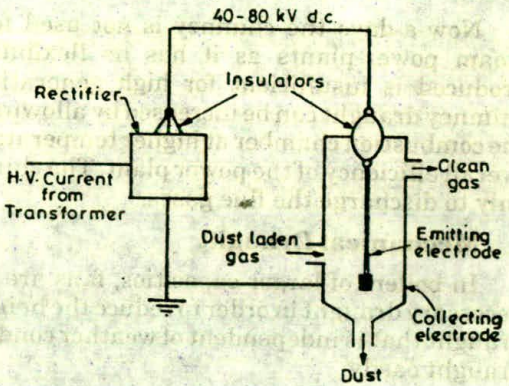


Fig. 3.30.

If only a chimney is used to create the necessary draught, the system is called natural draught system and if in addition to chimney a forced draught (F.D.) fan or an induced draught (I.D.), fan or both are used the system is called mechanical draught system. Fans or chimneys produce positive pressure and is called available draught whereas fuel bed resistance, turbulence and friction in air ducts, gas breechings, chimney, etc. create negative pressure and is called the required draught.

The various types of draught systems are as follows :

(*i*) Natural draught (*ii*) Mechanical draught

(*iii*) Steam Jet draught.

Natural Draught. Natural draught system is used in boilers of smaller capacities. Natural draught is created by the difference in weight of a column of cold external air and that of a similar column of hot gases in the chimney. This system is dependent upon the height of chimney and average temperature of the gases in the chimney. Fig. 3.31 shows natural draught system.

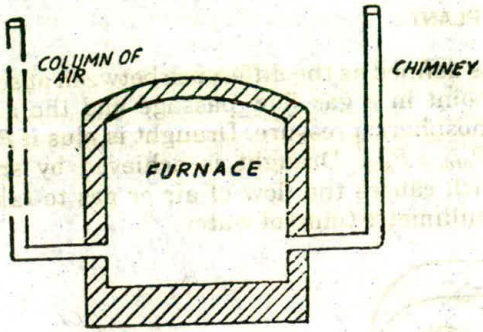


Fig. 3.31.

Now-a-days the chimney is not used for creating draught in steam power-plants as it has no flexibility, the total draught produced is insufficient for high generating capacity. By using chimney draught can be increased by allowing the flue gases to leave the combustion chamber at higher temperature and this reduces the overall efficiency of the power plant. The chimney is, therefore, used only to discharge the flue gases.

Mechanical Draught

In boilers of larger capacities, fans are employed to create the necessary draught in order to reduce the height of chimney, to obtain draught that is independent of weather conditions and to control the draught easily.

Mechanical draft may be induced, forced or balanced draft.

Induced draught system shown in Fig. 3.32 (a) is created by chimney and fan located in the gas passage on the chimney side of the boiler. In this system gas movement is achieved as result of a vaccum.

The various pressures indicated are as follows :

P_1 = Inlet pressure of forced draft fan.

P_2 = Outlet pressure of forced draft fan.

P_3 = Pressure below grate.

P_4 = Pressure above the grate.

P_5 = Inlet pressure of induced draft fan.

P_6 = Outlet pressure of induced draft fan.

Induced draught is not as simple and direct as forced because fans used in induced draft system operate in gases of much higher temperature (nearly 500° – 904°F). This becomes more expensive.

The fan sucks in gas from the boiler side and discharges it to the chimney (stack).

The draught produced is independent of the temperature of the hot gases and, therefore, the gases may be discharged as cold as possible after recovering as much heat possible in air preheater and economiser.

In forced draught system [Fig. 3.32 (*b*)] the fan installed near the boiler base supplies the air at a pressure above that of atmosphere and delivers it through air duct to the furnace. Most high rating combustion equipment employs forced draught fans for supplying air to the furnace. Forced draught is used in under fed stokers carrying a thick fuel bed.

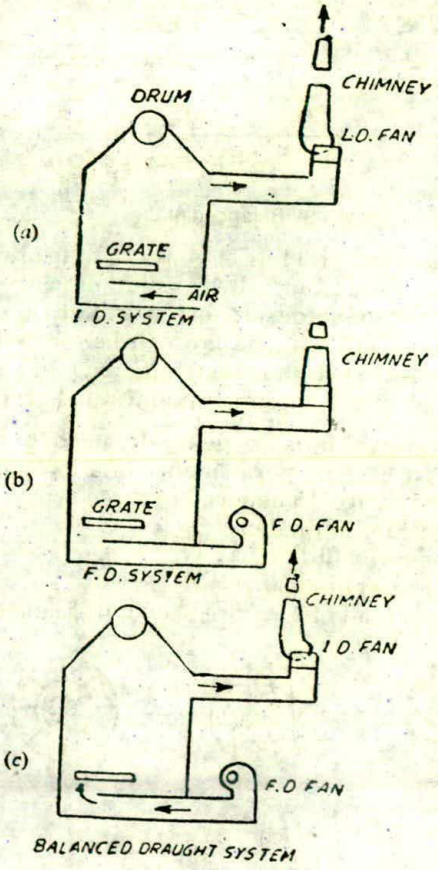


Fig. 3.32

Balanced draught system is a combination of induced and forced draught systems. The forced draught fan forces the air through the fuel bed on to the top of grate and the induced draught fan sucks in gases from the boiler side and discharges them to the chimney. This system is used where pressure above fire is slightly below atmospheric, Fig. 3.32 (c) shows this system.

Fig. 3.32 shows the pressure distribution for the balanced system.

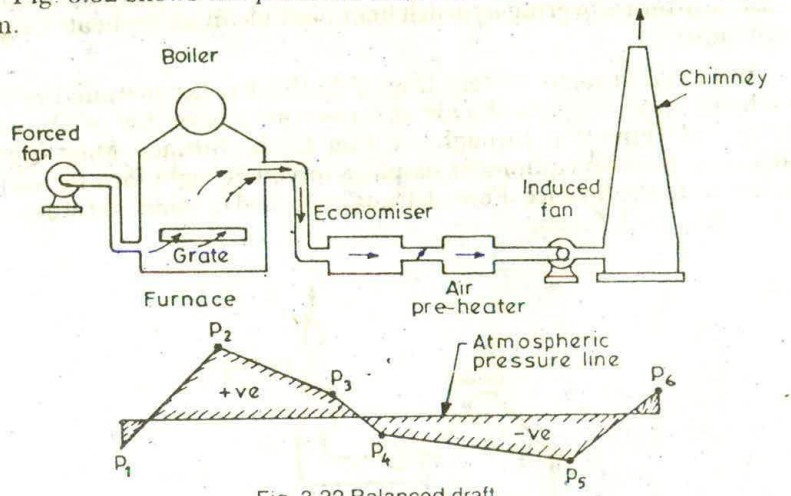


Fig. 3.32 Balanced draft.

Construction such as shielding or water cooling or water protect the bearings of fans. Secondary, the fans handle gases laden with dust which causes were of blades. In forced draught system the fans handle cool and clean air and the fan can be located where convenient. Balanced draft system is more efficient. In balanced draft system about 0.1 inch water vaccum is maintained over the fuel bed.

Multivane centrifugal fans are generally used for moving large volume of air and gases. The performance of a fan depends on the shapes of blades which are, in general, of three types :

1. Backward curved blades.
2. Forward curved blades.
3. Straight radial blades.

[Various types of blade forms are shown in Fig. 3.33]



Fig. 3.33.

The air leaving the tips of backward curved blades possesses low velocity. This makes them suitable for high rotor speed. Fans with backward curved blades are used in forced draught system. Forward and radial blades are used in induced draught fans.

3.13.1 Comparisons of forced and induced draughts

The forced draught system has the following advantages as compared to induced draught :

(*i*) The induced draught handles more volume of gases and at elevated temperature. Therefore, the size and power required for induced draught fan is more than forced fan.

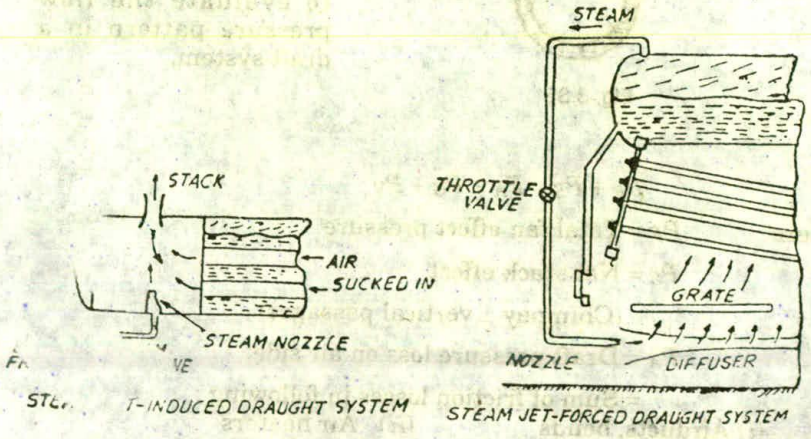
(*ii*) Improved route of burning of fuel is achieved by using forced draught because there is more uniform flow of air through the grate and furnace and also the air penetrates better into the fire bed.

(*iii*) In case of induced draught when doors are opened for firing there will be rush of cold air into the furnace and this reduces the heat transmission.

(*iv*) The induced draught fan handles flue gases at high temperature and thus water cooled bearing are needed for induced draught fan.

Steam Jet Draught. Steam jet draught may be induced or forced draught depending upon the location of steam jet producing the draught.

Induced draught produced by steam jet is shown in Fig. 3.34 (*a*). This system is used in locomotive boilers. Exhaust steam from the engine enters the smoke box through a nozzle to create draught. The air is induced through the flues, the grate and ash pit to the smoke box.



(*a*) (*b*)

Fig. 3.34.

Fig. 3.34 (*b*) shows a forced draught developed by steam jet. Steam from the boiler is passed through a throttle valve, throttle pressure being 1.5 to 2 kg/cm^2 gauge. Then the steam passes through a nozzle projecting in diffuser pipe. The steam comes out of nozzle with great velocity and drags a column of air along with it thus allowing the fresh air to enter. The mixture of steam and air possesses high kinetic energy and passes through the diffuser pipe. The kinetic energy gets converted into pressure energy and thus air is forced through the coal bed, furnace and flows to the chimney. Steam jet is system simple, requires less space and is economical. But it can be used only if steam at high pressure is available.

3.13.2 Draught Measurement

A U-tube manometer shown in Fig. 3.35 is employed to measure the draught. One end of manometer is open to atmosphere and the other end is connected to the boiler furnace, chimney or any other point in the gas flow passage where draught is to be measured. Due to pressure difference on the two sides of the tube the level of water in the two sides is altered to balance the pressure. The difference in level a in the two siders measures the draught.

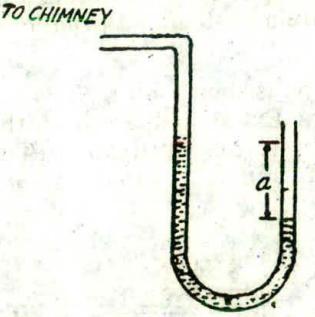


Fig. 3.35

Draft-loss. It is the pressure loss caused by friction between two points in the gas flow path.

Draft-system flow resistance. The following relation may be used to evaluate the flow pressure pattern in a draft system.

$$P_F + P_S = P_A + P_G + P_V$$

where P_F = Total fan effect pressure

P_S = Net stack effect

(Chimney ± vertical passages)

P_A = Draft pressure loss on air side.

= Sum of friction losses in following :

(*i*) Airducts, bends (*ii*) Air heaters

(*iii*) Stoker be[illegible]

(*iv*) Secondary air pressure at fuel burner.

P_θ = Draft pressure loss on gas side.

This is sum of friction losses in the following :

(*i*) Gas ducts, bends (*ii*) Economiser

(*iii*) Air heater (*iv*) Super heater

(*v*) Boiler setting (*vi*) Chimney

P_V = Gas exit velocity pressure.

3.14 Chimney

Chimneys are made up or steel of bricks and concrete. Concrete chimneys are more popular. The average life of concrete chimneys is 50 years and that of steel chimneys is about 15 years depending upon the care taken to prevent corrosion. The net area of chimney depends on the following factors :

(*i*) Volume of gases to be discharged when the boilers operate at maximum rating.

(*ii*) Draught to be produced.

Chimney generally denotes brick concrete construction whereas stack means steel construction.

Fig. 3.36 (*a*) shows a brick chimney and Fig. 3.36 (*b*) shows reinforced chimney. Chimney is provided with a lighting conductor, aircraft warning lights, and various means of access and inspection.

The various advantages of steel chimneys over masonry chimneys are as follows :

(*i*) Lower overall cost (*ii*) Slightly high efficiency

(*iii*) Easier construction (*iv*) Requires lesser space

(*v*) Lighter in weight.

R.C.C. chimneys are also becoming popular.

3.15 Calculation of Chimney Height

Air is required to burn coal or fuel in the furnace. We know

$$C + O_2 = CO_2$$

This shows that volume of chimney gases produced by the complete combustion of 1 kg of coal or oil is same as that of air required to support combustion if the temperature of flue gases and air is same.

Let H = Height of chimney above grate level in metres.

W = Weight of air in kg required per kg of fuel.

T = Average absolute temperature of chimney gases in K.

T_1 = Absolute temperature of air outside the chimney in K.

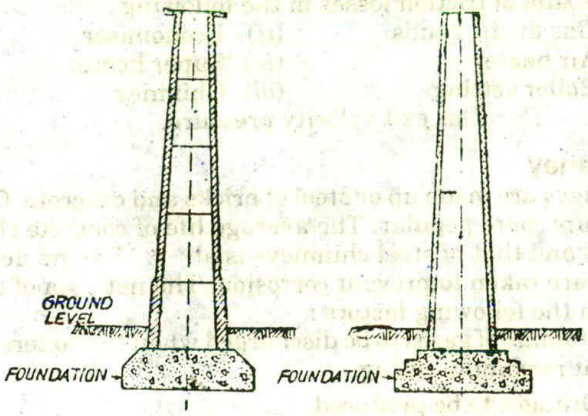


Fig. 3.36.

Weight of chimney gases produced

$= (W \times 1)$ kg of fuel burnt

Volume of chimney gases at 237° K

= volume of 1 kg air at 273° K

$$= \frac{RT}{P} = \frac{29.27 \times 273}{1.03 \times 10^4} \times 0.7734 \text{ m}^2.$$

Therefore, volume of one kg of air at T_1 K

$$= 0.7734 \times \frac{T_1}{273}$$

Thus volume of W kg of air at T_1 K

$$= \frac{0.7734 \times T_1 \times W}{273}$$

Density of air at T_1 K $= \dfrac{\text{Mass}}{\text{Volume}}$

$$= W \times \frac{273}{0.7734 \times T_1 W} = \frac{273}{0.7734 \times T_1}$$

Therefore pressure at the grate due to a column of cool air of H metres height

$$= \frac{273}{0.7734 \times T_1} \times H = 1.293 \times \frac{273}{T_1} \times H \quad \text{kg/m}^2 \quad ...(i)$$

Volume of chimney gases at T K per kg of air

$$= 0.7734 \times \frac{T}{273}$$

Volume of $(W + 1)$ kg of chimney gases at T K

$$= 0.7734 \times \frac{T}{273} \times W$$

Density of chimney gases at T K

$$= \frac{\text{Mass}}{\text{Volume}} = (W + 1) \times \frac{273}{0.7734 \times T \times W}$$

$$= 1.293 \left(\frac{W + 1}{W} \right) \times \frac{273}{T}$$

$$= 353 \left[\frac{W + 1}{W} \right] \times \frac{1}{T}$$

Therefore, pressure at the grate by a column of hot gases of height H metre = Density $\times H$ kg/m^2

$$= 1.293 \left(\frac{W + 1}{W} \right) \times \frac{273}{T} \times H \text{ kg/m}^2 \qquad ...(ii)$$

Therefore, pressure P causing the draught

$$P = \left[\left(1.293 \times \frac{273 \times H}{T_1} \right) - \left(1.293 \times \frac{(W - 1)}{W} \times \frac{273}{T} \times H \right) \right]$$

$$= 353\, H \left[\frac{1}{T_1} - \left(\frac{W + 1}{W} \right) \times \frac{1}{T} \right] \text{ kg/m}^2.$$

If this draught is h mm of water as measured by a U-tube water manometer

$$h = 353\, H \left[\frac{1}{T_1} - \left(\frac{W + 1}{W} \right) \times \frac{1}{T} \right] \text{ mm of water}$$

(We know 1 kg/m^2 = 1 mm of water column)

Let h' = height of column of hot gases.

$$h' \times 1.293 \times \left(\frac{W + 1}{W} \right) \times \frac{273}{T} = P$$

$$= 353\, H \left[\frac{1}{T_1} - \left(\frac{W + 1}{W} \right) \times \frac{1}{T} \right]$$

$$h' = \frac{353\,H\left[\frac{1}{T_1} - \left(\frac{W+1}{W}\right)\times\frac{1}{T}\right]}{1.293\times 273\times\left(\frac{W+1}{W}\right)\times\frac{1}{T}}$$

$$h' = H\left[\left(\frac{W}{W+1}\right)\times\frac{T}{T_1} - 1\right].$$

Example 3.2. *A chimney is 28 metres high and the temperature of hot gases inside the chimney is 320°C. The temperature of outside air is 27°C and furnace as supplied with 15 kg of air per kg of coal burnt. Calculate*

(a) Draught in mm of water.

(b) Draught height in metres of hot gases.

Solution. We have

(a) $$h = 353\times H\left[\frac{1}{T_1} - \left(\frac{W+1}{W}\right)\times\frac{1}{T}\right]$$

$$= 353\times 28\left[\frac{1}{(27+273)} - \frac{15+1}{15}\times\frac{1}{(320+273)}\right]$$

$$= 353\times 28\left[\frac{1}{300} - \frac{16}{15}\times\frac{1}{593}\right]$$

$$= 353\times 28\,[3.33\times 10^{-3} - 1.8\times 10^{-3}]$$

$$= 353\times 28\times[1.50\times 10^{-3}] = 15.1 \text{ mm of water.}$$

(b) $$h' = H\left[\frac{W}{W+1}\times\frac{T}{T_1} - 1\right] = 28\left[\frac{15}{1}\times\frac{593}{330} - 1\right]$$

$$= 24.88 \text{ metres.}$$

Example 3.3. *Determine the height of chimney to produce a static draught of 22 mm of water if the mean flue gas temperature in a chimney is 290°C and ambient temperature in boiler house is 20°C. The gas constant (R) for air is 29.26 kgfm/kg °K and for chimney flue gas is 26.2 kgfm/kg °K. Assume barometer reading as 760 mm of mercury.*

Solution. Let

P = Absolute pressure of gas (kg/m^2)

V = Volume of gas (m^2)

R = Gas constant

T = Absolute temperature of gas (K)

Now $PV = RT$

$$V = \frac{RT}{P}$$

Difference of pressure (ΔP)

= Height of chimney (H)

$\times (\rho_{air} - \rho_{flue})$ kg/mm^2.

ΔP = 22 mm of water = 22 kg/m^2.

(As 1 kg/m^2 = 1 mm of water)

$$\rho_{air} = \frac{1}{V} = \frac{P}{RT}$$

$$= \frac{1.033 \times 10^4}{29.26 \times (273 + 20)} = 1.2 \text{ kg/m}^3$$

(P = Pressure = 760 mm of Hg = 1.033 kg/cm^2)

$$\rho_{flue} = \frac{1}{V} = \frac{P}{RT} = \frac{1.033 \times 10^4}{26.2 \times (273 \cdot \cdot 00)} = 0.69 \text{ kg/m}^3.$$

$$\text{Height of chimney } (H) = \frac{\Delta P}{(\rho_{air} - \rho_{flue})} = \frac{22}{1.2 - 0.69}$$

= 43.1 metres. **Ans.**

Example 3.4. *Determine the height of chimney to get net draught of 12 mm if the total draft losses are 4 mm. The temperature of air is 25°C and the temperature of chimney gases is 300°C. The mass of air used per kg of fuel used is 18 kg. One kg of air occupies a volume of 0.7734 m^3 at N.T.P.*

Solution. Let

H = Height of chimney in metre

A = Gross sectional area of chimney in m^2.

$$\text{Density of air} = \frac{1}{0.7734} \times \frac{273}{273 + 25} = 1.24 \text{ kg/m}^3$$

Density of chimney gases at 0°C

$$= \frac{18 + 1}{18 \times 0.7734} = \frac{19}{18 \times 0.7734}$$

Density of chimney gases at 300°C

$$= \frac{18}{18 \times 0.7734} \times \frac{273}{273 + 300} = 0.65 \text{ kg/m}^3$$

Mass of chimney gases = $A \times H \times 0.65$ kg.

Mass of equal column of external air $= A \times H \times 1.24$ kg.

Difference in masses $= 1.24\,AH - 0.65\,AH = 0.59\,A \times H$ kg.

$$P = \text{Draft in kg/m}^2 = \frac{0.59\,AH}{A} = 0.59\,H \text{ kg/m}^2$$

$= 0.59\,H$ mm of water.

(As 1 kg/m^2 = 1 mm of water).

$\therefore \quad 0.59\,H = 16$

$H = 27.1$ metres. **Ans.**

Example 3.4. (*a*) *A chimney produces a draught of 1.8 cm of water when temperature of flue gases is 280°C and ambient temperature is 21°C. The flue gases formed per kg of fuel burnt are 24 kg. Taking diameter of chimney as 1.7 m determine the mass of flue gases flowing through the chimney.*

Solution.

h = Draught

$= 1.8$ cm

$= 18$ mm of water

T = Temperature of flue gases

$= 280° + 273°$

$= 553°$K

T_1 = Ambient Temperature

$= 21 + 273$

$= 294°$K,

W = Mass of air reqd. per kg of fuel

$= 24 - 1$

$= 23$ kg

$$h = 353\,H\left[\frac{1}{T_1} - \left(\frac{W+1}{W}\right) \times \frac{1}{T}\right]$$

$$18 = 353\,H\left[\frac{1}{294} - \left(\frac{23+1}{23}\right) \times \frac{1}{553}\right]$$

$H = 34.1$ m of air

h' = Height of column of hot gases

$$= H\left[\left(\frac{W}{W+1}\right) \times \frac{T}{T_1} - 1\right]$$

$$= 34.1\left[\frac{23}{24} \times \frac{553}{294} - 1\right]$$

$$= 28.9 \text{ m of air}$$

C = Velocity of gases

$$= \sqrt{2g \times h'}$$

$$= \sqrt{2 \times 9.81 \times 28.9}$$

$$= 23.5 \text{ m/s}$$

Wg = mass of flue gases

$$= A \times C \times \rho_g$$

where A = Area of chimney

$$= \frac{\pi}{4} \times (1.7)^2 \text{ m}^2$$

$$\rho_g = 353\left[\frac{W+1}{W}\right] \times \frac{1}{T}$$

$$= 353\left[\frac{23+1}{23}\right] \times \frac{1}{553}$$

$$= 0.67 \text{ kg/m}^3$$

$$Wg = \frac{\pi}{4}(1.7)^2 \times 23.5 \times 0.67$$

$$= 35.7 \text{ kg/s.}$$

3.16 Methods of Burning Fuel Oil

Fuel oil is burnt by means of burners. The function of a burner is to atomise the fuel and mix it with proper amount of air for combustion. The various types of burners used are as follows :

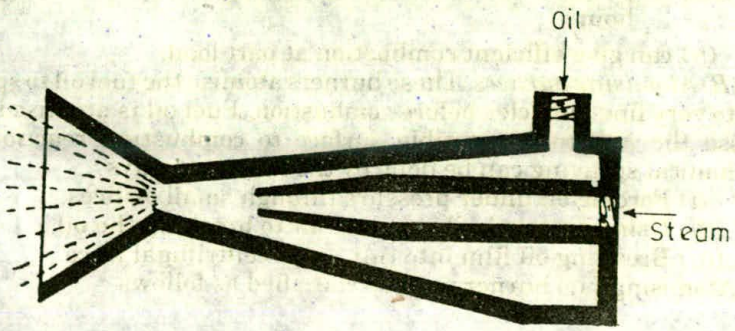


Fig. 3.37

(*a*) Vaporising burners (*b*) Atomising burners.

(*A*) *Vaporising burners.* In vaporising burners the fuel is vaporised by heating. Such burners are used in domestic and industrial applications. Vaporising burners may be classified as follows :

(*i*) Rotating cup type burner.
(*ii*) Atmospheric pressure atomising burner
(*iii*) Recirculation burner
(*iv*) Wick type burner.

Fig. 3.38 (*a*) shows a rotary cup oil burner. This burner sprays oil on fast turning cup to break up oil film at rim by centrifugal force. It mixes with secondary air spinning in opposite direction.

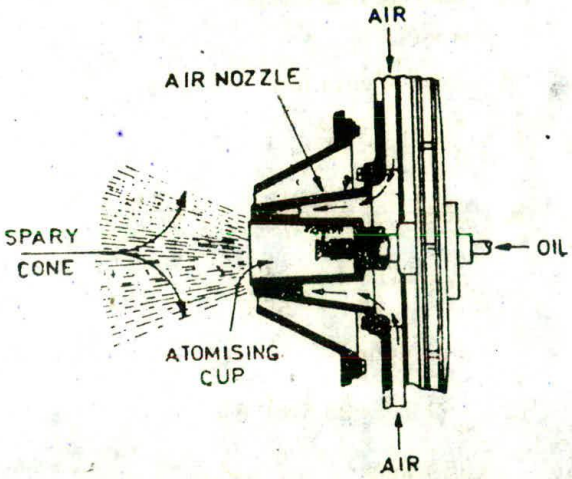


Fig. 3.38 (*a*)

Vaporising oil burners

(*i*) Vaporise the fuel before ignition
(*ii*) Mix the vaporised fuel thoroughly with air
(*iii*) Minimise soot formation.

They (*i*) produce more heat by burning more amount of fuel per hour.

(*ii*) can give efficient combustion at part load.

(*B*) *Atomising burners.* These burners atomise the fuel oil to split it into very fine particles before combustion. Fuel oil is atomised to expose the maximum possible surface to combustion reactions. Mechanical spraying can be done by the following ways :

(*i*) Forcing oil under pressure through small orifices.
(*ii*) Using pressurised steam or air to break up the oil.
(*iii*) Breaking oil film into tiny drops centrifugal force.

Atomising fuel burners can be classified as follows :

(*a*) Mechanical or oil pressure atomising burners.
(*b*) Steam or high pressure air atomising burners.
(*c*) Low pressure air atomising burners.

These burners (*i*) atomise the fuel into fine particles to equal size.
(*ii*) supply air in required quantity.
(*iii*) minimise soot formation.

They (*i*) give high combustion intensity
(*ii*) give high thermal efficiency
(*iii*) operate efficiently at varying load.

Mechanical Atomising Burners

Mechanical atomising burners have the following four principal parts :
(*i*) Atomiser
(*ii*) Air register
(*iii*) Diffuser
(*iv*) Burner throat opening

Atomiser breaks up oil mechanically into a fine uniform spray that will burn with minimum of excess air when projected into the furnace. Air register supplies air needed for combustion. Diffuser is a hollow metal cone mounted near the furnace end of the atomiser assembly. It stablilises the flame to prevent it from being blown away from the atomiser tip. Burner throat opening is made of refractory and is circular and concentric with burner outlet. The atomiser and diffuser assembly should be so positioned. That the flame clears the throat opening sufficiently to avoid striking.

Steam atomising burners are of two types :
(*i*) Outside mix type
(*ii*) Inside mix type

In outside mix type burners oil is ejected through outside of holes and is blasted by a high velocity jet of steam from other hole. Mixing takes place outside the burner as shown in Fig. 3.38.1.

In case of inside mixing type burners steam and oil are mixed inside the burner before mixture is projected in the furnace as shown in Fig. 3.38.2. These burners provide high efficiency at high firing rates.

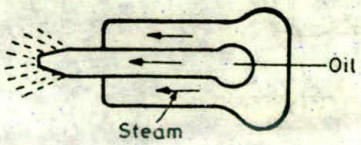


Fig. 3.38.1

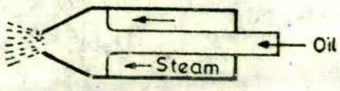


Fig. 3.38.2

Low pressure burners use air pressure between 0.015 bar to 0.15 bar. They are simple in shape and are quite commonly used.

(*i*) *Blast-atomisation.* In this method the oil is atomised by compressed air or steam. Steam atomising burners may be inside burners or outside burners.

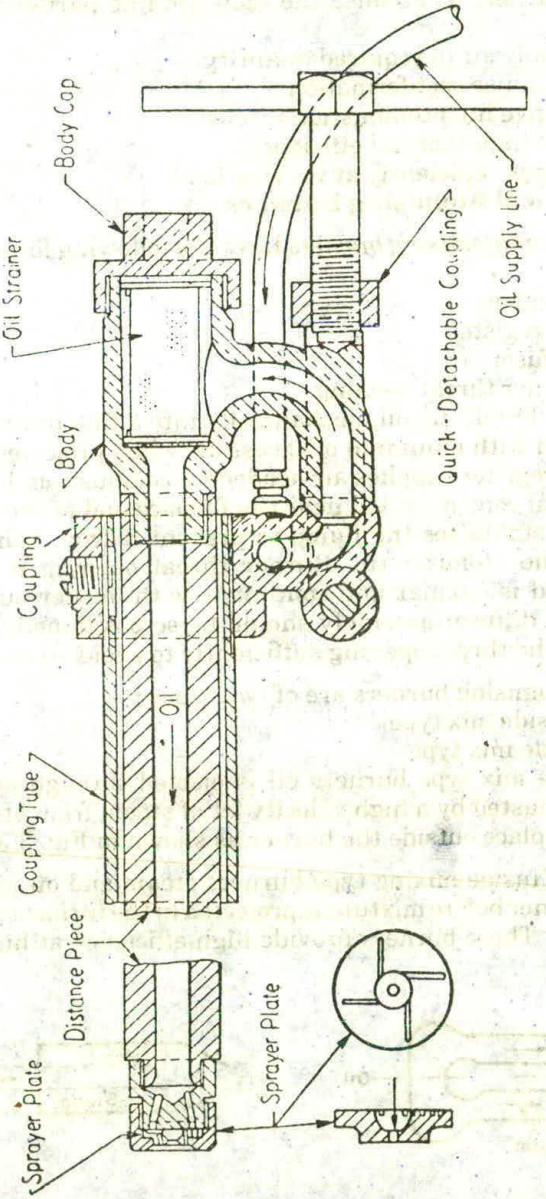


Fig. 3.38 (*b*).

In the inside burners the steam and oil come in contact inside the burner and atomisation of mixture takes place while passing through the orifice of the burner. Fig. 3.37 (*a*) shows an injector inside mixing burner. In outside burner, the oil is pumped to the oil orifice and is picked up and atomised by jet of steam outside the burner.

(*ii*) **Mechanical atomisation.** In this method the fuel oil is atomised by subjecting it to a high pressure and passing it through an orifice. Fig. 3.38 (*b*) shows Babcock and Wilcox mechanical atomising burner. The fuel oil flowing through the centre tube is atomised and discharged through tangential slots in the sprayer plate. The oil then passes a conical chamber with an orifice at its apex and due to whirling action oil leaves the orifice in the form of a hollow cone of minute particles.

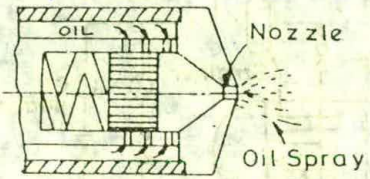


Fig. 3.38 (*c*).

Fig. 3.38 (*c*) shows spring loaded piston type burner also called oil pressure type burner. The oil comes out of nozzle in the form of spray.

3.16 (*a*) Fuel oil and gas handling

Fuel handling system is designed depending on the type and nature of fuel. Fig. 3.38 (*d*) shows liquid fuel handling arrangement.

Fuel storage tanks of concrete or steel are located near the power plant. Underground tanks are usually preferred. A vent pipe open to the atmosphere allows the storage tank to breathe. The level indicator is used to record the level of oil in the tank. Oil pumped from the tank is first passed through strainers, and then through heaters to bring the liquid fuel to the conditions necessary for the burners. Man-hole is provided for cleaning the storage tank.

Pipes are used to handle the gas in power plants using gas as fuel. The pipe line may divide into two parallel lines each fitted with the following :

(*i*) meters (*ii*) regulators

(*iii*) stop valves.

Plants can not justify storing gas on their premises. However underground storage proves feasible in some areas. Many plants use

natural gas as fuel. For best economy the pipe lines should be kept flowing at full capacity.

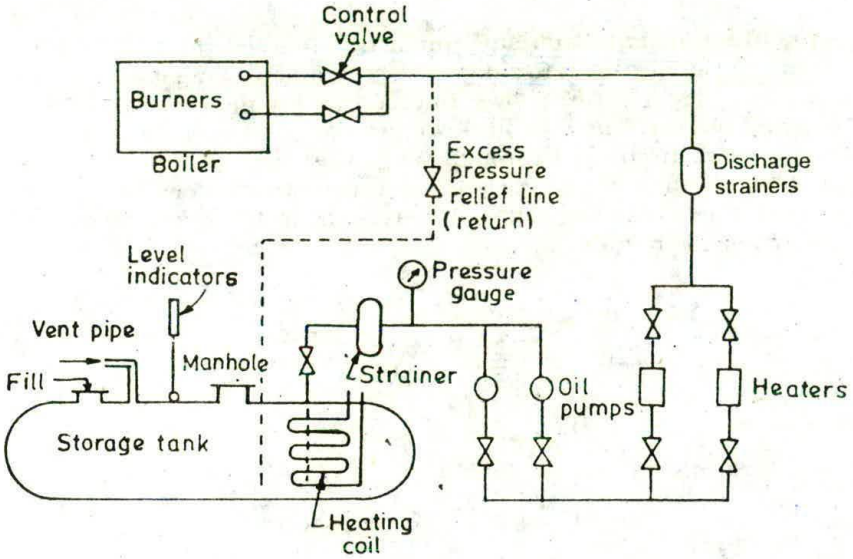


Fig. 3.38 (*d*)

3.16 (*b*) Gas Burners

Gas burners are used to mix air and fuel gas in the desired proportions before ignition. Gas as a fuel has the following advantages :

(*i*) It can be handled easily.
(*ii*) Furnace temperature can be easily controlled.
(*iii*) There is no pollution.

Two types of burners are shown in Fig. 3.39 (*a*) Fig. 3.39 *b*). A long flame results by using burners shown at Fig. 3.39 (*a*). When both the gas and air are under pressure burner shown in Fig. 3.39 (*b*) is used.



Fig. 3.39 (*a*)

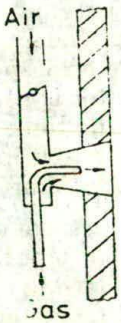


Fig. 3.39 (*b*)

3.17 Slag Removal

Ash is removed in dry state in case of furnaces burning coals of high fusion temperature and in the liquid form if the coal used is of low fusion temperature. Ash when in the form of liquid slag is

collected on the furnace by the various methods shown. Slag collected on the furnace floor is tapped off through a slag spout in the side wall (Fig. 3.39) or it may be removed at the rear of furnace. (Fig. 3.40). Two-stage furnace arrangement (Fig. 3.41) and (Fig. 3.42) is also used to remove the slag. In primary furnace nearly complete combustion of fuel takes place and temperature is quite high and cooling takes place in secondary furnace.

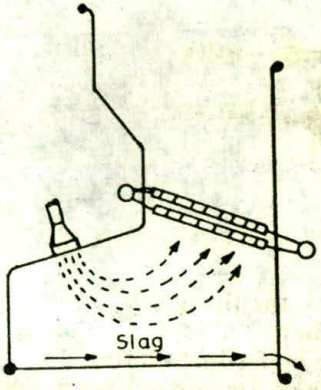


Fig. 3.39

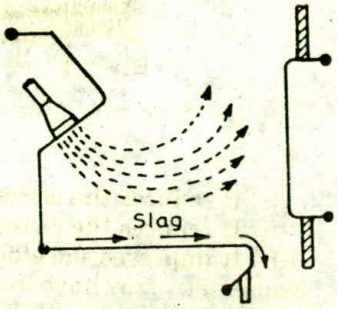


Fig. 3.40

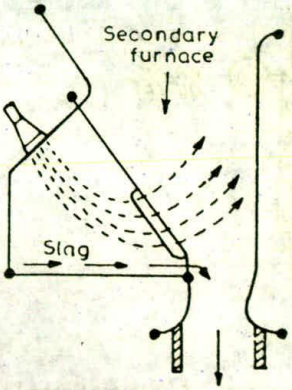


Fig. 3.41

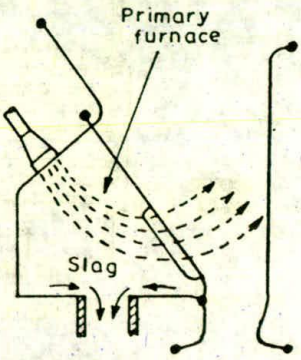


Fig. 3.42

.18 Economiser

In order to utilise the heat accompanying combustion gases eaving the furnace, the gases are passed through the heat recovery quipment such as economiser and air preheater.

Economiser. Economiser is a device intended for heating the feed water by means of flue gases from boiler. There are steaming economisers in which the water is raised to the boiling point and partially (10—20%) evaporates and non-steaming economisers in which the temperature of water is below the boiling point by 20 – 30°C. The advantages of an economiser are as follows :

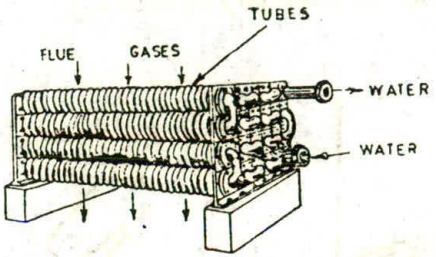


Fig. 3.43

(*i*) It reduces the losses of heat with the flue gases.
(*ii*) It reduces the consumption of fuel.
(*iii*) It improves the efficiency of the boiler installation.

Economiser may have iron or steel tubes. Smooth or ribbed. Fig. 3.43 shows a general view of an iron economiser.

Flue gases flow over the tubes.

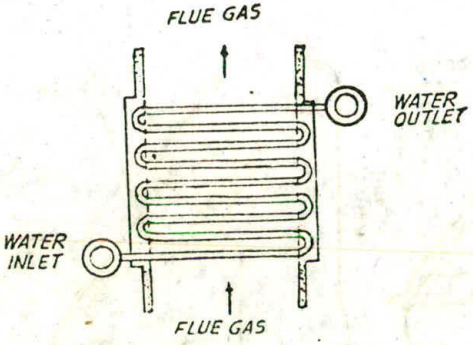


Fig. 3.44

Fig. 3.44 shows an economiser. It consists of series of steel tubes through which the feed water flow. The combustion gases pass over the tubes and transfer some of their heat to the feed water. The boiler efficiency rises by about 1% for each 10°F rise in feed water temperature. Economisers may be parallel-flow or counter-flow, when the gas flow and water-flow are in the same direction

economisers are called parallel-flow whereas in counter-flow economiser the gas flow and water-flow are in the opposite direction. Installation of an economiser depends on its initial cost, type of boiler and nature of feed water used.

Fig. 3.44 (*a*) shows by-pass arrangement which enables to isolate or include the economiser in the path of the flue gases.

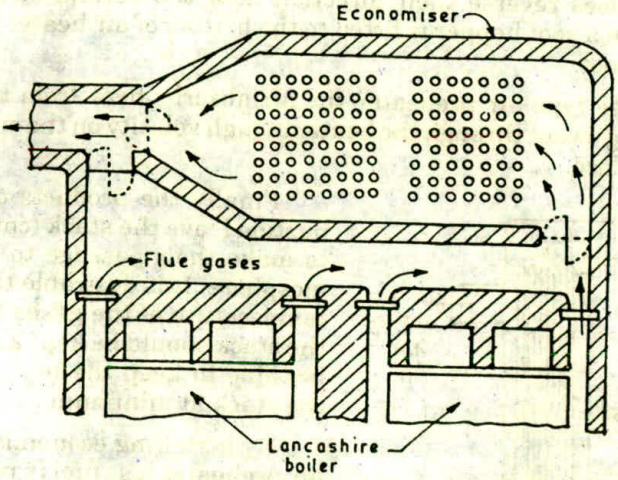


Fig. 3.44 (*a*)

3.18.1 Soot Blower

Soot blower is a device which blows off the soot from the economiser tubes. Soot which gets deposited on the economiser tubes due to the flow of flue-gases over the tubes. The soot obstructs the transfer of heat from flue gases of the feed water.

A soot blower consists of a tube having a number of nozzles. High pressure steam is blown through the nozzles which strikes against the tubes and removes the soot.

3.18.2 Air Preheater

It 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 the type of fuel, type of fuel burning equipment and the rating at which the boiler and furnace operated. The principal benefits of preheating the air are increased thermal efficiency and increased steam capacity per square metre of boiler surface. There are two types of air preheater:

1. Tubular type
2. Plate type

A tubular type air preheater as shown in Fig. 3.45. 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 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.

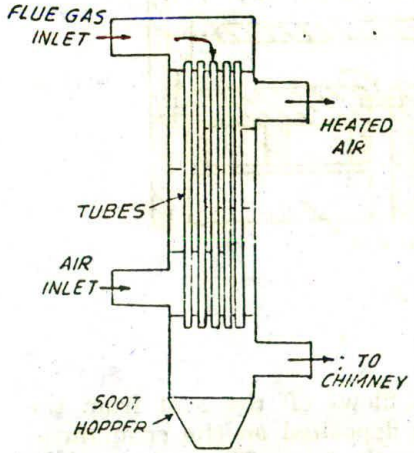


Fig. 3.45.

Finally the products of combustion leave the stack (chimney) to make their passage to the atmosphere. It is desirable that the temperature of the gases leaving the stack should be kept as low as possible to keep the heat loss to the stack at minimum.

By installing economiser and air preheater less fuel is required per unit mass of steam raised and boiler efficiency is increased. The justifiable cost of economiser and air preheater depends upon the gain in boiler efficiency.

Air preheater should be used where a study of costs indicates that some money can be saved or some beneficial action on combustion can be obtained by its use. Some factors that need to be taken into account in examining a case for justification of air preheat system are as follows :

(*i*) Improvement in combustion efficiency.
(*ii*) Cost of the equipment and estimated maintenance cost.
(*iii*) Cost of extra draft.
(*iv*) The extent to which air can be preheated.
(*v*) Saving in-heat discharged to the chimney.

3.18.3 Heat transfer in economiser and air preheaters

In economiser water is passed through the tubes and hot flue gases pass over the tubes whereas in air preheater air passes through the tubes and flue gases pass over the tubes and transfer the heat to the air. The most effective use of given heat transfer surface is obtained when two fluids (water or air and flue gases)

travel in the opposite direction (counter flow). Fig. 3.46 (*a*) shows the variation of temperature along the flow paths of the fluids.

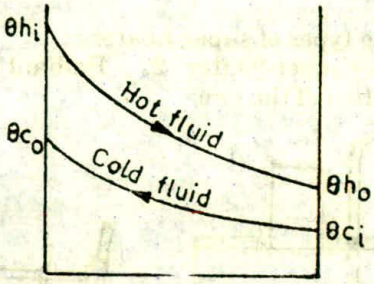


Fig. 3.46 (*a*).

The heat transfer from the hot flue gases to water in case of economiser and to air in case of air preheater is found as follows :

$$Q = U.A.\theta_m$$

where Q = Quantity of heat transferred

U = Overall heat transfer coefficient

A = Area of heat transfer surface

θ_m = Log Mean temperature difference

$$= \frac{\theta_i - \theta_o}{\log \frac{\theta_i}{\theta_o}}$$

θ_{co} = Outlet temperature of cold fluid

θ_{ci} = Inlet temperature of cold fluid

θ_{ho} = Outlet temperature of hot fluid

θ_{hi} = Inlet temperature of hot fluid

θ_i = Temperature difference at inlet = $\theta_{hi} - \theta_{ci}$

θ_o = Temperature difference at outlet = $\theta_{ho} - \theta_{co}$.

3.19 Super Heater

The steam produced in the boiler is nearly saturated. This steam as such should not be used in the turbine because the dryness fraction of the steam leaving boiler will be low. This results in the presence of moisture which causes corrosion of turbine blades etc. To raise the temperature of steam super-heater is used. It consists of several tube circuits in parallel with one or more return bends connected between headers. Super-heater tubes range from 1 to 2 inch of diameter. Super-heater supplies steam at constant tempera-

ture at different loads. The use of super-heated steam increases turbine efficiency.

There are three types of super-heaters :

1. Convective super-heater 2. Radiant super-heater
3. Combination of the two.

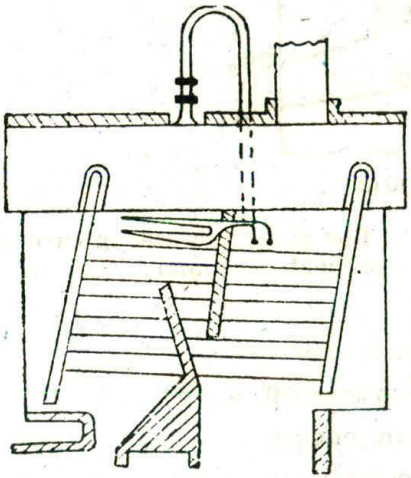


Fig. 3.46.

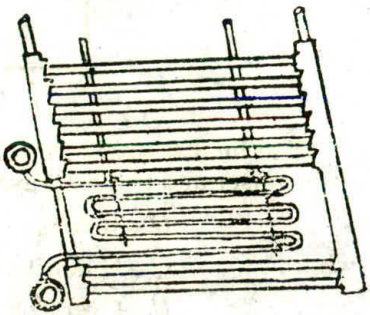


Fig. 3.47

Convective super-heater makes use of heat in the gases entirely by convectic. whereas a radiant super-heater is placed in the furnace and wall tubes and receive heat from the burning fuel through radiation process.

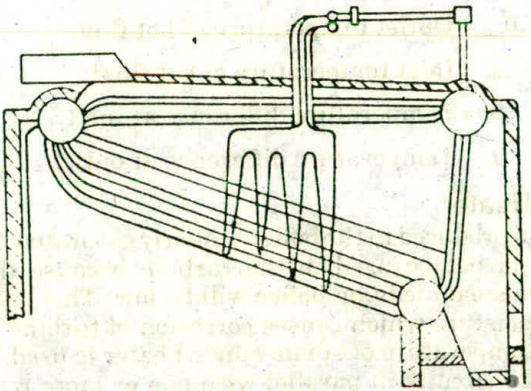


Fig. 3.48

The final temperature of steam depends upon the gas flow rate, quantity of gas flow and the temperature of the gases leaving the

super-heater section. The flue gas temperature should be nearly 175°C higher than the temperature of super-heated steam. Material used for super-heater tubes should have high temperature strength and high resistance to oxidation. Special steel alloys such a chromium molybdenum alloy is used for tubes of super-heater for modern high pressure boilers.

According to location the super-heaters are classified as follows:

(*i*) Over deck (*ii*) Inter deck
(*iii*) Inter tube (*iv*) Inter bank.

Fig. 3.46 shows over deck location of a super-heater and inter deck location is shown in Fig. 3.47. Inter tubes and interbank location of super-heater is shown in Fig. 3.48 and Fig. 3.49 respectively.

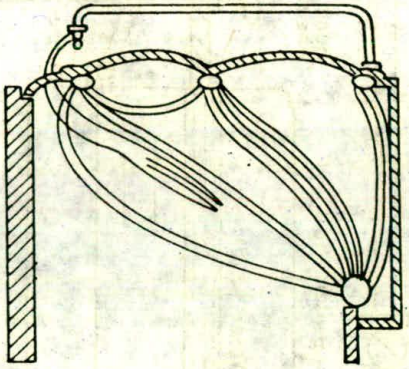


Fig. 3.49

Inter deck super-heaters are essentially convective superheater. The heat transfer conditions in a super-heater vary with load. When load is decreased the gas mass flow decreases proportionately and in a convective superheater fewer degrees of superheat are obtained whereas in a radiant superheat steam receives more heat than at higher loads. A radiant superheater has a falling characteristic with increased steam output of boiler. Modern boilers using high pressures use combination of convective and radiant superheater. Fig. 3.50 shows the locating of both convective and radiant super-heaters in a bent tube boiler.

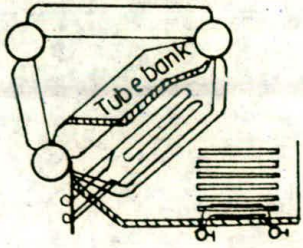


Fig. 3.50

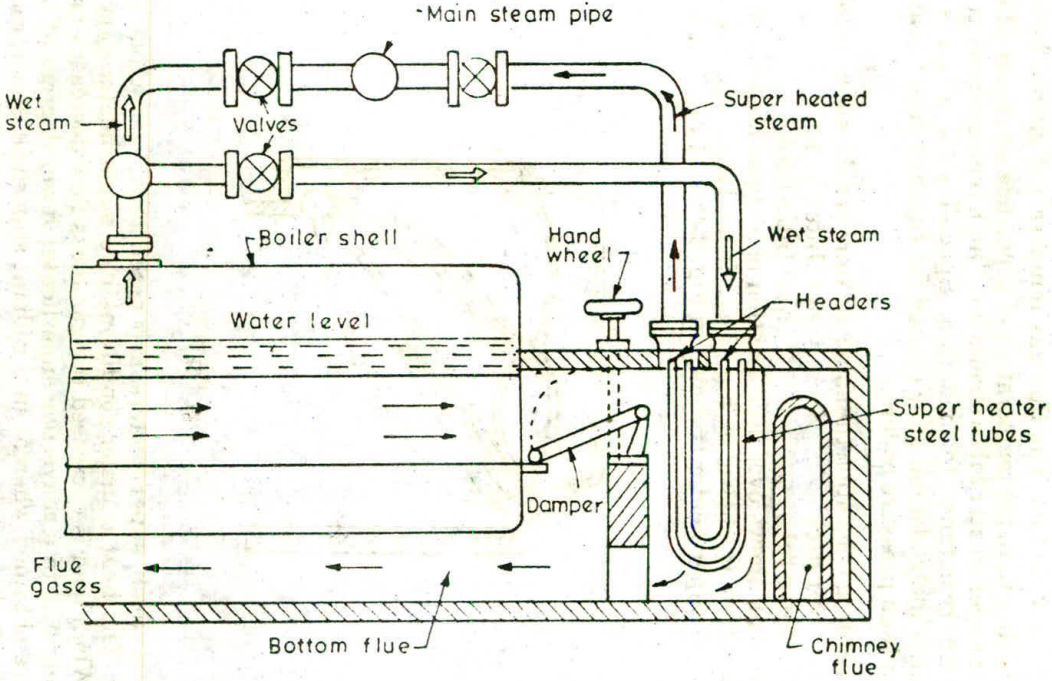

Main steam pipe
Wet steam
Valves
Super heated steam
Boiler shell
Hand wheel
Wet steam
Headers
Water level
Super heater steel tubes
Damper
Flue gases
Bottom flue
Chimney flue

Fig. 3.50 (*a*)

3.19.1 Sugden Superheater

Fig. 3.50 (*a*) shows sugden's super heater used in a Lancashire boiler. This super heater uses 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. It shows how the steam pipes may be arranged so as to pass the steam through the superheater or direct to the main steam pipe.

3.20 Advantages of Super-heated Steam

Super-heated steam is vapour whose temperature has been increased above that of its boiling point at that pressure.

The various advantages of using super-heated steam are as follows :

(*i*) Super-heated steam has an increased capacity to work due to a higher heat contact. Therefore, an economy in steam consumption in steam turbines and steam engine achieved.

(*ii*) Super-heating raises the over all efficiency of the plant. The temperature of the super-heated steam b g higher it gives a higher thermal efficiency when for working a prime mover.

(*iii*) Super-heating of steam avoids the er sion o: turbine blades in the last stages of expansion of s am. In order to avoid blade erosion it is desirable to limit the moisture content 10 to 12% in the exhaust of the steam turbines.

3.21 Super-heat Control

It is desirable that there should be a close control over the final temperature of steam over a reasonably wide range of load.

The various methods employed to achieve this are as follows :

1. **Use of Desuperheater.** To control the temperature of steam a desuperheater (attemperator) is used. In the desuperheater (Fig. 3.51) some quantity of cold water is injected into or around the pipe carrying the steam. This causes the evapora ion of water so injected and thus the temperature of steam is lowered.

2. **Use of Tilting Burners.** Tilting burners e furnace are used to regulate the temperature of gases leavin rnace (Fig. 3.52).

3. **Use of Dampers.** Dampers are provided to control the direction and flow of hot combustion gases in order to vary the quantity of gas passing through the super-heater.

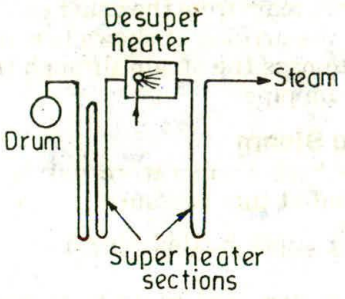


Fig. 3.51

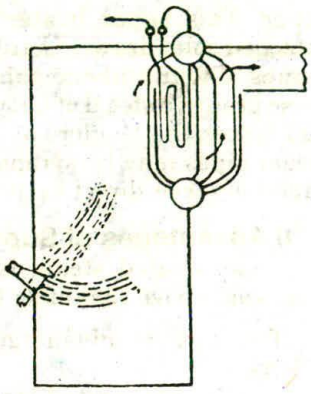


Fig. 3.52

4. **Use of Auxiliary Burners.** Auxiliary burners (Fig. 3.53) can be used to control degree of super-heat.

5. **Twin Furnace.** Arrangement [Fig. 3.54] may be used for the control of super-heating temperature.

3.22 Feed Water Treatment

Natural water supplies contain solid, liquid and gaseous impurities and as such this water cannot be used for the generation of steam in the boilers. This requires that the impurities present in the raw water should be removed before it can be used in the boilers.

Although in steam power plants the main condensate returns to the boiler as feed water but make up water is needed to replace the losses due to blow down, leakages etc. in the cycle.

The various impurities present in the natural water (raw water) may be in the following forms :

(*i*) Dissolve salts such as carbonate, sulphates chlorides of calcium, sodium and magnesium. Sometimes some iron, aluminium or silica salts are also present.

(*ii*) Dissolved gases such as carbon dioxide, oxygen and SO_2.

(*iii*) Mineral acids.

(*iv*) Suspended matter such as alumina and silica may be present as mud and salt.

In the water intended for steam boilers all the impurities are harmful especially if present in considerable quantities. The salts of calcium and magnesium are extremely harmful and when water containing them is heated and steam generated they precipitate as solid residue and form a hard scale on wall surface. The scale so formed is not desirable as it hampers the process of heat transfer.

Presence of mineral acids in water is always undesirable as it may result in chemical reaction with the boiler materials.

These impurities may cause the following troubles :

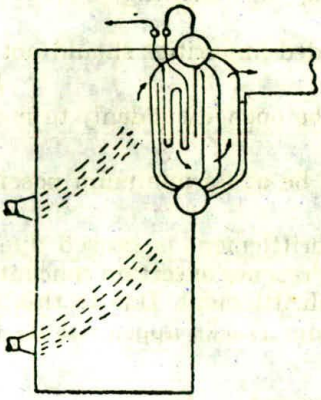


Fig. 3.53

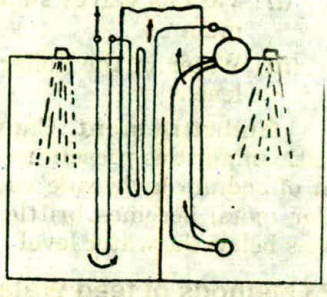


Fig. 3.54

(*i*) Scale formation (*ii*) Corrosion
(*iii*) Foaming and Priming (*iv*) Embrittlement.

1. **Scale Formation.** Impurities present in the water may cause scale formation in the boiler drums of header tubes and feed water piping system. This will reduce the heat transfer rate and will cause over-heating of tubes which may result in blistering and rupturing. The scale formation in the feed water pipes chokes the flow which requires higher pressure to maintain the water flow. Scale is due mainly to salts of calcium and magnesium. When scale has formed, the tubes should be cleaned with water or electric powered rotary brushes and cutters are pushed through the tubes during boiler overhauls.

2. **Corrosion.** Corrosion occur in the boiler shell, tubes, plates due to acidity present in water. This reduces the life of construction materials. Corrosion is the destructive conversion of metal into oxides or salts. Corrosion takes place due to the presence of oxygen, carbon dioxide or chlorides dissolved in water. Corrosion due to oxygen produces small pits.

3. **Foaming and Priming.** A layer of foam is caused in the boiler drum by soluble and insoluble salts and other organic impurities which are carried in suspension. Foaming prevents the free escape of steam bubbles as they rise to the surface of water. Oil and other impurities which may be present in boiler water may cause foaming.

Priming or carrying-over is the passing of small water particles with steam as it leaves the boiler. These water particles make the steam unfit for use in engines. This is caused by the impurities in water, a high water level and the method of operation of the boiler.

To prevent foaming and priming the following precautions should be observed :

(*i*) Oil, soap and other suspended impurities should not be present in boiler water.

(*ii*) Various valves should not be opened suddenly to maximum.

(*iii*) Water in the boiler should be at its minimum possible level.

4. **Embrittlement.** Caustic embrittlement is caused due to caustic impurities present in water. Presence of certain concentration of sodium hydroxide causes embrittlement. Due to this the boiler metal becomes brittle and inner cracks appear along the seams below the water level.

3.23 Methods of feed Water Treatment

It is desirable that the water to be used in the boiler should be free from various impurities. The impure water is chemically treated in different ways depending upon the nature and concentration of impurities. The different treatments adopted to remove the various impurities are as follows :

1. **Mechanical Treatment.** It includes sedimentation, coagulation and filtration. Suspended matter can be removed easily by these processes. Sedimentation involves allowing the water to stand quietly for some time. In this way the solid matter settles down and is removed periodically. In case of coagulation some coagulants like aluminium sulphate, sodium aluminate or ferrous sulphate are added to the impure water. This removes the minute colloidal suspensions. Filtration consists in passing the water through filters. The suspended matter adheres to the filter material. The filters may be either gravity filter or pressure filter.

Fig. 3.54 (*a*) shows a pressure filter. The raw water is passed through alum pot and then through a tank containing fine sand, graded layer of gravel. These filters can be easily installed on the pipe line as much lesser space is required.

2. **Thermal Treatment.** It includes distillation and deaerative heating of water. By these processes dissolved gases of water are removed.

Deaerating Heater. A tray type deaerating heater is shown in Fig. 3.55. In this heater feed water after passing through the vent condenser is sprayed upwards in the spray pipe. Water falls in the

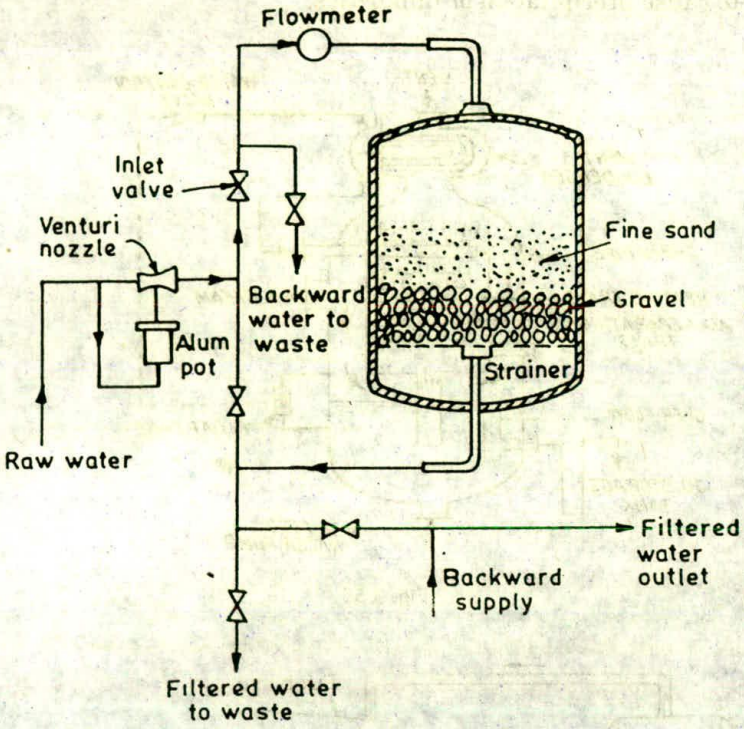


Fig. 3.54 (a).

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 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 the main turbine bled steam or may be from other sources. Storage tank with controls helps to add make up water when needed to maintain the feed water flow.

Closed Feed water heater

Fig. 3.55 (A) shows a closed feed water heater in which steam bled from steam turbine is used for heating the feed water. This process is also called regenerative process and increases the efficiency of the generation cycle.

3. **Chemical Treatment.** It includes addition of some chemicals to cause precipitation or impurities.

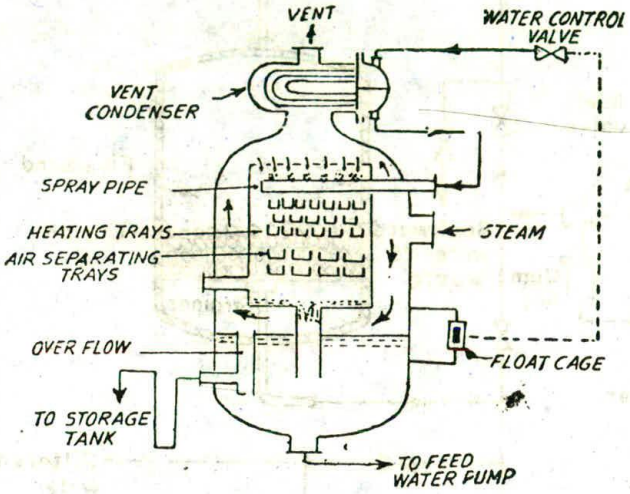


Fig. 3.55

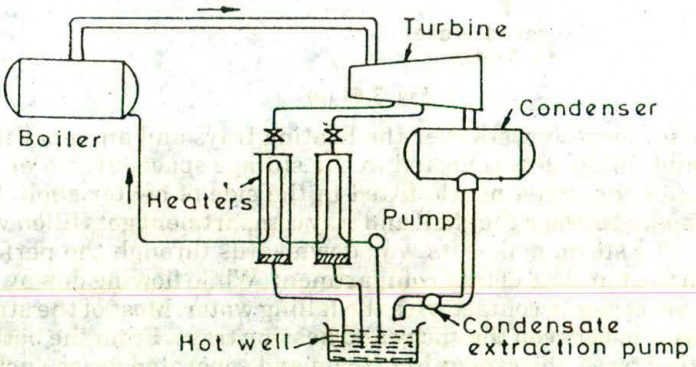


Fig. 3.55 (a)

(a) *Internal Treatment.* In this process the reagents are added to water present in boiler. Various reagents used are sodium carbonate, sodium phosphate, sodium hydroxide etc. Sodium phosphate when added removes carbonate impurities.

$$3\ CaCO_3 + 2Na_3PO_4 \rightarrow Ca_3(PO)_2 \downarrow 3Na_2CO_3$$

Internal treatment is suitable for low pressure (about 300 p.s.i.) boilers.

(*b*) **External Treatment.** In this treatment raw water is received in a tank where the reagent are mixed. The reaction becomes rapid if the water is heated before the addition of reagents.

The various reagents used in external treatment are as follows :

(*i*) *Lime Soda Treatment.* In this method lime $Ca(OH)_2$ is added to remove the carbonate hardness of water and soda ash Na_2CO_3 is added to remove the sulphate hardness.

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2CaCO_3 \uparrow + 2H_2O$$

$$MgSO_4 + Na_2CO_3 \rightarrow MgCO_3 \downarrow + Na_2SO_4$$

(*ii*) *Ion Exchange Process.* In this process sodium zeolite N_2Z ($Na_2\ Al_2\ Si_2\ O_2$) is added. It reacts with calcium and magnesium salts to form zeolites. Zeolite is reproduced on the addition of brine (sodium chloride) solution.

$$CaSO_4 + Na_2Z \rightarrow Na_2SO_4 + CaZ$$

$$CaZ + 2NaCl \rightarrow N_2Z + CaCl_2$$

A zeolite softener Fig. 3.56 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. The raw water enters the zeolite softner at the top. It flows downwards through the bed although the system can be by-passed while back washing, if necessary. The figure also shows arrangements for the periodic back washing with brine needed by this system.

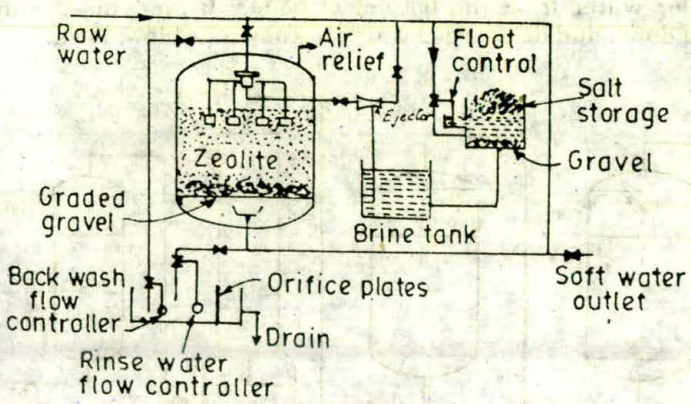


Fig. 3.56 Ion exchange system.

4. **Demineralisation.** It is used to remove mineral contents of water. In this system [Fig. 3.56 (*a*)] raw water enters the hydrogen zeolite exchanger (cation removal) at the top and then flows to the anion exchanger and degasified and finally passes through silicon absorber.

In spite of the best treatment some quantity of dissolved and suspended impurities enter the boiler. Table 3.0 indicates the recommended boiler water concentration of impurities at different operating pressures (p).

Table 3.0

Pkg/cm²	*Silica PPM*	*Suspended solids PPM*	*Alkalinity PPM*	*Total Solids PPM*
0–25	100	300	650	3000
25–50	60	150	500	2500
50–100	8	40	200	1000
Above 100	6	4	70	400

The above values show that safe limit of concentration decreases with increase in boiler working pressure. Concentration of these solids can be reduced to a great extent by blowing down some quantity of water from the bottom of boiler drum. Periodical blow down helps in maintaining the concentration of impurities within the allowable limits.

5. **Blow down.** Water entering the boiler may contain some dissolved solids. The concentration of these solids goes on increasing as the water is vaporised. 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 drum. This is called blowing down and discharged water is known as blow down.

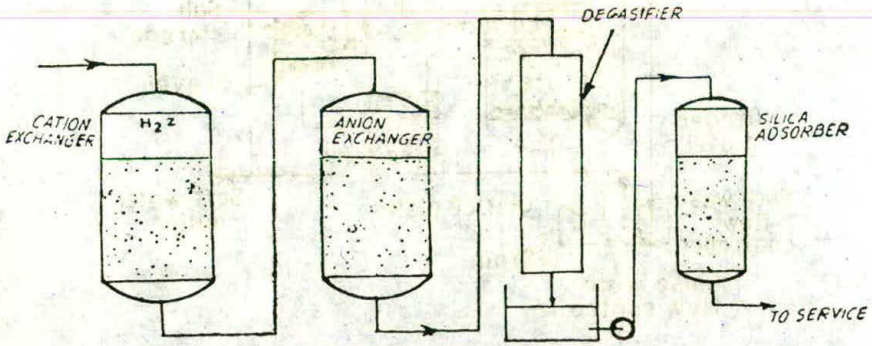


Fig. 3.56 (*a*)

The blow down mainly contains the undesirable impurities which concentrate at the bottom of drum. As a result of blow down the concentration of these impurities inside the boiler drum can be temporarily reduced. Therefore a boiler may have periodical blow down so that the concentration of impurities can be kept within permissible limits.

3.24 To determine blow down

Draining of some of the boiler water carrying excessive concentration of solids and replacing it with fresh feed water keep the solid concentration within safe limits. This is called blowing down the boiler and the discharged water is called blow down.

The blow down is calculated as follows :

K = Blow down % = W/Wf

where W = weight of water blow down from boiler in kg per hour

Wf = weight of feed water supplied to boiler for steam and blow down in kg per hour.

Blow down may be continuous or intermittent. Continuous blow down is about 1 to 10% of the incoming feed water.

The impurities in blow down are found by the following relation :

$$M = M_1 + M_2 + M_3$$

where M = Impurities in blow down (weight of blow down) × (Allowable salt concentration) ppm.

M_1 = Feed water impurities = (weight of feed water) × (Impurity concentration) ppm.

M_2 = Internal treatment chemicals.

M_3 = Steam impurities = (weight of steam) × (Impurity concentration) ppm.

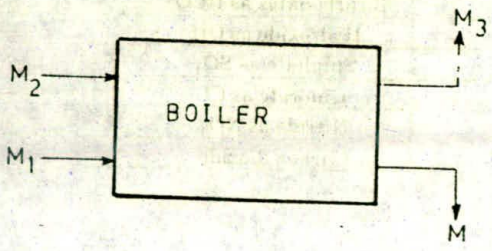


Fig. 3.56 (*b*)

Fig. 3.56 (*b*) shows mass balance of impurities and treatment chemicals in boiler.

3.25 pH Value of Water

It is the logarithm of the reciprocal of hydrogen ion concentration in water. In water either hydroxyl ions (OH^-) or hydrogen ions (H^+) predominate causing either an alkaline or acidic condition. Acidity or alkalinity is measured in pH values ranging from 1 to 14. pH value 1 is strongly acidic. pH 14 is strongly basic and pH 7 indicates a neutral solution. pH value of a sample of water can be measured by a pH meter.

3.26 Analysis of Water

Analysis of water is carried out to determine the quantity of impurities and other chemical substances in a sample of water. The data contained in a typical water analysis report is as follows :

Water Analysis Report

Serial No.... Date....
Source of sample.... Quantity of sample.....
Date of collection..... Date of analysis.....

S.No.	*Particular*	*Parts per million (Ppm)*
1.	Colour water	—
2.	Suspended solids	—
3.	Turbidity	—
4.	Organic matter	—
5.	Chloroform, oil etc	—
6.	pH value	—
7.	Alkalinity as $CaCO_3$	—
8.	Hardness as $CaCO_3$	—
9.	Silica as SiO_2	—
10.	Iron as Fe_2O_3	—
11.	Sodium	—
12.	Magnesium	—
13.	Calcium	—
14.	Carbonates as CO_3	—
15.	Bicarbonates as HCO_3	—
16.	Hydroxide as OH	—
17.	Sulphate as SO_4	—
18.	Chloride as Cl	—
19.	Nitride as NO_3	—
20.	Carbon dioxide	—

3.27 Feed Water Heaters

Feed water heaters are used to heat the feed water before it is supplied to the boiler.

Heating of boiler feed water serves the following purposes :

1. It causes scale forming dissolved salts to precipitate outside that boiler.
2. It removes dissolved gases such as oxygen and carbon dioxide which corrode boiler metal.
3. By using pre-heated feed water, the steaming capacity of boiler is increased.
4. It avoids the thermal stresses which can be induced in the boiler surface by cold water entering a hot drum.

There are two types of feed water heaters :

1. **Contact or open heaters.** In these heaters feed water get mixed with the heating steam. These heaters include tray type heater (Fig. 3.52) and jet type heater.

2. **Surface or closed heaters.** Surface heaters have shell and tube construction, and may be steam tube type or water tube type. Generally water tube type heaters are used. They ordinarily use bled steam for heating. Heating the feed water with steam at a lower pressure than boiler pressure raises the over-all efficiency of the plant. Fig. 3.56 (c) shows a closed feed water in which water flow through tubes and steam flows all around the tubes. Steam while following transfers its heat to the feed water. Surface heater has construction similar to a surface consider except that surface heater is designed for higher pressure and temperatures.

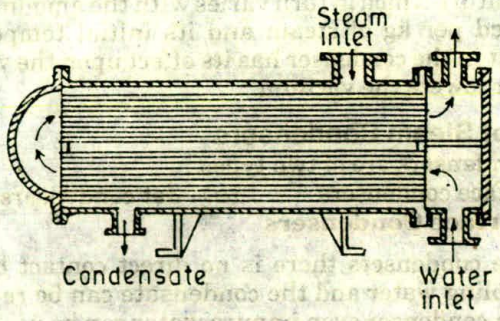


Fig. 3.56 (c).

Chemical tests are performed at frequent intervals on samples of water to have information of some improtant items such as variation in mineral characteristics of raw water supply, condition of boiler water with respect to treatment adjustment and blow down adjustment percentage of condensate and make up in the feed water

steam purity and correction of feed water and boiler water for corrosion control etc.

3.28 Steam Condensers

A steam condenser is meant to receive the exhaust steam from the turbine or engine, condense it and maintain a pressure at the exhaust lower than atmospheric. Some extra work is obtained due to exhaust at a pressure lower than the atmospheric. This improves the efficiency at a pressure lower than the atmospheric. This improves the efficiency of the plant. Air inside the condenser should be pumped out continuously in order to maintain the vacuum. The condensation of steam occurs in the range of 25°C to 38°C.

Steam pressure in a condenser depends mainly on the flow rate and temperature of the cooling water and on the effectiveness of air removal equipment. Some of the advantages of a steam condenser are as follows :

(*i*) It increases power output. Power plant cycle improves in efficiency as the turbine exhaust pressure drops.

(*ii*) It recovers most of the feed water (in case of surface condenser) which is available at 45°C to 50°C. This saves the amount of fuel to be burnt in boiler.

(*iii*) The use of condenser, decreases the size of boiler installation.

The main disadvantage of condenser is that it adds to the initial cost of power plant as the condenser requires additional equipment such as cooling tower or cooling pond, vacuum pump, water circulating pump etc.

The vacuum obtainable in a condenser is governed by the outlet water temperature which in turn varies with the amount of condensing water used per kg of steam and its initial temperature. Air entertainment in the condenser has its effect upon the vacuum. The addition of air lowers the vacuum.

3.29 Types of Steam Condensers

Steam condensers are of two types :

(*i*) Surface condensers (*ii*) Jet condensers.

3.29.1 Surface Condensers

In surface condensers there is no direct contact between the steam and cooling water and the condensate can be re-used in the boiler. In such condenser even impure water can be used for cooling purpose whereas the cooling water must be pure in jet condensers. Although the capital cost and the space needed is more in surface condensers but it is justified by the saving in running cost and increase in efficiency of plant achieved by using this condenser. Depending upon the position of condensate extraction pump, flow of

condensate and arrangement of tubes the surface condensers may be classified as follows :

(*i*) **Down flow type.** Fig. 3.56 (*d*) shows a sectional view of down flow condenser. Steam enters at the top and flows downward. The water flowing through the tubes in one direction lower half comes out in the opposite direction in the upper half. Fig. 3.57 shows a longitudinal section of a two pass down-flow condenser.

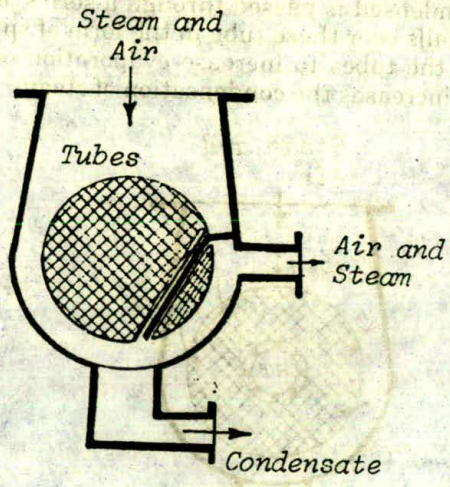


Fig. 3.56 (*d*).

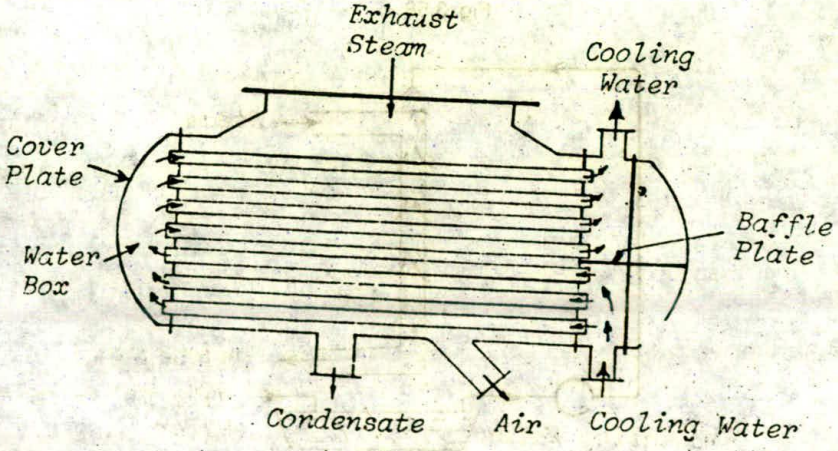


Fig. 3.57.

(*ii*) **Central flow condenser.** Fig. 3.58 shows a central flow condenser. In this condenser the steam passages are all around the periphery of the shell. Air is pumped away from the centre of the condenser. The condensate moves radially towards the centre of tube nest. Some of the exhaust steam while moving towards the centre meets the undercooled condensate and pre-heats it thus reducing undercooling.

(*iii*) **Evaporation condenser.** In this condenser (Fig. 3.59) steam to be condensed is passed through a series of tubes and the cooling water falls over these tube in the form of spray. A steam of air flows over the tubes to increase evaporation of cooling water which further increases the condensation of steam.

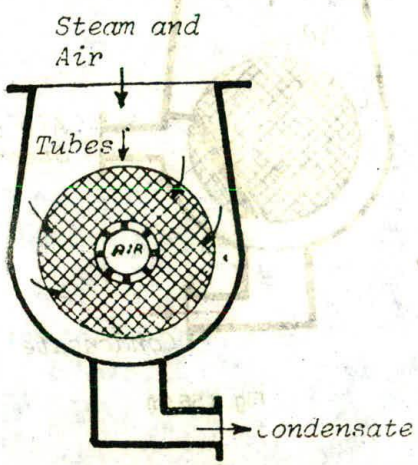


Fig. 3.58.

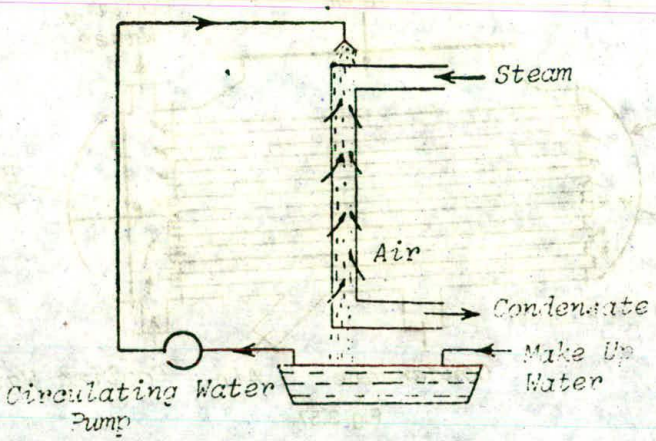


Fig. 3.59.

Advantages and disadvantages of a surface condenser

The various advantages of a surface condenser are as follows :

(*i*) The condensate can be used as boiler feed water.

(*ii*) Cooling water of even poor quality can be used because the cooling water does not come in direct contact with steam.

(*iii*) High vacuum (about 73.5 cm of Hg) can be obtained in the surface condenser. This increases the thermal efficiency of the plant.

The various disadvantages of the surface condenser are as follows :

(*i*) The capital cost is more.

(*ii*) The maintenance cost and running cost of this condenser is high.

(*iii*) It is bulky and requires more space.

Requirements of a modern surface condenser. The requirements of ideal surface condenser used for power plants are as follows :

(*i*) The steam entering the condenser should be evenly distributed over the whole cooling surface of the condenser vessel with minimum pressure loss.

(*ii*) The amount of cooling water being circulated in the condenser should be so regulated that the temperature of cooling water leaving the condenser is equivalent to saturation temperature of steam corresponding to steam pressure in the condenser.

This will help in preventing under cooling of condensate.

(*iii*) The deposition of dirt on the outer surface of tubes should be prevented.

This is achieved by passing the cooling water through the tubes and allowing the steam to flow over the tubes.

(*iv*) There should be no air leakage into the condenser because presence of air destroys the vacuum in the condenser and thus reduces the work obtained per kg of steam. If there is leakage of air into the condenser air extraction pump should be used to remove air as rapidly as possible.

3.29.2. Jet Condensers. In jet condensers the exhaust steam and cooling water come in direct contact with each other. The temperature of cooling water and the condensate is same when leaving the condensers.

Elements of the jet condenser are as follows :

(*i*) Nozzles or distributors for the condensing water.

(*ii*) Steam inlet.

(*iii*) Mixing chambers : They may be (*a*) parallel flow type (*b*) counter flow type depending on whether the steam and

water move in the same direction before condensation or whether the flows are opposite.

(*iv*) Hot well.

In jet condensers the condensing water is called injection water.

3.29.3 Types of jet condensers

(*i*) **Low level jet condensers (Parallel flow type).** In this condenser (Fig. 3.60) water is sprayed through jets and it mixes with steam. The air is removed at the top by an air pump. In counter flow type of condenser the cooling water flows in the downward direction and the steam to be condensed moves upward.

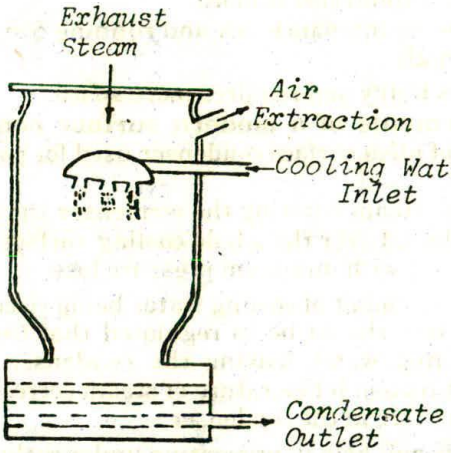


Fig. 3.60.

(*ii*) **High level or Barometric condenser.** Fig. 3.61 shows a high level jet condenser. The condenser shell is placed at a height of 10.33 m (barometric height) above the hot well. As compared to low level jet condenser this condenser does not flood the engine if the water extraction pump fails. A separate air pump is used to remove the air.

(*iii*) **Ejector Condenser.** Fig. 3.62 shows an ejector condenser. In this condenser cold water is discharged under a head of about 5 to 6 m through a series of convergent nozzles. The steam and air enter the condenser through a non-return valve. Steam gets condensed by mixing with water. Pressure energy is partly converted into kinetic energy at the converging cones. In the diverging cone the kinetic energy is partly converted into pressure energy and a pressure higher than atmospheric pressure is achieved so as to discharge the condensate to the hot well.

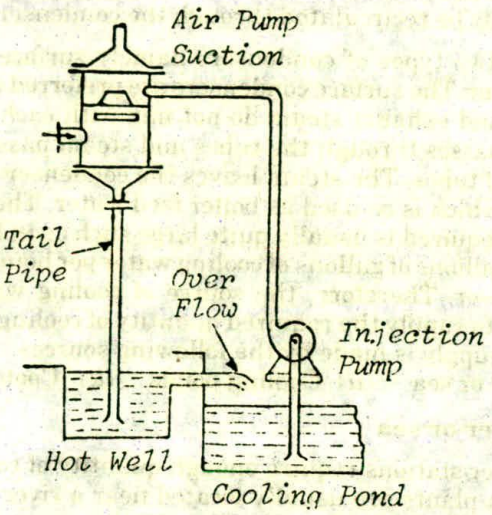


Fig. 3.61

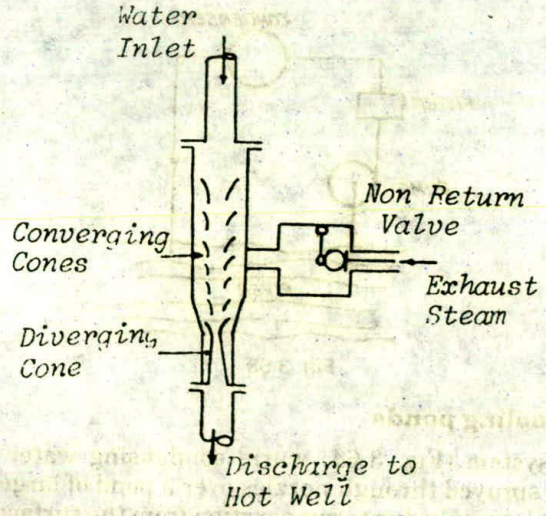


Fig. 3.62

3.30 Condenser Cooling Water Supply

A condenser is a device in which exhaust steam from steam engines or steam turbines is condensed and the heat energy given up by the steam during condensation is taken up by the cooling

water. The water coming out of the condenser is hot and is cooled in order that it may be recirculated through the condenser.

There are two types of condensers namely surface condenser and jet condenser. The surface condensers are preferred because the cooling water and exhaust steam do not mix with each other. The cooling water passes through the tubes and steam passes over the outer surface of tubes. The steam leaves the condenser in the form of condensate which is re-used as boiler feed water. The amount of cooling water required is usually quite large such as in large steam power plants millions of gallons of cooling water per hour is required for the condenser. Therefore, 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 :

(*i*) River or sea (*ii*) Cooling ponds (*iii*) Cooling towers.

3.30.1 River or sea

Large power stations require enough quantity of cooling water per hour. Such plants are usually located near a river or sea. The water is constantly drawn from the river by the pump, filtered and circulated through the condenser. Hot coolant is discharged back into the river (Fig. 3.63).

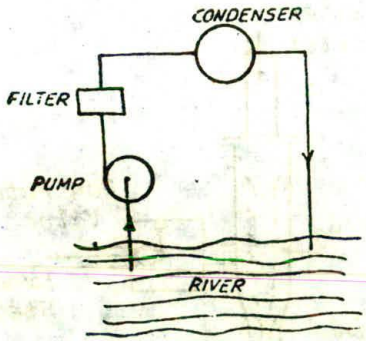


Fig. 3.63

3.30.2 Cooling ponds

In this system (Fig. 3.64) warm condensing water from the condenser is sprayed through 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.

Some of the factors which influence the rate of heat dissipation from a cooling pond are as follows :

(*i*) Area and depth of pond

(*ii*) Temperature of water entering the pond

(*iii*) Atmospheric temperature
(*iv*) Wind velocity
(*v*) Relative humidity
(*vi*) Shape and size of water spray nozzles.

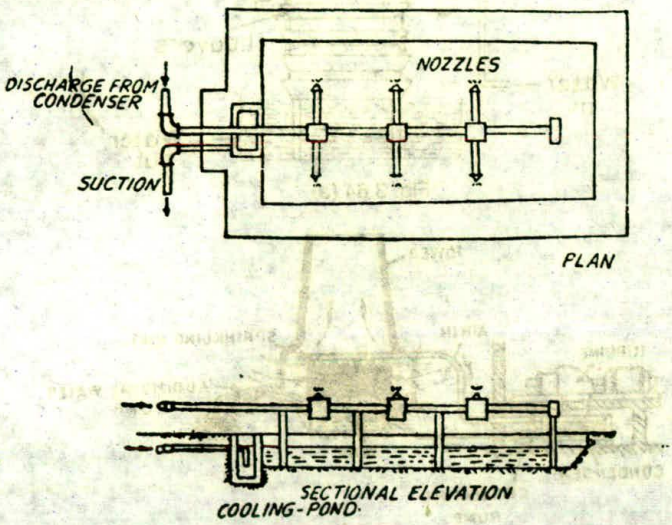


Fig. 3.64

3.30.3 Cooling Towers

The different types of cooling towers are as follows :

1. Atmospheric cooling tower.
2. Natural draught cooling towers.
3. Forced or induced draught cooling tower.

Atmospheric cooling tower. In this cooling tower hot water is allowed to fall over louvers. The air flowing across in transverse direction cools the falling water. These towers are used for small capacity power plants such as diesel power plants. Fig. 3.64 (*a*) shows an atmospheric cooling tower.

Natural draught cooling towers. In natural draught cooling tower, the hot water from the condenser is pumped to the troughs and nozzles situated near the bottom. Troughs spray the water which falls in the form of droplets into a pond situated at bottom of the tower. The air enters the cooling tower from air openings provided near the base, rises upward and take up heat of falling water.

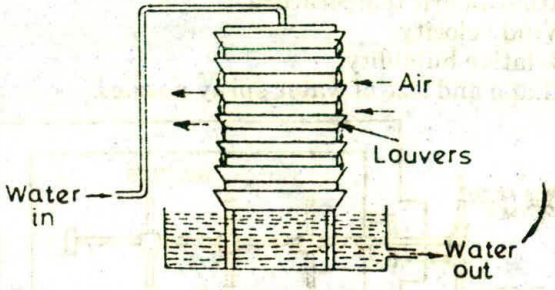


Fig. 3.64 (a)

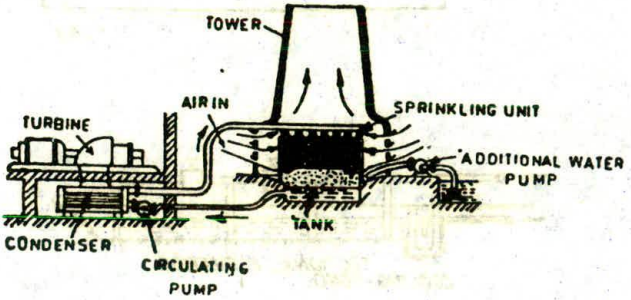


Fig. 3.65

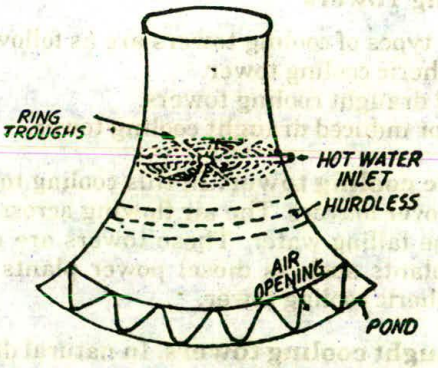


Fig. 3.66

Cooling towers may be made up of timber, concrete or steel. A concrete hyperbolic cooling tower is shown in Fig. 3.66. Fig. 3.67 shows the water circulation from the cooling tower to the condenser. Fig. 3.65 shows the cooling tower in which the position of turbine has also been shown. The system consists of turbine, condenser. Circulating pump, tank, additional water pump and sprinkling unit.

The air is delivered through the holes in the side walls of the tower. The circulating water is delivered to the upper part of the watering unit where it flows down and gives its heat to the surrounding air. The cooled water flows into the tank and is circulated through the condenser. Towers made up of the concrete are preferred because they are stable against larger air pressure, their maintenance cost is low and they have larger capacities.

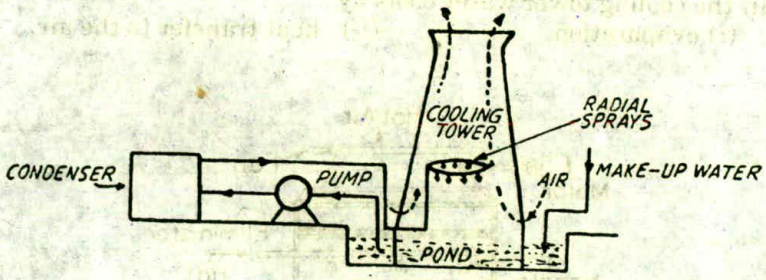


Fig. 3.67

Forced draught cooling towers. In this tower draught fan is installed at the bottom of tower. The hot water from the condenser enters the nozzles. The water is sprayed over the tower filling slats and the rising air cools the waters. A forced draught cooling tower is shown in Fig. 3.68.

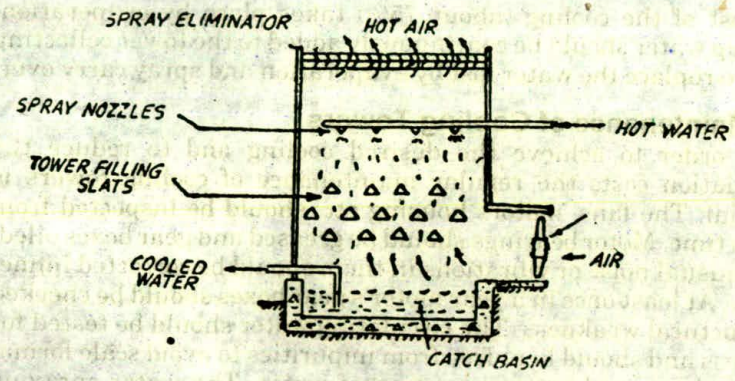


Fig. 3.68

The various factors that affect cooling of water in a coo... are as follows :

(*i*) Size and height of cooling tower.
(*ii*) Velocity of air entering the tower.
(*iii*) Temperature of hot water coming out of condenser.
(*iv*) Temperature of air.
(*v*) Humidity of air.

(*vi*) Accessibility of air to various parts of cooling tower.

Mechanical draft cooling towers may be forced draft cooling towers or induced draft towers. Fig. 3.68 (*a*) shows an induced draft cooling tower. The hot water is allowed to pass through. The draft fan installed at top of tower draw air through the tower. The air moving the upward direction cools the water. Induced draft towers produces less noise.

In the cooling tower water cools by :

(*i*) evaporation. (*ii*) heat transfer to the air.

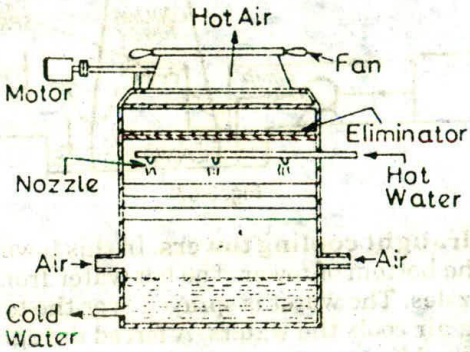


Fig. 3.68 (*a*)

Most of the cooling (about 75%) takes place by evaporation. Make up water should be continuously added to the tower collecting basin to replace the water lost by evaporation and spray carry over.

3.31 Maintenance of Cooling Towers

In order to achieve the desired cooling and to reduce the depreciation costs the regular maintenance of cooling towers is essential. The fans, motors housing etc. should be inspected from time to time. Motor bearings should be greased and gear boxes oiled. Any unusual noise or vibrations in them should be corrected immediately. At least once in a year motor's gear boxes should be checked for structural weakness. The circulating water should be tested for hardness and should kept free from impurities to avoid scale formations and to avoid corrosive action of water. The water spraying nozzles should be inspected regularly for clogging.

3.32 Condenser Efficiency

Condenser efficiency is defined as follows :

$$\text{Condenser efficiency } (\eta) = \frac{\text{Rise in temperature of cooling water}}{\text{Temperature corresponding to vacuum in condenser}}$$

– Inlet temperature of cooling water

$$\eta = \frac{T_2 - T_1}{T_3 - T_1}$$

where T_1 = Inlet temperature of cooling water

T_2 = Outlet temperature of cooling water

T_3 = Temperature corresponding to vacuum in the condenser.

3.33 Vacuum Efficiency

Vacuum efficiency is defined as ratio of actual vacuum to theoretical vacuum. Vacuum efficiency (η_v) is defined as follows :

$$\eta_v = \frac{P_1}{P_2}$$

where P_1 = Actual vacuum in condenser

P_2 = Theoretical vacuum in condenser.

Theoretical vacuum in the condenser is the vacuum if no air is present in it.

3.34 Condenser Pressure

The total condenser pressure (P) is given by the relation

$$P = P_s + P_a$$

where P_s = Steam saturation pressure corresponding to steam temperature

P_a = Air pressure.

Air must be removed constantly to keep P_a low.

Example 3.5. *The vacuum in a condenser is 68 cm. of Hg with barometer reading 76 cm of Hg. If the inlet and outlet temperatures of cooling water to a condenser are 28°C and 42°C respectively, calculate the condenser efficiency.*

Solution. $T_1 = 28°C$

$T_2 = 42°C$

Rise in temperature = 42 - 28 = 14°C

Absolute pressure in the condenser

= 76 – 68 = 8 cm of Hg = 0.108 kg/cm^2,

Saturation temperature corresponding to 0.108 kg/cm^2 = 47°C.

$\therefore$ Condenser efficiency $= \dfrac{14}{47 - 28}$

$= \dfrac{14}{19} \times 100 = 73.6\%$.

3.35. To Calculate the Weight of Cooling Water

The weight of cooling water required for condenser to condense a given amount of steam is calculated as follows :

Let W = Weight of cooling water required (kg) to condense W_1 (kg) of steam

T_1 = Inlet temperature of cooling water in °C

T_2 = Outlet temperature of cooling water in °C

T_3 = Temperature of condensate in °C

q = Dryness fraction of steam entering the condenser

L = Latent heat of steam entering the condenser

H_w = Heat of water at pressure entering the condenser

T = Temperature of water at the pressure of steam entering the condenser in °C

H = Total heat of 1 kg of steam entering the condenser in kcal = $H_w + qL$

H_1 = Total heat of condensate leaving the condenser (kcal)

Heat gained by cooling water $= W (T_2 - T_1)$ kcal.

Heat lost by steam $= W_1 (H - H_1)$ kcal.

$\therefore$ $W (T_2 - T_1) = (H - H_1) W_1$

$$W = \frac{(H - H_1) W_1}{T_2 - T_1}$$

$$W = \frac{(H_w + qL - H_1) W_1}{T_2 - T_1}$$

Now in place of H_w and H_1 the corresponding temperature T and T_3 respectively can be substituted with sufficient accuracy.

$\therefore$ $$W = \frac{(T + qL - T_3) W_1}{T_2 - T_1}$$

Example 3.6. *Calculate the quantity of cooling water required in kg/min for a surface condenser to condense 18 kg of steam per minute. The dryness fraction of steam is 0.9 and the temperature of steam entering the condenser is 37°C. The inlet and outlet temperature of cooling water are 18°C and 32°C respectively. The condensate temperature is 37°C. The latent heat of steam should be taken as 576 kcal/kg.*

Solution. W_1 = weight of steam to be condensed/minute

= 18 kg

W = weight of cooling water required

$\therefore$ $T_1 = 18°C$; $T_2 = 32°C$

$T_3 = 37°C$; $T = 37°C$

$q = 0.9$; $L = 576$ kcal/kg

$\therefore$ $W(T_2 - T_1) = W_1(T + qL + T_3)$

$$W = \frac{W_1(T + qL - T_3)}{T_2 - T_1}$$

$$= \frac{18(37 + 0.9 \times 576 - 37)}{32 - 18} = 666 \text{ kg per min.}$$

Example 3.7. *Calculate the quantity of cooling water required for a jet condenser to condense 40 kg of steam per minute. The vacuum in condenser is 710 mm of mercury (Barometer 760 mm of mercury). The inlet temperature of cooling water is 14 C. The latent heat of steam 576 is kcal/kg.*

Solution. W_1 = weight of steam = 40 kg

W = weight (kg) of cooling water required/minute

$T_1 = 14°C$

Absolute pressure in the condenser

= 760 − 710 = 50 mm of mercury

$$= \frac{50}{10} \times 0.01359 = 0.068 \text{ kg/cm}^2$$

Now T_3 = Temperature of condensate

= 38°C (corresponding to 0.068 kg/cm^2 from steam tables)

T_2 = Outlet temperature of cooling water

$= T_3 = 38°C$

$$W(T_2 - T_1) = W_1(T + qL - T_3)$$

$$W = \frac{W_1(T + qL - T_3)}{T_2 - T_1}$$

$$= \frac{40(38 + 1 \times 576 - 38)}{38 - 14} = 960 \text{ kg.}$$

3.36 Selection of a Condenser

The selection of a condenser depends upon various factors. The floor space required by a jet condenser is less than a surface condenser. The first cost and maintenance cost of a jet condenser is less than an equivalent surface condenser. The main advantage of a surface condenser is that it recovers the distilled condensate for boiler feed water whereas in a jet condenser the condensate gets mixed with cooling water and, therefore, cannot be used for boiler feed water. Surface condensers are most commonly used in power plants.

3.37 Sources of Air in a Condenser

Air may enter the condenser through different sources and it should be removed continuously in order to maintain vacuum inside the condenser. As a condenser is required to maintain low pressure of exhaust steam which is possible only if a partial vacuum exists inside the condenser.

The various sources of air in the condenser are as follows :

(*i*) Air may enter the condenser through various joints of different parts where internal pressure is less than atmospheric pressure.

(*ii*) The feed water in boiler may contain some air in it. Therefore, the exhaust steam may carry some amount of air along with it.

(*iii*) In case of jet condensers, the air dissolved in cooling water enters the condenser.

3.37 (*a*) Effects of Air Leakage

Various effects of air leakage in the condenser are as follows :

(*i*) It increases the pressure in the condenser and reduces the work done per kg of steam.

(*ii*) The heat transfer rates are greatly reduced because air offers high resistance to heat flow. This requires more quantity of cooling water to maintain heat transfer rates.

(*iii*) The pressure of air lowers the partial pressure of steam and its corresponding temperature. The latent heat of steam increases at low pressure. Therefore more quantity

of water is required to condense one kg of steam as the quantity of latent heat removed is more.

Therefore air should be removed from the condenser. The air from the condenser is removed with the help of air pumps.

3.38 Air Extraction Pump

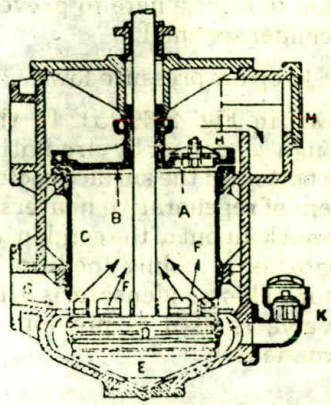


Fig. 3.69

Air pump is used to remove the air from the condenser. Edward's air pump (Fig. 3.69) is generally used for this purpose. It consists of a piston (*D*) which has a conical head (*E*). The bottom of the pump casing is also of conical shape in order that piston head can be easily seated. The piston slides inside the barrel (*C*) having a cover (*B*) which has a number of delivery valves (*A*). Passage (*G*) is connected to the condenser. On the down stroke of the piston a partial vacuum is produced above it since delivery valves are closed and sealed by water. When the piston uncovers the ports (*E*) air and condensate from the condenser rush into the space above the piston. As the piston further moves down the conical part (*E*) displaces the condensate which has collected in the bottom portion of the pump and forces it to flow into the upper portion through the ports (*F*). Now when the piston moves upward it raises the pressure slightly over that of the atmosphere and delivery valve (*A*) gets opened and allows air and condensate to move out and flow over weir (*H*) and finally to hot well. The relief valve (*K*) provided at the base of cylinder is used to release the pressure if due to some reasons the pressure below the piston exceed the atmospheric pressure.

3.39 Condenser Auxiliaries

The auxiliaries are required for the condenser to function properly. They are as follows :

(*i*) Cooling water supply pump to maintain the required flow of cooling water in the condenser.

(*ii*) Condensate pump to remove the condensate from the condenser.

(*iii*) Feed water pump to supply the feed water to boiler.

(*iv*) Air removal pump to remove the air from the condenser.

3.40 Condenser Performance

The condenser performance depends greatly on the cleanliness of the tube heat transfer surface. Cooling water carries in debris and impurities that foul up the tube interiors and reduce heat transfer rate. Tubes should be cleaned periodically.

If the cooling water flows should be accidentally interrupted a relief valve must release exhaust steam to atmosphere to prevent building up a destructive pressure in condenser shell.

Air must be removed constantly to keep air pressure low.

A condensing installation is shown in Fig. 3.69 (*a*). In this system the cooling water is forced through condenser by circulating pump. The condensate moves from the bottom of the surface coolers of steam ejectors and then to the system of regenerative heaters of the turbine. The function of ejector is to suck air out of the condenser. The ejector coolers use the condensate as a cooling medium to condense the live steam in the ejector. This condensate is then returned to the condenser. An air valve is used to prevent an excessive increase in pressure in the condenser.

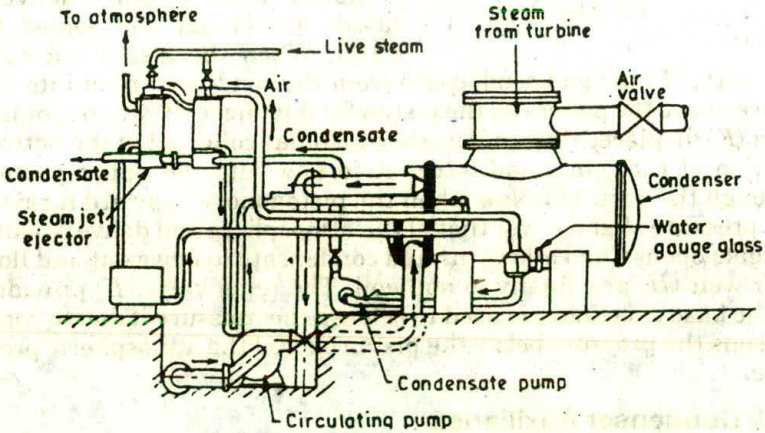


Fig. 3.69 (*a*)

3.41 Steam Separator

To avoid the turbine blades from the harmful effects of moisture it is desirable that steam entering the turbine should not contain drops of water. To achieve this steam separator is located in the supply line close to the turbine. The steam separator removes suspended drops or slug of water from the steam.

The steam separators may be classified as follows :

(*i*) **Reverse Current Separator.** A reverse current system separator is shown in Fig. 3.70. In this separator the direction of steam is suddenly changed. This causes the heavier water particles to fall down into the chamber of separator while steam being lighter flows out.

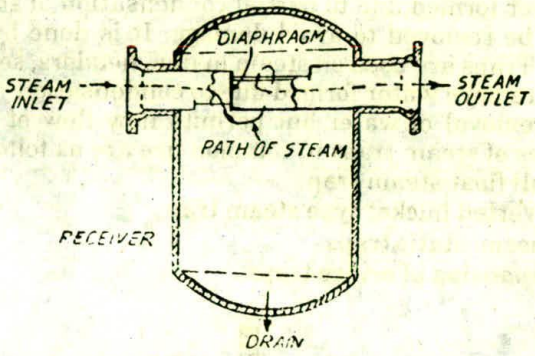


Fig. 3.70.

(*ii*) **Separator with baffle plates.** In this separator a few baffle plates are placed in the path of steam. The water particles adhere to these plates.

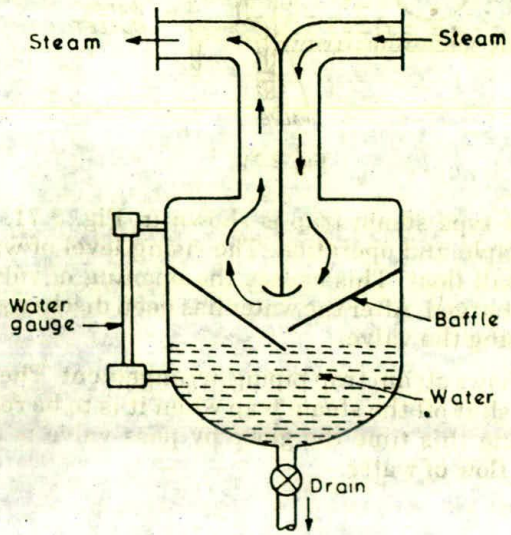


Fig. 3.70 (*a*)

Fig. 3.70 (*a*) shows baffle plate steam separator. Steam entering the separator moves down and strikes the baffle plates and gets deflected water particles fall to the bottom of separator and are drained off. Steam leaving the separator is free from moisture.

(*iii*) **Separator with screens.** In this separator, the water particles are separated by mechanical filtration.

3.42 Steam Trap

The water formed due to partial condensation of steam is pipe line should be removed to avoid damage. It is done by locating a steam trap. Traps are used on steam mains, headers, separator etc. where they remove water formed due to condensation. Trap allows automatic removal of water but permits now flow of steam. The various types of steam traps in common use are as follows :

(*i*) Ball float steam trap.
(*ii*) Inverted bucket type steam trap.
(*iii*) Thermostatic traps.
(*iv*) Expansion of orifice traps.

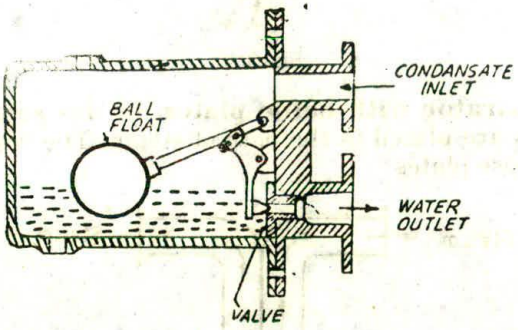


Fig. 3.71

A ball float type steam trap is shown in Fig. 3.71. It is quite simple in principle and operation. The rising level of water in the trap lifts the ball float. This causes the opening of valve and the water gets discharged. After the water has been discharged the float drops thus closing the valve.

Fig. 3.72 shows steam trap piping arrangement. The gate valve can be used to shut off the steam trap when it is to be repaired and removed. During this time the globe by pass valve is utilised for regulating the flow of water.

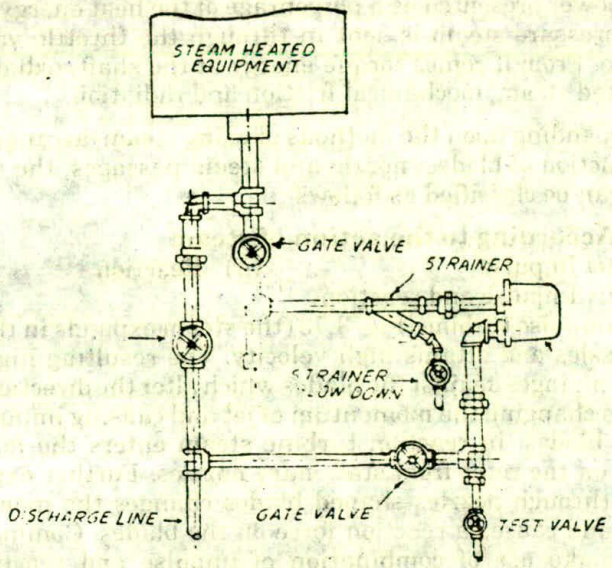


Fig. 3.72

3.43. Steam Turbines

Steam turbine is a heat engine which uses the heat energy stored in steam and performs work. The main parts of a steam turbine are as follows :

(*i*) A rotor on the circumference of which a series of blades or buckets are attached. To a great extent the performance of the turbine depends upon the design and construction of blades. The blades should be so designed that they are able to withstand the action of steam and the centrifugal force caused by high speed. As the steam pressure drops the length and size of blades should be increased in order to accommodate the increase in volume. The various materials used for the construction of blades depend upon the conditions under which they operate. Steel or alloys are the materials generally used.

(*ii*) Bearing to support the shaft.

(*iii*) Metallic casing which surrounds blades, nozzles, rotor etc.

(*iv*) Governor to control the speed.

(*v*) Lubricating oil system.

Steam from nozzles is directed against blades thus causing the rotation. The steam attains high velocity during its expansion in nozzles and this velocity energy of the steam is converted into mechanical energy by the turbine. As a thermal prime mover, the

thermal efficiency of turbine is the usual work energy appearing as shaft power presented as a percentage of the heat energy available. High pressure steam is sent in through the throttle valve of the turbine. From it comes torque energy at the shaft, exhaust steam, extracted steam, mechanical friction and radiation.

Depending upon the methods of using steam, arrangement and construction of blades, nozzle and steam passages, the steam turbines can be classified as follows :

1. According to the action of steam

(*i*) Impulse (*ii*) Reaction

(*iii*) Impulse and reaction.

In impulse turbine (Fig. 3.73) the steam expands in the stationary nozzles and attains high velocity. The resulting high velocity steam impinges against the blades which alter the direction of steam jet thus changing the momentum of jet and causing impulsive force on the blades. In reaction turbine steam enters the fast moving blades on the rotor from stationary nozzles. Further expansion of steam through nozzles shaped blades changes the momentum of steam and causes a reaction force on the blades. Commercial turbines make use of combination of impulse and reaction forces because steam can be used more efficiently by using the impulse and reaction blading on the same shaft. Fig. 3.74 shows an impulsed reaction turbine.

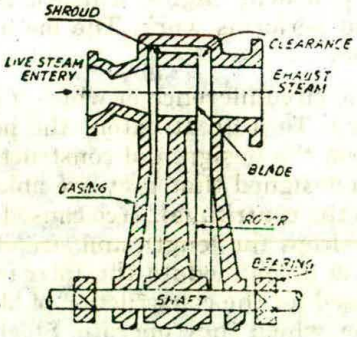


Fig. 3.73

2. According to the direction of steam flow

(*i*) Axial (*ii*) Radial

(*iii*) Mixed.

3. According to pressure of exhaust

(*i*) Condensing (*ii*) Non-condensing

(*iii*) Bleeder.

4. According to pressure of entering steam

(*i*) Low pressure (*ii*) High pressure

(*iii*) Mixed pressure.

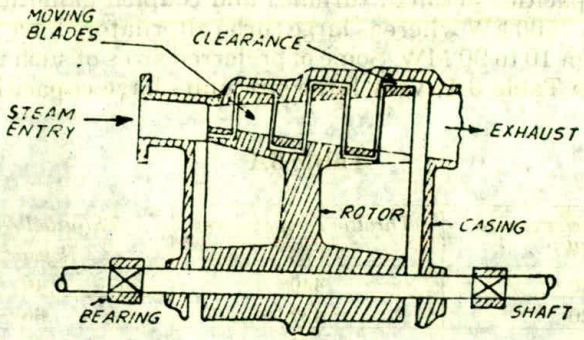


Fig. 3.74

5. According to step reductions
(*i*) Single stage (*ii*) Multi-stage
6. According to method of drive such as
(*i*) direct connected (*ii*) geared.

3.44 Advantages of Steam Turbine Over Steam Engine

The various advantages of steam turbine are as follows :

(*i*) It requires less space.

(*ii*) Absence of various links such as piston, piston rod, cross head etc. make the mechanism simple. It is quiet and smooth in operation.

(*iii*) Its over-load capacity is large.

(*iv*) It can be designed for much greater capacities as compared to steam engine. Steam turbines can be built in sizes ranging from a few horse power to over 200,000 horse power in single units.

(*v*) The internal lubrication is not required in steam turbine. This reduces to the cost of lubrication.

(*vi*) In steam turbine the steam consumption does not increase with increase in years of service.

(*vii*) In steam turbine power is generated at uniform rate, therefore, flywheel is not needed.

(*viii*) It can be designed for much higher speed and greater range of speed.

(*ix*) The thermodynamic efficiency of steam turbine is higher.

3.45. Steam Turbine Capacity

The capacities of small turbines and coupled generators vary from 500 to 7500 kW whereas large turbo alternators have capacity varying from 10 to 90 MW. Some of preferred sizes of such units are indicated in Table 3.1. Very large size units have capacities up to 500 MW.

Table 3.1

Turbo-alternator size (MW)	*Throttle Temperature (°C)*	*Throttle Pressure (kg/cm^2)*
10	440	40
20	482	60
30	482	60
40	510	87
60	510	87
90	560	100

Generating units of 200 MW capacity are becoming quite common. The steam consumption by steam turbines depends upon steam pressure, and temperature at the inlet, exhaust pressure number of bleeding stages etc. The steam consumption of large steam turbines is about 3.5 to 5 kg per kWh.

$$\text{Turbine kW} = \frac{\text{Generator kW}}{\text{Generator efficiency}}$$

Generators of larger size should be used because of the following reasons :

(*i*) Higher efficiency.
(*ii*) Lower cost per unit capacity.
(*iii*) Lower space requirement per unit capacity.

3.45.1 Nominal rating

It is the declared power capacity of turbine expected to be maximum load.

3.45.2 Capability

The capability of steam turbine is the maximum continuous out put for a clean turbine operating under specified throttle and exhaust conditions with full extraction at any openings if provided.

The difference between capability and rating is considered to be overload capacity. A common practice is to design a turbine for capability of 125% nominal rating and to provide a generator that will absorb rated power at 0.8 power factor. By raising power factor to unity the generator will absorb the full turbine capability.

3.46 Steam Turbine Governing

Governing of steam turbine means to regulate the supply of steam to the turbine in order to maintain speed of rotation sensibly constant under varying load conditions. Some of the methods employed are as follows :

(*i*) Bypass governing. (*ii*) Nozzle control governing.
(*iii*) Throttle governing.

Fig. 3.75 shows by pass governing arrangement. In this system the steam enters the turbine chest (*C*) through a valve (*V*) controlled by governor. In case of loads of greater than economic load a bypass valve (V_1) opens and allows steam to pass from the first stage nozzle box into the steam belt (*S*).

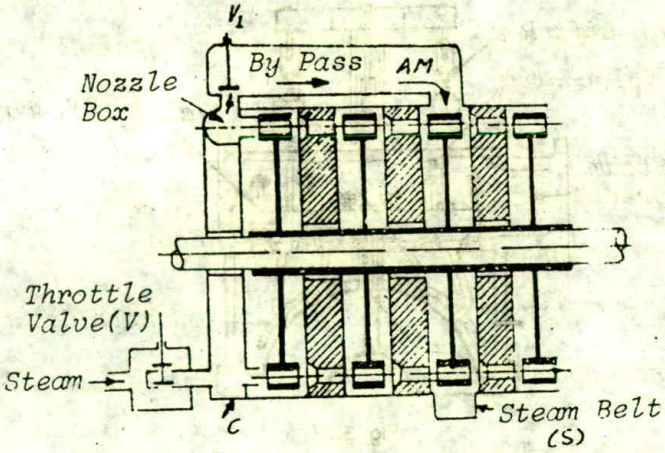


Fig. 3.75

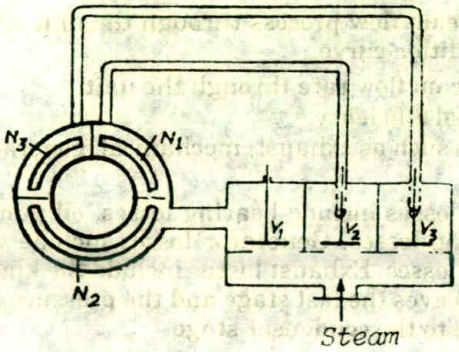


Fig. 3.76

Fig. 3.76 shows nozzle governing arrangement. In this method of governing the supply of steam of various nozzle groups N_1, N_2, and N_3 is regulated by means of valves V_1, V_2 and V_3 respectively.

Fig. 3.77 shows nozzle governing control system. Fig. 3.78 shows throttle governing. In this method of governing the double beat valve is used to regulate the flow of steam into the turbine. When the load on the turbine decreases, its speed will try to increase. This will cause the fly bar to move outward which will in return operate the lever arm and thus the double beat valve will get moved to control the supply of steam to turbine. In this case the valve will get so adjusted that less amount of steam flows to turbine.

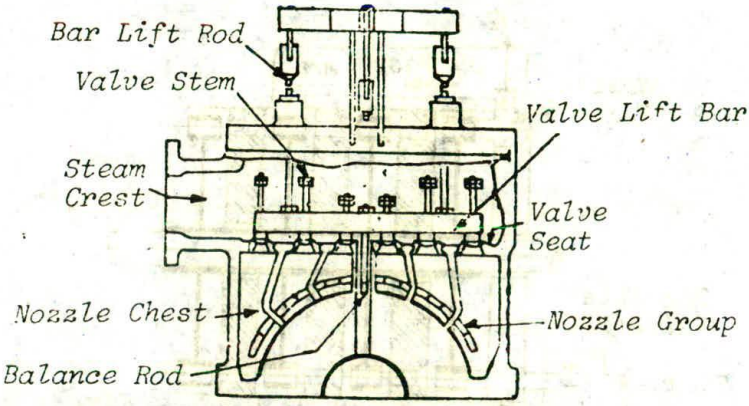


Fig. 3.77

3.47 Steam Turbine Performance

Turbine performance can be expressed by the following factors :

(*i*) The steam flow process through the unit–expansion line or condition curve.

(*ii*) The steam flow rate through the unit.

(*iii*) Thermal efficiency.

(*iv*) Losses such as exhaust, mechanical, generator, radiation etc.

Mechanical losses include bearing losses, oil pump losses and generator bearing losses. Generator losses include will electrical and mechanical losses. Exhaust losses include the kinetic energy of the steam as it leaves the last stage and the pressure drop from the exit of last stage to the condenser stage.

For successful operation of a steam turbine it is desirable to supply steam at constant pressure and temperature. Steam pres-

sure can be easily regulated by means of safety valve fitted on the boiler. The steam temperature may try to fluctuate because of the following reasons :

(*i*) Variation in heat produced due to varying amounts of fuel burnt according to changing loads.

(*ii*) Fluctuation in quantity of excess air.

(*iii*) Variation in moisture content and temperature of air entering the furnace.

(*iv*) Variation in temperature of feed water.

(*v*) The varying condition of cleanliness of heat absorbing surface.

The efficiency of steam turbines can be increased :

(*i*) By using super heated steam.

(*ii*) Use of bled steam reduces the heat rejected to the condenser and this increases the turbine efficiency.

3.47.1 Steam Turbine Testing

Steam turbine tests are made for the following :

(*i*) Power (*ii*) Valve setting

(*iii*) Speed regulation (*iv*) Over speed trip setting

(*v*) Running balance.

Steam condition is determined by pressure gauge, and thermometer where steam is super heated. The acceptance test as ordinarily performed is a check on (*a*) Output, (*b*) Steam rate or heat consumption, (*c*) Speed regulation, (*d*) Over speed trip setting.

Periodic checks for thermal efficiency and load carrying ability are made. Steam used should be clean. Unclean steam represented by dust carry over from super heater may cause a slow loss of load carrying ability.

Thermal efficiency of steam turbine depends on the following factors :

(*i*) Steam pressure and temperature at throttle valve of turbine.

(*ii*) Exhaust steam pressure and temperature.

(*iii*) Number of bleedings.

Lubricating oil should be changed or cleaned after 4 to 6 months.

3.47.2 Choice of Steam Turbine

The choice of steam turbine depends on the following factors :

(*i*) Capacity of plant

(*ii*) Plant load factor and capacity factor

(*iii*) Thermal efficiency

(*iv*) Reliability

(v) Location of plant with reference to availability of water for condensate.

3.48 Steam Turbine Generators

A generator converts the mechanical shaft energy it receive from the turbine into electrical energy. Steam turbine driven *a.c.* synchronous generators (alternators) are of two or four pole designs.

These are three phase measuring machines offering economic advantages in generation and transmission. Generator losses appearing as heat must be constantly removed to avoid damaging the windings. Large generators have cylindrical rotors with minimum of heat dissipation surface and so they have forced ventilation to remove the heat. Large generators generally use an enclosed system with air or hydrogen coolant. The gas picks up the heat from the generator any gives it up to the circulating water in the heat exchanger.

3.48.1 Steam Turbine Specifications

Steam turbine specifications consist of the following :

(i) Turbine rating. It includes :
- (a) Turbine kilowatts
- (b) Generator kilovolt amperes
- (c) Generator Voltage
- (d) Phases
- (e) Frequency
- (f) Power factor
- (g) Excitor characteristics.

(ii) Steam conditions. It includes the following :
- (a) Initial steam pressure, and Temperature
- (b) Reheat pressure and temperature
- (c) Exhaust pressure.

(iii) Steam extraction arrangement such as automatic or non-automatic extraction.

(iv) Accessories such as stop and throttle valve, tachometer etc.

(v) Governing arrangement.

3.49 Boilers

Boiler is an apparatus used to produce steam. Thermal energy released by combustion of fuel is transferred to water which vaporises and gets converted into steam at the desired pressure and temperature. The steam produced is used for :

(i) producing mechanical work by expanding it in steam engine or steam turbine.

(*ii*) heating the residential and industrial buildings
(*iii*) performing certain processes in the sugar mills, chemical and textile industries.

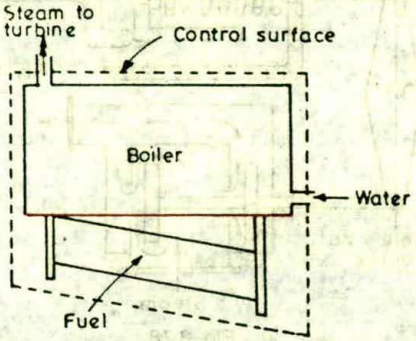


Fig. 3.78 (*a*)

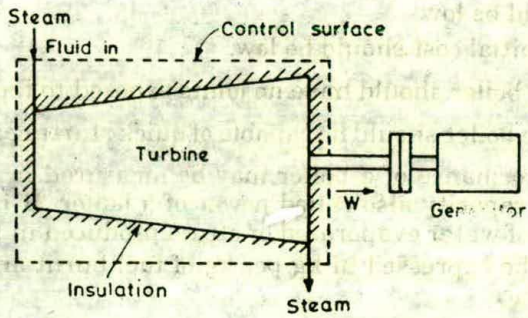


Fig. 3.78 (*b*) Shows flow of steam through the steam turbine.

Boiler is a closed vessel in which water is converted into steam by the application of heat. Usually boilers are coal or oil fired. A boiler should fulfil the following requirements :

(*i*) **Safety.** The boiler should be safe under operating conditions.

(*ii*) **Accessibility.** The various parts of the boiler should be accessible for repair and maintenance.

(*iii*) **Capacity.** The boiler should be capable of supplying steam according to the requirements.

(*iv*) **Efficiency.** To permit efficient operation, the boiler should be able to absorb a maximum amount of heat produced due to burning of fuel in the furnace.

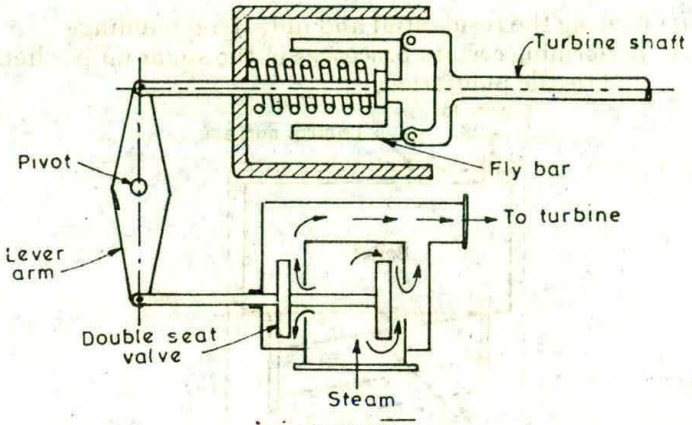


Fig. 3.78.

(*v*) It should be simple in construction and its maintenance cost should be low.

(*vi*) Its initial cost should be low.

(*vii*) The boiler should have no joints exposed to flames.

(*viii*) The boiler should be capable of quick starting and loading.

The performance of a boiler may be measured in terms of its evaporative capacity also called power of a boiler. It is defined as the amount of water evaporated or steam produced in kg per hour. It may also be expressed in kg per kg of fuel burnt or kg/hr/m^2 of heating surface.

3.50 Types of boilers

The boilers can be classified according to the following criteria.

1. According to flow of water and hot gases

(*i*) Water tube. (*ii*) Fire tube.

In water tube boilers, water circulates through the tubes and hot products of combustion flow over these tubes. In fire tube boiler the hot products of combustion pass through the tubes which are surrounded by water. Fire tube boilers have low initial cost, and are more compacts. But they are more likely to explosion, water volume is large and due to poor circulation they cannot meet quickly the change in steam demand. For the same output the outer shell of fire tube boilers is much larger than the shell of water-tube boiler. Water tube boilers require less weight of metal for a given size, are less liable to explosion, produce higher pressure, are accessible and can response quickly to change in steam demand. Tubes and drums of water-tube boilers are smaller than that of firetube boilers and due to smaller size of drum higher pressure can be used easily. Water-

tube boilers require lesser floor space. The efficiency of water-tube boilers is more.

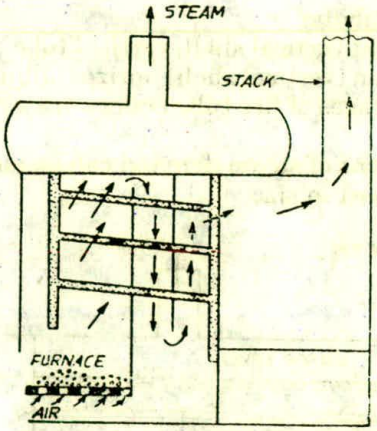


Fig. 3.79

The basic principle of water-tube boiler is shown in Fig. 3.79 and that of fire-tube boiler is shown in Fig. 3.80. Examples of water tube boilers are Babcock and Wilcox and La Mont Boilers whereas Cornish, Locomotive and Cochran Boilers are fire tubes boilers.

Water tube boilers are classified as follows :

1. Horizontal straight tube boilers
   (*a*) Longitudinal drum (*b*) Cross-drum.
2. Bent tube boilers
   (*a*) Two drum (*b*) Three drum
   (*c*) Low head three drum (*d*) Four drum.
3. Cyclone fired boilers

Various advantages of water tube boilers are as follows :

(*i*) High pressure of the order of 140 kg/cm^2 can be obtained.

(*ii*) Heating surface is large. Therefore steam can be generated easily.

(*iii*) Large heating surface can be obtained by use of large number of tubes.

(*iv*) Because of high movement of water in the tubes the rate of heat transfer becomes large resulting into a greater efficiency.

Fire tube boilers are classified as follows :

1. External furnace :
   (*i*) Horizontal return tubular
   (*ii*) Short fire box
   (*iii*) Compact.

2. Internal furnace :
   (*i*) Horizontal tubular
      (*a*) Short fire box (*b*) Locomotive (*c*) Compact (*d*) Scotch.
   (*ii*) Vertical tubular
      (*a*) Straight vertical shell, vertical tube
      (*b*) Cochran (vertical shell) horizontal tube.

Various advantages of fire tube boilers are as follows :
   (*i*) Low cost
   (*ii*) Fluctuations of steam demand can be met easily
   (*iii*) It is compact in size.

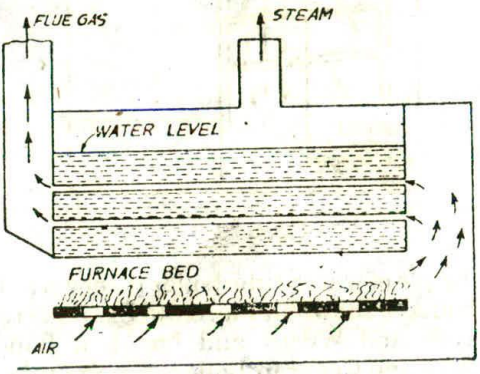


Fig. 3.80

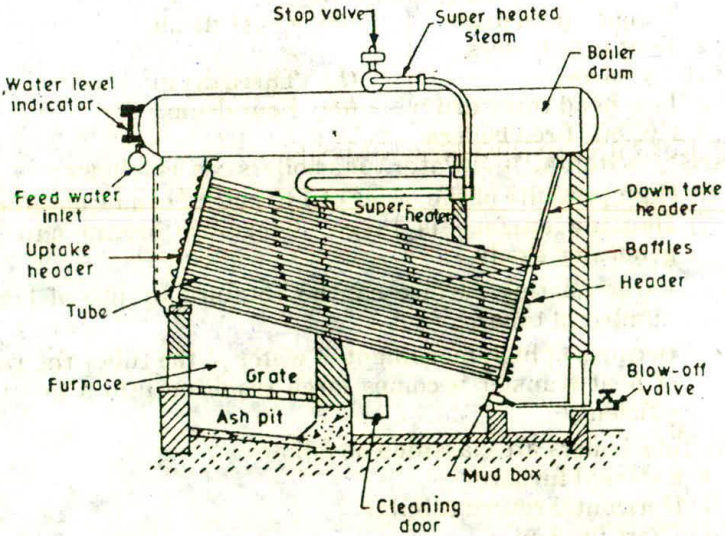


Fig. 3.81

The disadvantages of fire tube boilers are as follows :

(*i*) The steam obtained is generally wet.

(*ii*) Larger steam pressures can not be obtained. These boilers can produce a maximum pressure of about 17 kg/cm^2.

(*iii*) More time is needed to generate steam. The output of the boiler is also limited.

3.50 (*a*) Babcock and Wilcox Boiler

Fig. 3.81 shows a Babcock and Wilcox boiler. It is a water tube boiler. It consists of a drum, super heater, headers, tubes etc. The headers are inter-connected by means of tubes which form the real heating element of the boiler. The fuel is burnt on the grate and hot gases of combustion pass over the tubes and heat the water circulating through the tubes. The baffles provide a zig-zag path for the flue gases. The boiler is fitted with various mounting and accessories. The hot water and steam rise up through the uptake header into the boiler shell where steam separates from water and collects in the steam space. The cold water flows down into the tubes through the downtake header. Superheater is used to superheat the steam. The superheated steam can be taken out to the steam stop valve. Any sediment or mud in water gets collected in mud box and is blown off from time to time through the blow off valve.

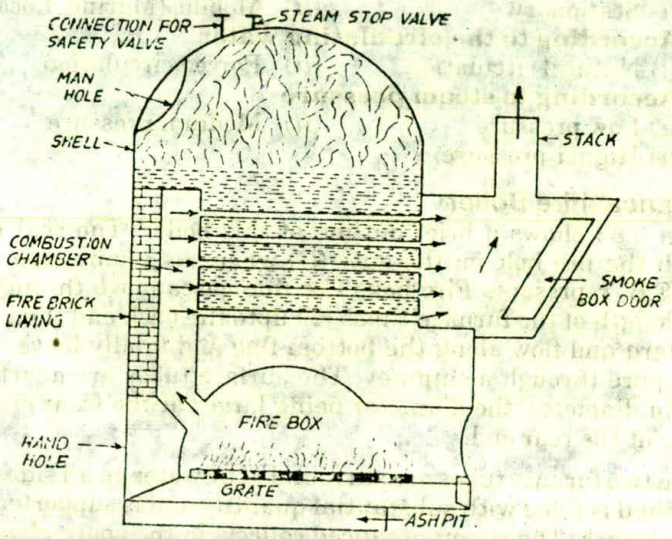


Fig. 3.82

3.50 (*b*) Cochran Boiler

A brief outline of this boiler is shown in Fig. 3.82. The coal burns on the grate inside the fire box. The flue gases after passing through

the combustion chamber make their way through the fire tubes. The gases heat the water and convert it into steam which collects in steam space, and can be taken out through steam stop valve. The flue gases escape to the atmosphere after passing through smoke box and stack. Man-hole is provided to clean the boiler when necessary. A fire brick lining is provided to prevent the shell from being damaged. It is a vertical type boiler, requires lesser space and is quite compact in design. In such boilers the ratio of heating surface to great area ranges between 10 to about 25 and steam can be produced upto a pressure of 10 kg/cm^2. This boiler is made in size upto about 2.743 metres diameter and 5.791 metres height and the maximum evaporative capacity from and at 100°C is 4730 kg per hour.

2. According to position of furnace

(*i*) Internally fired (*ii*) Externally fired

In internally fired boilers the grate combustion chamber are enclosed within the boiler shell whereas in case of extremely fired boilers and furnace and grate are separated from the boiler shell.

3. According to the position of principle axis

(*i*) Vertical (*ii*) Horizontal

(*iii*) Inclined.

4. According to application

(*i*) Stationary (*ii*) Mobile, (Marine, Locomotive).

5. According to the circulating water

(*i*) Natural circulation (*ii*) Forced circulation.

6. According to steam pressure

(*i*) Low pressure (*ii*) Medium pressure

(*iii*) Higher pressure.

3.51 Lancashire Boiler

Fig. 3.83 shows a brief outline of this boiler. The coal is fed through the fire hole on the gate (*G*) where its combustion takes place. F.B. represents Fire-box. The flue gases move through the entire length of the furnace tubes (*T*) upto the back end then move downward and flow along the bottom flue and finally leave to the atmosphere through a chimney. The surface tubes are nearly one metre in diameter, the diameter being larger at the front end and smaller at the rear end.

The two furnace tubes are surrounded by water on all sides. The boiler shell is filled with substantial quantity and is supported over the brickwork. The steam produced collects in the space above the water level. Blow cock (B.C.) is provided to empty the boiler so that repairing, inspection or cleaning can be carried out when desired. Such boilers are generally constructed for working pressure upto 17.5 kg/cm^2 and evaporation capacity of 8300 kg hour.

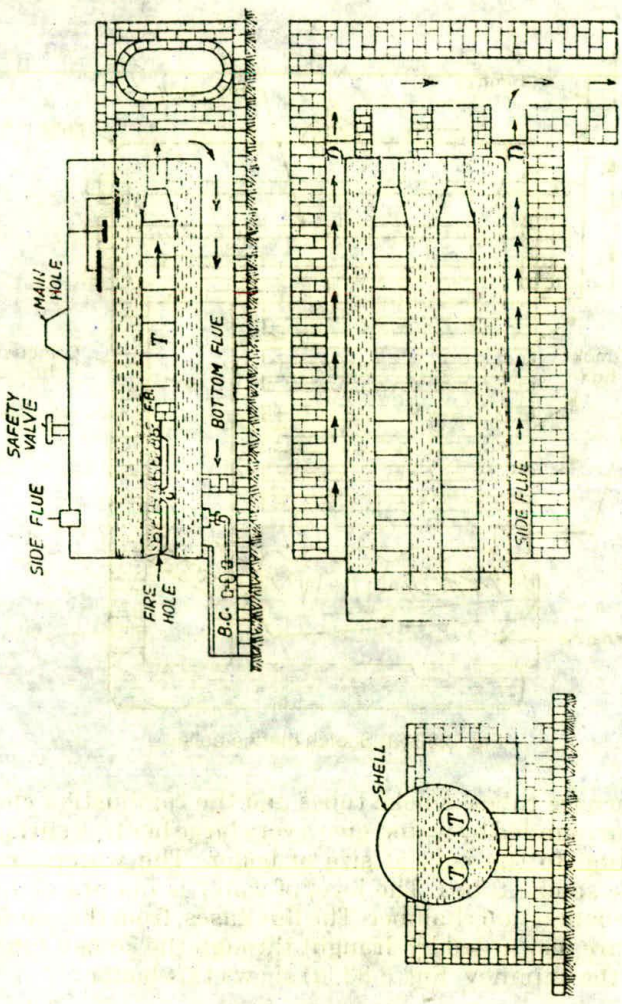


Fig. 3.83.

3.51 (*a*) Scotch marine boiler

It is a fire tube boiler. It is compact, more efficient and has the ability to use any type of water. These boilers may be

(*i*) single ended

and (*ii*) double ended.

Single ended boiler as shown in Fig. 3.83 (*a*) may have one to four furnaces. A single ended boiler has a length up to 3.5 metres whereas double ended boiler many up to 6.5 metre long.

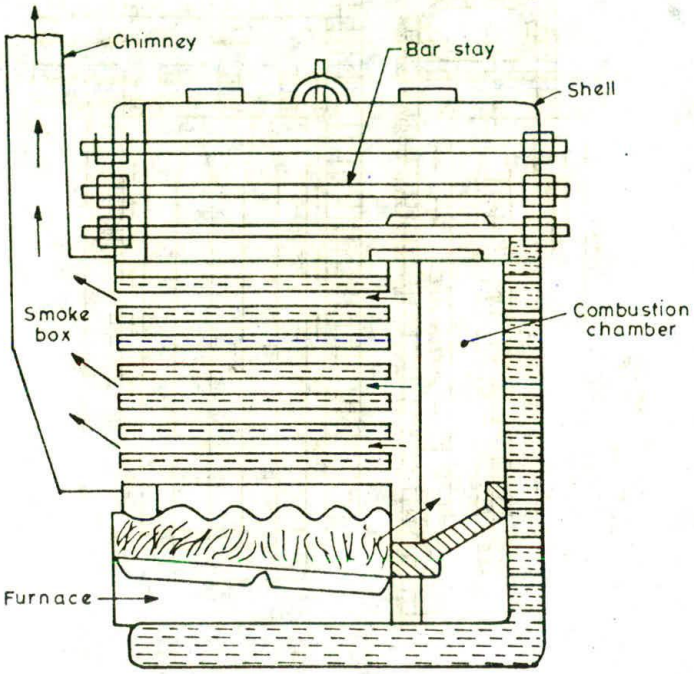


Fig. 3.83 (*a*) Scotch marine boiler.

The furnace tubes, smoke tubes and the combustion chamber, all being surrounded by water, give a very large heating surface area in proportion to the cubical size of boiler. The water circulates around the smoke tubes. The level of water is maintained a little above the combustion chamber. The flue gases, from the combustion chamber, are forwarded by draught through the smoke tubes, and finally up the chimney. Fig. 3.83 (*a*) shows this boiler.

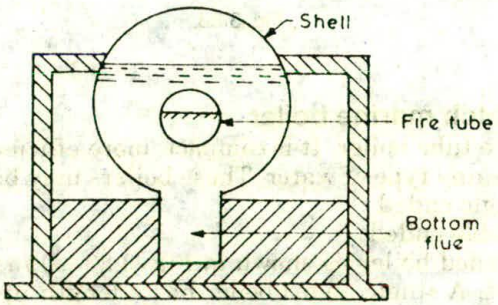


Fig. 3.83 (*b*) Cornish boiler.

3.51 (*b*) Cornish Boiler

Fig. 3.83 (*b*) shows this boiler. Its construction is similar to Lancashire boiler. It is a fire tube boiler. It has only one flue tube as compared to Lancashire boiler which has two flue tubes. The diameter of flue tube may be about 0.6 times that of shell. The diameter of boiler may be 1 to 2 m and length 5 to 7.5 metre. As compared to Lancashire boiler the capacity of cornish boiler is less.

3.52 Boiler Mountings and Accessories

Mountings are the components used for the safety of boiler. The boiler requires the following mountings a feed check valve to prevent the return of water from boiler in base the feed pump is not operating, a steam stop valve to regulate the flow of steam from the boiler, safety valve (at least two) to protect the boiler from pressures higher than the designed value, a blow off valve to empty the boiler when needed and to discharge the mud and sediments that collect in the boiler, water level indicators to show the water level inside the boiler, a pressure gauge to indicate the pressure of steam in the boiler, fusible plugs to protect the boiler against low water level.

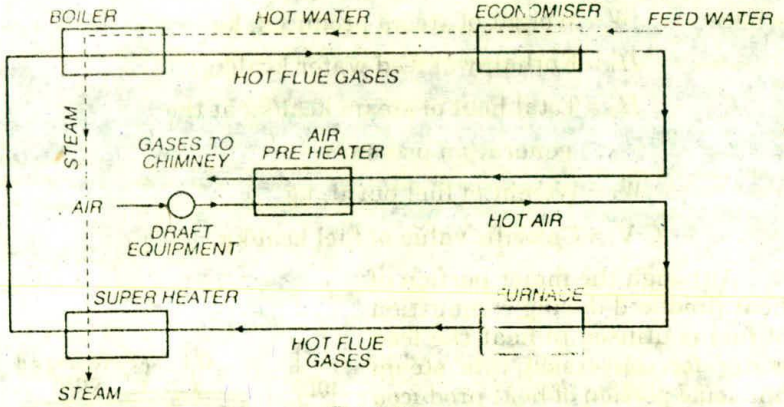


Fig. 3.84

Boiler accessories are used to operate it efficiently. The various accessories used are as follows : feed pumps to supply water in the boiler economisers to heat the feed water before it enters the boiler, air pre-heaters, to heat the air before it enters the furnace, super-heaters to heat the steam above saturation temperature, and draft equipment to supply air to furnace.

3.53 Flue Gas and Water Flow

Fig. 3.84 shows the flue gas flow and feed waterflow. Steam flow in boiler unit. The heat of flue gases is utilised in heating the feed water in economiser and also in heating the air to be supplied to boiler furnace.

3.54 Causes of Heat Loss in Boilers

The various causes of heat loss in a boiler are as follows :

(*i*) Loss due to heat carried away in chimney gases.

(*ii*) Loss due to incomplete combustion of fuel. This can be due to insufficient air supply or fuel bed being in poor conditions.

(*iii*) Loss due to moisture formed by combustion of hydrogen in fuel.

(*iv*) Loss due to moisture in coal.

(*v*) Loss due to radiation and convection from boiler.

(*vi*) Heat loss due to unburnt fuel which is passed on to the ash pit.

3.55 Thermal Efficiency of Boiler

Thermal efficiency of a boiler is defined as the ratio of heat actually utilised by water in generation of steam to the heat supplied during combustion of fuel.

$$\eta_{Boiler} = \frac{W\,(H_2 - H_1)}{W_1 \times CV}$$

where W = Weight of steam produced, kg

H_1 = Enthalpy of feed water kcal/kg

H_2 = Total heat of steam kcal/kg at the generation pressure

W_1 = Weight of fuel burnt, kg

C.V. = Calorific value of fuel kcal/kg.

Although the major portion of heat produced during combustion of fuel is utilised to heat the feed water for conversion into steam but some portion of heat produced is lost in flue gases leaving the chimney and some amount of heat is lost due to radiation from furnace to the outside. The boiler efficiency is nearly 75% without heat recovery equipment and it varies from 85 to 90% with heat recovery equipment.

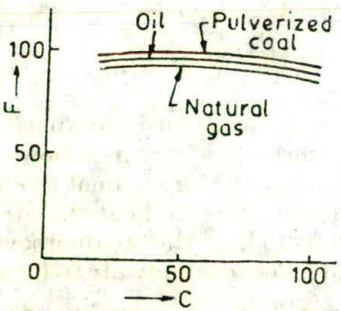


Fig. 3.85.

Boiler efficiency can be improved by taking into account the following factors :

(*i*) Proper supervision should be carried out.

(*ii*) Too much excessive air should not be supplied.

(*iii*) Boiler, superheater, economiser and air heater surfaces should be cleaned at proper intervals.

(*iv*) Type of fuel used also controls boiler efficiency. Fig. 3.85 compares the performance in burning bituminous coal, oil or natural gas in the boiler.

Efficiency (η) indicates steam generating unit efficiency and C represents per cent of rated capacity.

(*v*) Proper supply of excess air.

(*vi*) Minimising combustible in refuse.

(*vii*) Minimising combustible in flue gas.

(*viii*) Maintaining required cleanliness of heat transfer surfaces.

Efficiency of a boiler depends on the following factors :

(*i*) Steam pressure

(*ii*) Calorific value of fuel

(*iii*) Effectiveness in burning of fuel.

Indication of the effective burning of fuel is given by the percentage of carbon dioxide (CO_2) in the flue gases. The percentage of C Q to give maximum efficiency and satisfactory operation will depend on :

(*a*) type of fuel such as oil, gas, coal.

(*b*) method of firing.

(*iv*) Capacity of boilers

(*v*) Use of heat recovery apparatus such as air preheater, economiser etc.

3.56 Boiler Performance

The performance of a steam boiler may be expressed in terms of the following :

(*i*) Heat release per cubic metre of furnace volume.

(*ii*) Efficiency.

(*iii*) Heat transferred per square metre of the heating surface area per hour.

(*iv*) Rate of combustion in kcal per square metre of the grate area per hour for solid fuel.

(*v*) Amount (kg) of steam produced per hour.

3.56.1 Selection of Fuel for Boiler

In choosing the fuel for boiler the following economic considerations are important :

(*i*) Plant efficiency

(*ii*) Cost of fuel per billion killocalories

(*iii*) Cost of fuel burning equipment.

(*iv*) Operation and maintenance cost of fuel burning equipment and heat absorbing apparatus.

(*v*) Cost of fuel preparation and storage equipment.

(*vi*) Fuel transportation cost.

3.56.2 Equivalent Evaporation

To compare evaporative capacity or performance of different boilers working under different conditions it is desirable 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 requires 2257 kJ to get converted to steam at 100°C.

Therefore equivalent evaporation is defined as the amount of water evaporated from water at 100°C to dry and saturated steam at 100°C. However (*i*) the evaporation rate of boiler may also be expressed in terms of kg of steam per kg of fuel.

(*ii*) The capacity of a boiler may also be expressed in terms of total heat added per hour.

Factor of evaporation (Fe)

It is defined as follows

$$Fe = \frac{H_1}{H_2}$$

where H_1 = Heat received by 1 kg of water under working conditions.

H_2 = Heat received by one kg of water evaporated from and at 100°C.

Heat losses in a boiler plant

The heat losses which may take place in a boiler plant are as follows :

(*i*) heat loss due to incomplete combustion of fuel

(*ii*) heat loss due to unburnt fuel

(*iii*) convection and radiation heat loss

(*iv*) heat lost in flue gases.

3.57 Boiler Trial

Steam is generated in boilers under certain conditions of inlet water and exist steam while a certain rate of fuel is being burnt. In order to study the performance of boiler the experiments are conducted by operating the boiler for a certain length of time and recording the data. This procedure is known as boiler trial. A heat

balance sheet is prepared which indicates the heat supplied, heat utilised through various sources and heat wasted.

The main objects of boiler trial are as follows :

(*i*) To determine the thermal efficiency of the boiler when working at a definite pressure.

(*ii*) To draw up heat balance sheet for the boiler to check the performance of the boiler.

Example 3.8. *Determine the boiler efficiency if the boiler generate 20,000 kg of steam at 10.2 kg/cm^2 dry and saturated. The amount of coal used is 2100 kg and the calorific value of coal is 8600 kcal/kg. The feed water temperature is 105°C.*

Solution. Total heat of steam at 10.2 kg/cm^2

$$= 664 \text{ kcal/kg}$$

$$\eta_{Boiler} = \frac{23{,}000\,(664 - 105)}{2100 \times 8600} = 0.71$$

$$= 71\%. \quad \textbf{Ans.}$$

3.58 Boiler Maintenance

Regular maintenance and careful supervision of working of various components of boiler result in the efficient operation of the boiler. The various factors which should be carefully observed for the proper maintenance of the boiler are as follows :

1. The combustion equipment should be so adjusted that the temperature in the furnace does not exceed the designed value. The air supply to the furnace should be in correct proportion.
2. The water level in the boiler should not be allowed to fall beyond the minimum level.
3. The temperature should change slowly and uniformly in the various parts of the boiler. Rapid changes in temperature cause unequal expansion.
4. The water used for steam generation should be free from scale forming impurities because the scale if deposited on tube and boiler shell does not allow the heat transfer to take place effectively and sometimes causes over heating of tubes and boiler shell which may result in tubes failure and boiler explosion.
5. Soot and ash deposited in tubes on gas side should be removed regularly.
6. Bearings of pumps, stokers, pulverisers and fans etc. should be lubricated regularly.

7. At least once in a year the internal inspection of boiler is necessary. The boiler should be inspected for corrosion, cracks, leaks and other irregularities.
8. Piping system, joints and valves should be checked for leakage.

3.59 Control and Measuring Instruments

The various control and measuring instruments provided in a boiler are as follows :

(*i*) Steam flow metres.
(*ii*) Thermometers showing temperature of gas, steam and water.
(*iii*) Draught meters.
(*iv*) Devices to analyse flue gases.

3.59.1 Soot blowers

In a system power plant the heating surfaces of boilers especially coal fired water tube boiler have a tendency to become coated with a layer of soot, cinder and flyash. This loosely adhering layer does not allow the heat transfer to take place properly and should be removed after it has built up sufficiently to result in a significant increase in flue gas temperature. Soot blower is used to remove this layer of soot, cinder and flyash.

Soot blowers should be operated frequently enough to keep the tubes clean.

3.60 Circulation of Water in Boilers

Reliable circulation of water in the boiler is essential for proper boiler design. Circulation means continuous flow of water in a closed circuit designed to create continuous motion of the steam and water in the boiler and intensively heat from the heating surface. Heat transfer rate is improved and boiler walls are protected from chemical destruction by continuous motion of water as it washes of the bubbles of steam from the heating surface. Circulation of water in boiler is carried out in two ways :

(*i*) Natured circulation. (*ii*) Forced circulation.

Natural circulation of water is on the different densities of water and steam and water mixture. Fig. 3.85 (*a*) shows the simplest natural circulation arrangement consisting of a drum, a header and two pipes. As heat is supplied the steam starts forming in left hand pipe. The steam and water mixture rises and separates into steam and water, steam accumulating in the drum above water. The amount of steam produced in the right hand pipe is small also and formation of steam is less intensive. Due to this reason the density of steam and water mixture in right hand pipe will be greater than in left hand pipe and therefore a continuous flow of water from right hand pipe to left hand pipe, will take place.

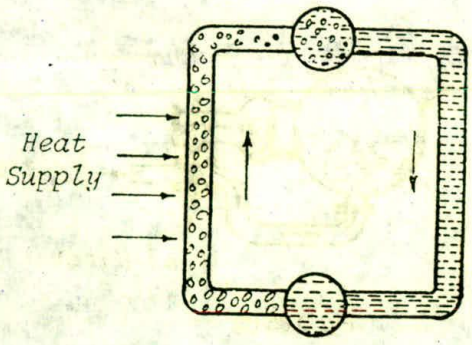


Fig. 3.85 (*a*)

In forced circulation of water pumps are used to maintain the continuous flow of water in the boiler. The relation between the amount of water passing through a circulation circuit in a definite time and the amount of steam generated in the circuit during the same time is called circulation ratio. The value of circulation ratio varies from 8 to 50 in natural circulation water tube boilers. Boilers with natural circulation arrangement require larger diameter tubes and also natural circulation system does not ensure safe and reliable operation. Boilers with forced circulation require smaller diameter tubes thereby reducing the weight of boiler. The system is helpful in giving the most rational shape to the boiler, providing the required rate of circulation and in such boilers circulation ratio is small.

3.61 Feed Water Regulators

Water, fuel and air are the three variables entering into the production of steam in boiler. It is necessary that feed water should flow into the boiler almost as rapidly as steam flows out. Maintaining a fixed water level is not advisable. Every change in load on boiler must be met with a change in feed water input. Feed water regulation should be automatic as it cannot be done successfully by hand.

The commonly used feed-water regulators are of following types :

(*i*) Float type (*ii*) Vapour pressure type

(*iii*) Thermostatic expansion type.

Fig. 3.85 (*b*) shows a float type feed water regulator. This regulator has a float chamber piped to boiler drum. It is installed opposite the normal water level of the boiler so that level can be duplicated in the float chamber. With the change in level the motion of float mechanically opens or closes a balanced regulating valve in feed water line.

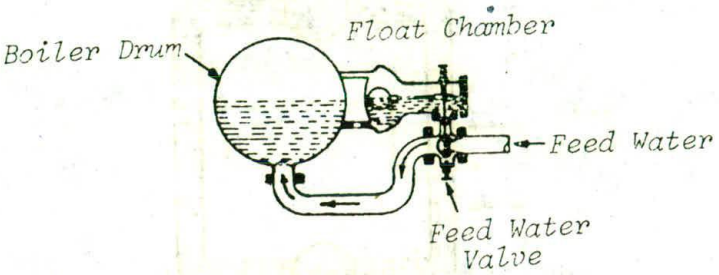


Fig. 3.85 (*b*)

3.62 High Pressure Boiler

The present tendency is towards the use of high pressure boilers. The boiler pressures have reached as high as 250 kg/cm^2 and steam temperature 550°C. By using high pressure boilers, low grade fuels can be burnt easily, a saving in costly construction material can be achieved and a higher efficiency is possible. High pressure boilers are water-tube boilers, use pulverised coal firing and in such boilers furnace walls are water cooled and water tubes from the walls of the furnace. They use slag type furnace.

3.62.1 Unique features of high pressure boilers

The high pressure boilers possess special features which make them more advantageous. The unique features are as follows.

1. **Method of water circulation.** In these boilers water circulation is maintained with the help of pump which forces the water through the boiler plant. However sub-critical boilers may use natural circulation.

Circulation by a pump ensures :

(*i*) ensures positive circulation

(*ii*) increases evaporative capacity of the boiler

and (*iii*) less number of drums will be required.

2. **Type of tubing.** These boilers generally use several set of tubings through which water passes. This arrangement helps

(*i*) to reduce the pressure loss

and (*ii*) to achieve better control over the quality of the steam.

3. **Improved method of heating.** In high pressure boilers following improved methods of heating may be used to increase the heat transfer rate.

(*i*) To save heat by evaporation of water above critical pressure of the steam.

(*ii*) To heat water by mixing the superheated steam. It gives high heat transfer coefficient.

(*iii*) To use high water velocity inside the tubes and to increase gas velocity above sonic velocity. This will increase over all heat transfer coefficient.

3.62.2 Advantages

The various features (advantages) of such boilers which make them useful are as follows :

(*i*) In high pressure boilers pump 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.

(*ii*) The heat of combustion is utilised more efficiently by the use of small diameter tube in large number and in multiple circuit.

(*iii*) Pressurised combustion is used which increases rate of firing of fuel thus increasing the rate of heat release.

(*iv*) Due to compactness less floor space is required.

(*v*) It is economical to use high pressure and high temperature steam produced by such boilers.

(*vi*) All the parts are uniformly heated, therefore, the danger of over heating is reduced.

(*vii*) The efficiency of the plant is increased to about 40%.

3.63 Types of High Pressure Boilers

The various types of high pressure boilers commonly used are as follow :

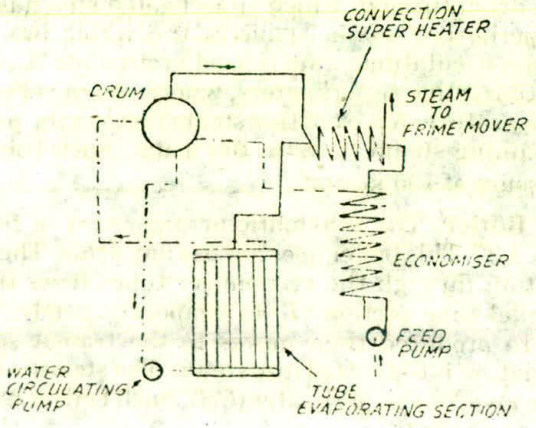


Fig. 3.85 (*c*)

(*i*) La Mont Boiler (*ii*) Loeffler Boiler
(*iii*) Benson Boiler (*iv*) Velox Boiler.

La Mont Boiler. Fig. 3.85 (*c*) shows the schematic arrangement of the boiler. Feed water from hot well is supplied to the separating drum (boiler) through the economiser. Water circulating pump maintains the forced circulation of water through the tubes in evaporation section. The steam produced flows to the drum. Dry steam from the top of drum is then passed through a convection superheater and the superheated steam flows to the turbine. This type of boiler has a working pressure of 170 kg/cm^2.

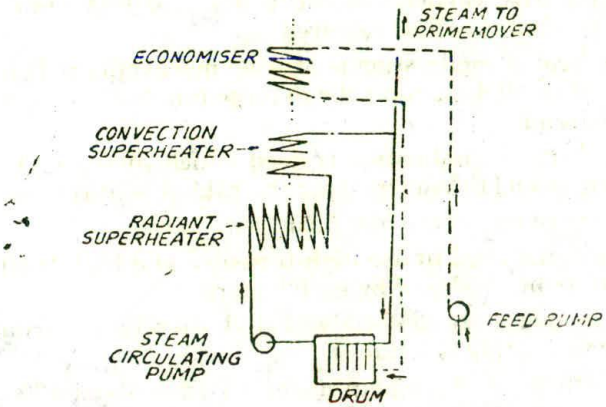


Fig. 3.86

Loeffler Boiler. In this boiler (Fig. 3.86) the drum is placed away from the furnace. Feed water passing through the economiser moves to the drum through which superheated steam is also passing. The superheated steam converts the water into saturated steam. A steam circulating pump is used to circulate steam through radiant and convective superheaters, where steam is heated to the required temperature. A part of this steam flows to the prime mover and the remaining steam flows to the drum. Such boilers have a working pressure of 135 kg/cm^2.

Benson Boiler. The schematic arrangement of the boiler is shown in Fig. 3.87. This boiler does not use any drum. The feed water after circulating through the economiser tubes flows through the radiant parallel tube section (*T*) to evaporate partly. The steam water mixture produced then moves to the transit section (*TS*) where this mixture is converted into steam. The steam is now passed through the convection superheater (*CS*). Such boilers have a working pressure of 230 kg/cm^2.

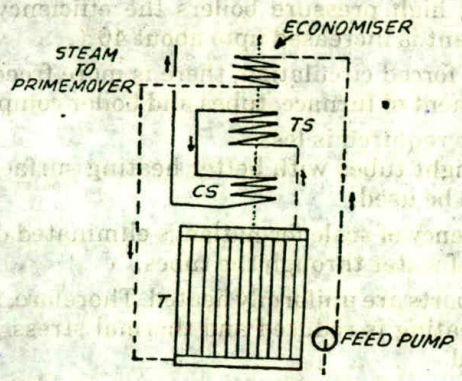


Fig. 3.87

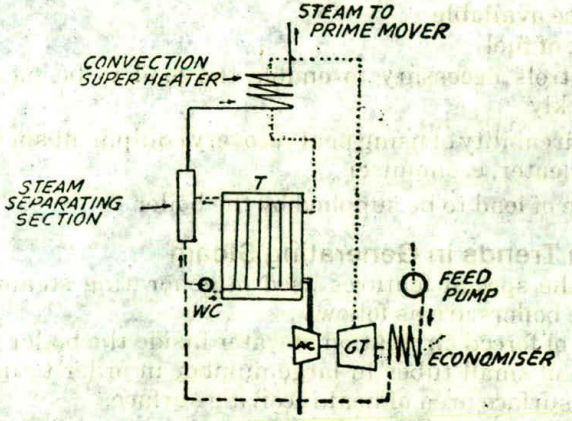


Fig. 3.88

Velox Boiler. In this boiler (Fig. 3.88) pressurised combustion is used. The axial flow compressor (*AC*) driven by gas turbine (*GT*) raises the incoming air from atmospheric 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 (*WC*) to the tube evaporating section (*T*). Steam separated in steam separating section flows to the superheater.

This boiler can generate a pressure of about 84 kg/cm^2.

3.63.1 (*a*) Advantages of High Pressure Boilers

The various advantages of high pressure boilers are as follows :

(*i*) The steam can be raised quickly to meet the variable load.
(*ii*) By using high pressure boilers the efficiency of steam power plant is increased upto about 40%.
(*iii*) By using forced circulation, there is more freedom in the arrangement of furnace, tubes and boiler components.
(*iv*) The space required is less.
(*v*) Light weight tubes with better heating surface arrangement can be used.
(*vi*) The tendency of scale formation is eliminated due to high velocity of water through the tubes.
(*vii*) Various parts are uniformly heated. Therefore, the danger of overheating is reduced and thermal stress problem is simplified.

3.63.2 Selection of boiler

Selection of boiler depends upon the following factors :
(*i*) Type of fuel
(*ii*) Space available
(*iii*) Cost of fuel
(*iv*) Controls necessary to enable the load to be picked up quickly
(*v*) Desireability of using heat recovery equipment such as air preheater, economiser
(*vi*) Type of load to be supplied by the boiler.

3,64 Modern Trends in Generating Steam

Some of the special features used in generating steam using high pressure boilers are as follows :
(*i*) Use of forced circulation of water inside the boiler.
(*ii*) Use of small tubes in large number in order to increase the surface area of heat receiving surface.
(*iii*) Treating the feed water thoroughly before use.
(*iv*) Use of multiple tubes circuits.
(*v*) Use of pressurised combustion.
(*vi*) Use of superheaters.

The process of steam generation can be divided into three stages namely
(*i*) heating of water upto boiling point
(*ii*) evaporation of boiling water and its conversion into dry saturated steam,
(*iii*) transformation of dry saturated steam into superheated steam.

These stages are shown on temperature (T) and heat input (h) diagram (see Fig. 3.88 (*a*)). At point 1 the ice is heated. As point 2, ice starts melting. At point 3 entire ice has melted. Further heating

causes water to boil at point 4. At point 5 the saturated steam is obtained. The steam is thin super heated as shown at point 6. Use of super heated steam in steam engines and steam turbines raises the efficiency.

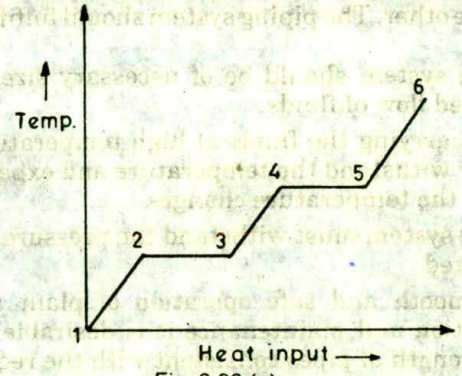


Fig. 3.88 (*a*)

3.65 Gas Fired Boilers

Industrial gases like coal gas, producer gas, blast furnace gas and sewage gas are also used in firing steam boilers. Where such gases are available in abundance, their use proves very economical. Gas fired boilers have the following advantages :

(*i*) Gases can be burnt with low excess air resulting in higher efficiency.

(*ii*) Storage of fuel (gases) is not required.

(*iii*) As no ash is produced, therefore, problem of ash disposal is eliminated.

(*iv*) It is a clean system of firing as soot and smoke produced as almost negligible.

(*v*) The system does not require higher chimney.

3.65.1 Selection of boiler (steam generator)

Boiler is used to supply steam to the turbine. While selecting a boiler the following points should be considered.

(*i*) Type of load.

(*ii*) Amount and type of fuel to be burnt.

(*iii*) Space available for boiler installation.

(*iv*) Cost of boiler.

The cost of boiler depends upon the following factors :

(*a*) Operating pressure.

(*b*) Operating temperature.

(*c*) Method of firing.

(*d*) Type of boiler—Generally water tube boilers are used in central power plants.

(*e*) Efficiency of boiler.

(*f*) Amount of steam to be generated.

3.66 Piping System

Piping system is an essential part of steam power plant. It is employed to transit water, steam, air, oil and vapour from one-place equipment to the other. The piping system should fulfil the following requirements :

(*i*) Piping system should be of necessary size to carry the required flow of fluids.

(*ii*) Pipes carrying the fluids at high temperature should be able to withstand the temperature and expansion caused due to the temperature changes.

(*iii*) Piping system must withstand the pressure to which it is subjected.

(*iv*) For smooth and safe operation of plant and for easy inspection and maintenance it is desirable to use minimum length of pipes consistent with the requirements of the power station. Also a pipe should be run as direct and straight as possible. The number of fitting and bends required to make the necessary connections should be kept at a minimum to avoid pressure drop.

(*v*) The piping system used for steam should be installed in such a way that horizontal runs must slope in the direction of steam flow with steam traps at all points where water may accumulate to make it easy to drain the same and to prevent air accumulation of water during steam flow.

3.67 Types of Piping System

A power plant uses many fluids like water, steam, air, oil, gas etc. during its operation. This requires a variety of integrated piping systems mentioned as follows :

(*i*) Steam piping—raw water, feed water, condensate and condenser cooling water.

(*ii*) Steam piping—Main, reheat, bleed exhaust steam.

(*iii*) Blow of piping—Boiler, evaporator, feed treatment.

(*iv*) Miscellaneous piping—Water treatment, service water, lubricating oil drains compressed air etc.

Brackets attached to the building columns and hangers suspended from beams usually support piping in a power plant.

3.68 Size and Strength of Pipe

The size of the pipe depends upon the velocity of fluid in the pipe and the internal pressure of fluid and thermal expansion limitations.

Wrought iron and mild steel pipes used for different pressures are graded as follows :

1. Standard.
2. Extra heavy or extra strong.
3. Double extra heavy or double extra strong.

Pipes up to 12 inch (300 mm) diameter are designated by their nominal inside diameter and pipes above 300 mm diameter are specified by their outside diameter.

Various codes and standards specify minimum pipe diamensions and materials to meet certain requirements. The codes should be consulted for allowable stress values. They depend on temperature and vary for different types of steel. Pipe diameter affects the fluid speed for a given mass flow rate. High temperature steam in piping has the following effects :

(*i*) It decreases allowable stress.
(*ii*) It accelerates oxidation and corrosion.
(*iii*) It produces expansion.
(*iv*) It makes the pipe material creep.

3.69 Insulation

The pipes carrying the fluids at high temperature should be properly insulated to avoid heat loss to the surroundings. The insulating material should have low co-efficient of thermal conductivity. It should not damage the pipe material and should be able to resist the temperature to which it is subjected. It should be easily moulded and applied and have the requisite mechanical strength.

High temperature line can be effectively insulated by 85% magnesia block in varying thickness depending upon the temperature. The various materials in common use 85% magnesia, asbestos fibre, cork, hair felt, mineral wool, glass wool, expanded, mica etc. 85% magnesia contains 85% carbonate of magnesium and 15% binder and is used for temperature upto 325°C. Asbestos blankets can be used upto 500°C. Mineral wool can be used up to temperatures of 875°C. Mineral wool is made by blowing steam through fused clay lime stone of furnace slag to fibrise it. Expanded mica, hair felt and cork can be used up to 125°C. Glass wool can be used upto temperatures of 350°C. It is made by blowing steam through streams of molten glass.

3.70 Material for Pipes

The various materials used for the pipes are as follows :

(*i*) **Cast Iron.** Cast iron pipes are used underground for water and drainage systems and in other places where problem of corrosion is excessive. Cast iron pipes are used for water services upto a pressure of 15 kg/cm^2.

(*ii*) **Wrought Iron.** Pipes made up of wrought iron are used for condensate, feed water and blow off lines. Such pipes are used for

low and medium pressure range and should not be used when pressure is more than 250 p.s.i.

(*iii*) **Wrought Steel.** Most of the pipes used in power station are made up of wrought steel. Wrought steel pipes are cheaper.

(*iv*) **Alloys Steel.** For high temperature flows pipes are made up of alloy steel.

Chromium steel pipes are used for temperature higher than 525°C. For temperatures between 400°–525°C carbon molybdenum steel may be used.

(*v*) **Copper and Brass.** Pipes made up of copper and brass are costly and are mostly used for oil lines. Brass pipes are used upto pressure 20 kg/cm^2.

3.71 Expansion Bends

In order to allow for the expansion in pipes due to temperature changes, expansion bends are used in pipe lines. The various types of expansion bends used are shown in Fig. 3.89.

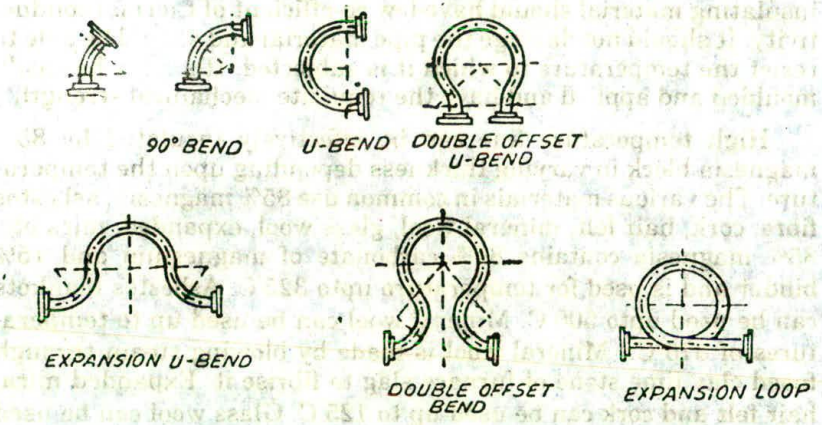


Fig. 3.89

3.72 Pipe Fittings

Joint fittings are necessary to assemble piping system and make connections. Fittings are made in variety of forms such as screwed or welded fittings which are generally used in sizes upto 90 mm whereas flanged or welded fittings are used for large sizes of pipes. The various fittings include elbows, bend, tees, crosses, plugs bushings and reducers. Fig. 3.90 shows various fittings.

Elbow is used to change the direction of two pipes which it connects. Tee is used for joining two pipes running in the same

direction and having an outlet for a branch pipe. Plugs and caps are used to close the ends of fittings and pipes. Reducers are used to join pipes of different sizes.

Fittings made up of cast iron, malleable iron, steel, steel alloys and brass are in common use. The materials used for fittings depend on service as regards pressure and temperature.

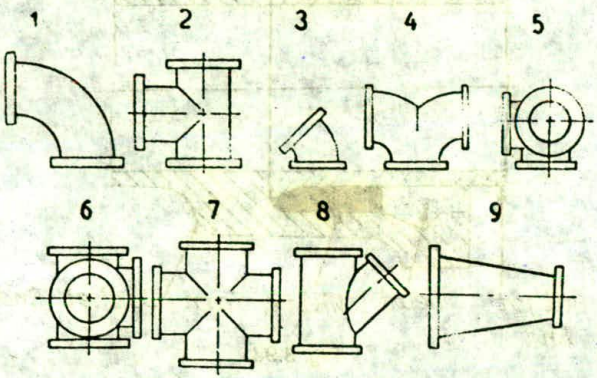


Fig. 3.90

In Fig. 3.90 various fittings shown are as follows :

1. Elbow (90°)
2. Tee
3. Elbow (45°)
4. Double branch elbow
5. Side outlet elbow
6. Side outlet Tee
7. Cross
8. Lateral
9. Reducer.

3.73 Pipe Joints

Various types of pipe joints are screwed joint (Fig. 3.91), welded joint (Fig. 3.92), socket and spigot joint (Fig. 3.[illegible]), expansion joint (Fig. 3.94) and flanged joint. Flanged fittings are generally used for larger size of pipe and for high temperature and high pressure work.

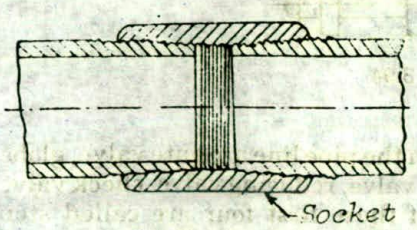


Fig. 3.91

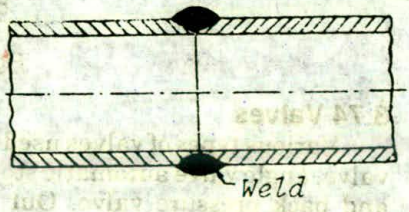


Fig. 3.92

The selection of type of pipe joint depends upon the following factors :

(*i*) Size of pipe.

(*ii*) Pressure and temperature of fluid inside the pipe.
(*iii*) Initial cost.
(*iv*) Ease of removal of sections between joints.
(*v*) Future maintenance.

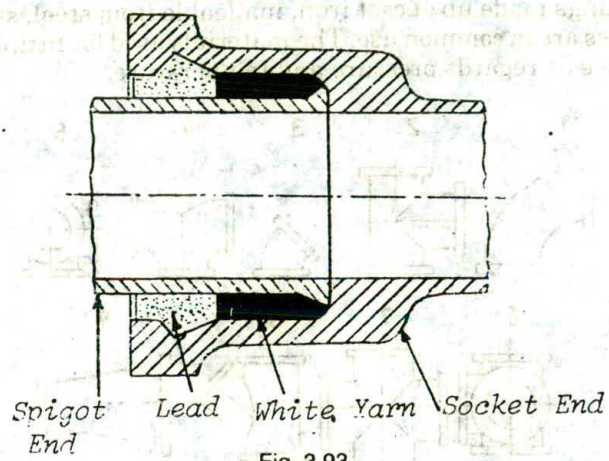


Fig. 3.93

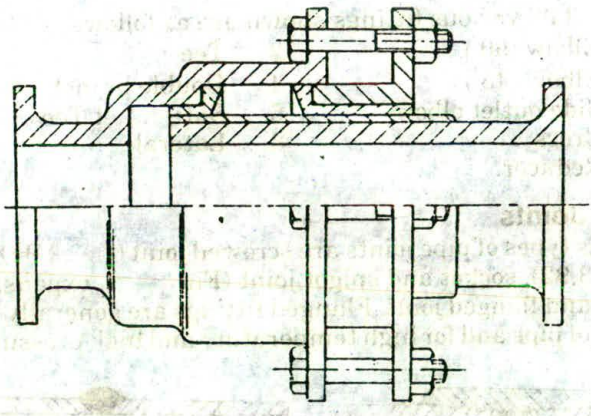


Fig. 3.94

3.74 Valves

Various types of valves used in the pipe line are gate valve, globe valve, angle valve automatic stop valve, reducing valve, check valve and back pressure valve. Out of these first four are called stop valves. They are used to stop the flow of fluids. The function of reducing valve is to change pressure in a steam line. Check valve permits flow in one direction only. Back pressure valve is used in

connection with the exhaust piping of an engine to permit undue rise in pressure.

Small size valve upto 75 mm are usually made up of brass. Material used in valve of larger size is either cast iron or cast steel or forged steel. Brass is used for valve seats, discs and spindles of valve used for steam or water.

3.75 Principles of Steam Power Plant Design

The essential principles of steam power plant design are as follows :

(*i*) Low capital cost
(*ii*) Reliability
(*iii*) Low operating and maintenance cost
(*iv*) High thermal efficiency
(*v*) Accessibility
(*vi*) A simple design.

The power plant should be designed such that it can be expanded if required. It should be simple in design. Use of automatic equipment is desired to reduce the labour cost. Heat recovery devices should be used wherever possible. Total capacity of the plant should be subdivided into four or five generating units so that during reduced load periods some of the units may be stopped.

3.76 Factors Affecting Steam Plant Design

The various factors which affect the design of a steam power plant are as follows :

(*i*) Steam pressure and temperature
(*ii*) Capacity of power plant
(*iii*) Ratings of generating units
(*iv*) Thermodynamic cycle
(*v*) Voltage generation.

The trend is towards using higher pressure and temperatures of steam. This improves the thermal efficiency. The capacity of the plant can be determined by studying the load duration curve and anticipated future load demand. The size of turbo-generator depends on the following :

(*i*) Rate of growth of load.
(*ii*) Availability of condensing water.
(*iii*) Space available.

Larger size turbo generator sets should be used.

The voltage of generation is usually 11 kV; though 22 kV and 33 kV are also used. In central power plants water tube boilers are commonly used. The type of fuel used in a boiler will influence the design and efficiency of the boiler plant considerably.

The steam power plant needs a lot of space for (*a*) storing the fuel (*b*) elaborated arrangements for fuel handling (*c*) ash handling

(*d*) lay out of high-pressure boilers (*e*) steam turbines (*f*) generators (*g*) control switch boards (*h*) cooling water arrangements.

In steam power plant the A.C. generators are driven by turbines with condensing arrangement at a high vacuum of about 73.6 cm: Hg. The size of the generating set may vary between 10 MW to 500 MW or even higher. Modern generators are 2 pole with 3000 R.P.M. as speed and 50 cycles per second as frequency.

3.77 Site Selection

The various factors to be considered while selecting the site for steam power plant are as follows :

(*i*) **Distance from coal mines.** Steam power plant should be situated near the coal mines so that cost of transportation of coal is low. If the plant cannot be located near coal fields the plant in such case should be connected by rail or road to the coal mines so that transportation of coal is easy.

(*ii*) **Distance from load centre.** The power plant should be located near the load centre so that the cost of transmission lines and losses occurring in them are less.

(*iii*) **Availability of water.** Water should be available in large quantities. If water available is pure it will be useful because impure water needs purification. The water required is about 560×10^3 kg of every one tonne of coal burnt.

(*iv*) **Ash disposal.** Near to power station site, large space should be available for the ash disposal.

(*v*) **Distance from popular area.** Smoke and other gases produced due to combustion of coal pollute the atmosphere. Therefore, the plant should be situated, as far as possible, away from the densely populated area.

(*vi*) The site selected should be capable of supporting a large building and heavy machinery.

3.77.1 Controls at steam power plant

Generally the electric load on power plant varies in an irregular manner. The control provided at a power plant help in meeting the variable load successfully. Controls for the following are provided at a steam power plant to run the plant smoothly.

(*i*) Fuel
(*ii*) Air
(*iii*) Feed water
(*iv*) Steam
(*v*) Ash
(*vi*) Flue gases
(*vii*) Furnace temperature
(*viii*) Condenser cooling water.

3.77.2 Feed water control

The supply of feed water depends upon the plant load. Some of the automatic method used to control feed water flow are as follows :

(*i*) Single element pilot operated system
(*ii*) Single element self operated system
(*iii*) Two element pilot-operated system
(*iv*) Three element pilot-operated system.

Fig. 3.94 (*a*) shows a single element pilot operated feed water control system. This allows manual correction of water level with flow variation. In this system the water level recorder (R) operates an air pilot valve which through a relay and indicator (P) controls the feed water regulating valve.

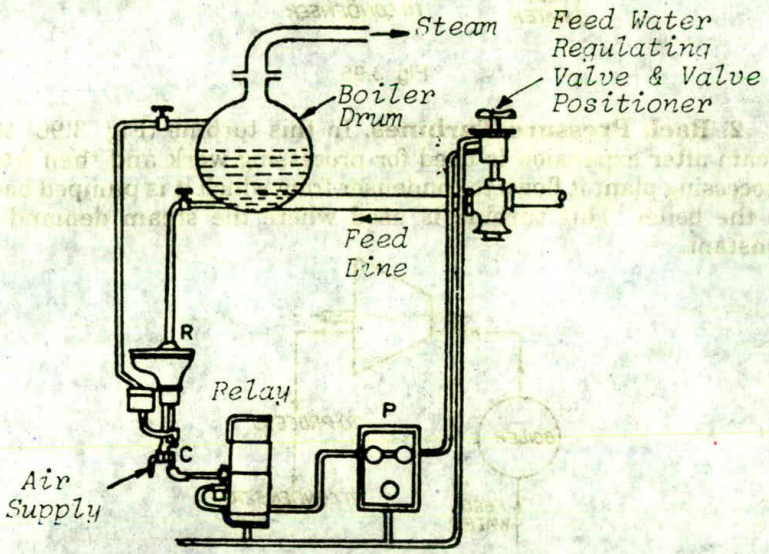


Fig. 3.94 (*a*).

The pilot valve (C) can be automatically reset and this makes it possible to hold boiler drum level constant at all rates of steam flow. Pilot valve's manual adjustment allows lowering the water level at low load and *vice versa*.

3.78 Industrial Steam Turbines

These turbines in addition to power generation supply some steam for manufacturing processes that (steam) would otherwise be wasted. Some such turbines are as follows :

1. Pass Out or Extraction Turbines. In these turbines (Fig. 3.95) the high pressure steam from the boiler enters the High

Pressure (H.P.) stage where it expands. A part of the steam leaving the high pressure stage is utilised for some processing work such as feed water heating, paper making, dyeing etc. Remaining steam enters low pressure stage and expands there and finally goes to condenser. This turbine is capable to meet variations in steam demands.

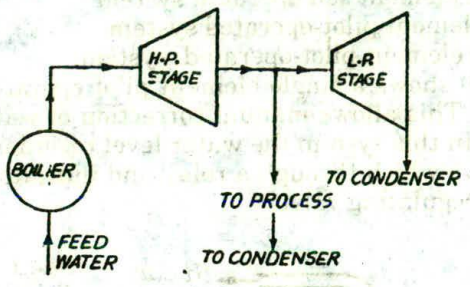


Fig. 3.95

2. Back Pressure Turbines. In this turbine (Fig. 3.96) the steam after expansion is used for processing work and then from processing plant it flows to condenser from which it is pumped back to the boiler. This turbine is used where the steam demand is constant.

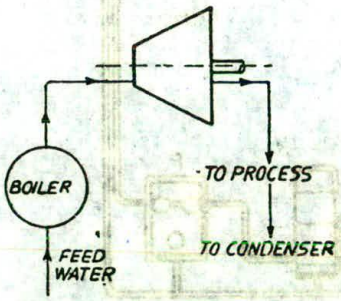


Fig. 3.96

3. Exhaust Turbine. In this turbine the steam leaving the steam engine enters the turbine where it expands thus further utilizing the steam leaving the engine which (steam) would otherwise be wasted. Fig. 3.97 shows such air arrangement.

4. Mixed Pressure Turbines. Sometimes in rolling mills and colliery engines the waste steam is intermittent and the pressure of exhaust steam in intermediate between turbine inlet steam pressure and that of turbine exhaust steam. The exhaust steam and

main steam enter the turbine where steam expands. Fig. 3.98 shows such turbine arrangement.

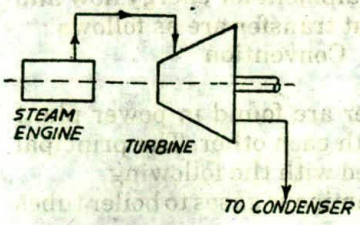


Fig. 3.97

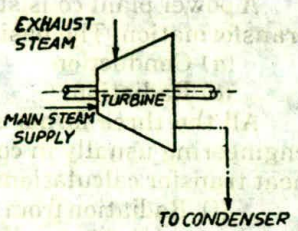


Fig. 3.98

Fig. 3.98 (*a*) shows the use of industrial steam turbines to apply process steam and generate by product power. C_1 and C_2 are the condensers and P_1 and P_2 are the condenser pumps.

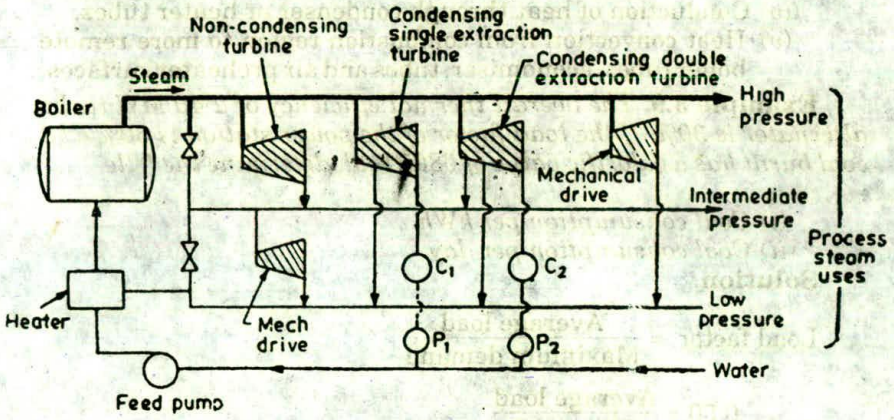


Fig. 3.98 (*a*)

3.79 Overall Thermal Efficiency

The overall efficiency of steam power plant depends upon the efficiency of boiler, turbine and alternator. The heat produced due to the burning of coal is not fully utilised for generating electrical energy because there are heat losses in the boiler turbine and mechanical and electrical losses in the turbine. The overall thermal efficiency of steam power station is given by the following relation :

$$\eta = \frac{H}{W \times \text{C.V.}}$$

η = Overall efficiency

where H = Heat equivalent per kWh.

W = Amount of coal consumed per kWh.

C.V. = Calorific value of coal.

3.80 Heat Flow

A power plant consists mainly of equipment for energy flow and transformation. The basic modes of heat transfer are as follows :

(*a*) Conduction (*b*) Convention

(*c*) Radiation.

All the three forms of heat transfer are found in power plant engineering usually in combination with each other. The principal heat transfer calculations are associated with the following :

(*i*) Radiation from fuel bed and luminous gases to boiler tubes and water walls.

(*ii*) Radiation and conduction in heat insulators like refractories and pipe coverings.

(*iii*) Conduction of heat through boiler, economiser and air preheater surfaces.

(*iv*) Conduction of heat through condenser or heater tubes.

(*v*) Heat convection from combustion region to more remote boiler tubes, economiser, tubes and air preheater surfaces.

Example 3.9. *The overall thermal efficiency of a 40 MW turbo alternator is 30%. If the load factor of the power station is 50% and coal burnt has a calorific value of 6800 kcal, determine the follo*

:

(*i*) *Coal consumption per kWh.*

(*ii*) *Coal consumption per day.*

Solution.

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$0.50 = \frac{\text{Average load}}{40 \times 1000}$$

assuming maximum demand equal to capacity of the power station.

$$\text{Average load} = 0.5 \times 40 \times 1000 = 20{,}000 \text{ kW}$$

$$\text{Energy produced per day} = \text{Average load} \times 24$$

$$= 20{,}000 \times 24 = 48 \times 10^4 \text{ kWh.}$$

Overall thermal efficiency

$$= \frac{860}{W \times 8600}$$

W = Coal consumption per kWh.

$\therefore$ (1 kWh = 860 kcal)

$$0.3 = \frac{860}{W \times 8600}$$

$$\therefore \quad W = \frac{860}{0.3 \times 8600} = 0.42 \text{ kg.} \quad \textbf{Ans.}$$

Coal required per day

$$= \text{Energy produced} \times W$$

$$= 48 \times 10^4 \times 0.42 \text{ kg.}$$

$$= \frac{48 \times 10^4 \times 0.42}{1000} \text{ tonnes}$$

$$= 201 \text{ tonnes.} \quad \textbf{Ans.}$$

Example 3.10. *In a steam power station the coal consumption is 0.4 kg per kWh output. If the calorific value of coal is 6800 kcal per kg, boiler efficiency is 70% and mechanical and electrical efficiency of alternator is 90%. Prepare roughly the heat balance sheet for the power station.*

Solution.

Let output = 1 kWh

$\therefore$ Heat input $= 0.4 \times 6100 = 2720$ kcal.

Electrical energy input $= \frac{2720}{860} = 3.16$ kWh

Losses. (*i*) Boiler house loss

$$= 3.16 \times 0.3 = 0.948$$

(as boiler efficiency is 70%).

Heat output of steam $= 3.16 - 0.948 = 2.212$ kWh.

Input to alternator $= \frac{1}{0.90} = 1.11$ kWh.

(*ii*) Loss in alternator

$= 1.11 - 1 = 0.11$ kWh.

(*iii*) Loss in turbine $= 2.212 - 1.11 = 1.102$ kWh.

This loss may be considered as rejected to cooling water.

Hence, output = 1 kWh.

Loss in boiler = 0.948 kWh.

Loss in alternator = 0.11 kWh.

Loss in turbine = 1.102 kWh.

Total $= 1 + 0.948 + 0.11 + 1.102 = 3.61$ kWh.

Example 3.11. *The daily output of a steam power station is 18×10^5 kWh. If the coal consumption is 700 tonnes per day, calculate the thermal efficiency of power station.*

Assume calorific value of coal 8500 kcal/kg.

Solution. Coal used $= 700 \times 1000$ kg.

Energy input per day $= 700 \times 1000 \times 8500 \times 595 = 10^7$ kcal

Energy output per day

$$= 18 \times 10^5 \text{ kWh}$$

$$= 18 \times 10^5 \times 860 \text{ kcal.}$$

(as 1 kWh = 860 kcal).

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{18 \times 10^5 \times 860}{595 \times 10^7} = 26\%.$$

3.81 Cost of Steam Power Plant

In recent days vast improvements have been made in generating electric power from steam. About 0.45 kg of coal is needed to produce 1 kWh of energy. It is observed that larger capacity power plants can utilise the thermal energy more efficiently than the smaller capacity plant. In the design of a thermal power station future availability of coal and its price has to be taken into account.

A steam power station may cost about Rs. 1600 per kW of capacity. A typical sub-division of investment cost of a steam power station is as follows :

(*i*) Turbo-generators and condensers —25%
(*ii*) Load building and foundations —25%
(*iii*) Boiler plant —18%
(*iv*) Fuel handling —6%
(*v*) Piping —5%
(*vi*) Switch yard, switching and wiring —16%
(*vii*) Miscellaneous —5%

The investment cost includes the following costs :

(*i*) Cost of land (*ii*) Cost of building (*iii*) Cost of mechanical and electrical equipment and their installation.

Conditions affecting the investment depend on a number of factors :

(*a*) Characteristics of the site.
(*b*) Size and number of power generating units.
(*c*) Fuel storing and fuel handling methods.

3.82 Heat Balance Sheet for Boiler

It indicates the heat supplied, heat utilised through various sources and heat wasted.

Prepare the heat balance sheet for a boiler having the following data :

Steam pressure	= 13 kg/cm^2
Water evaporated	= 300,000 kg
Coal fired	= 30,000 kg
Superheat temperature	= 300°C
Air temperature	
(*a*) To air preheater	= 45°C
(*b*) From air preheater	= 90°C
Feed water temperature	
(*a*) To economiser	= 50°C
(*b*) Form economiser	= 120°C
Flue gas exit temperature	= 115°C
Boiler house temperature	= 25°C
Mean specific heat of the flue gases	= 0.25
Coal analysis (as fired)	
	C = 64% ; H_2 = 4.5%
	O_2 = 5.5% ; H_2 = 1.5%
	S = 0.7% ;
Ash	= 9.8%
Total moisture	= 14%
Calorific value of coal	= 6800 kcal/kg
Duration of trial	= 8 hours

Flue gas (dry) analysis

CO_2 = 12.6%; CO = 0.4%

O_2 = 6% ; N_2 = 81.1%.

Solution. (*i*) **To find weight of water evaporated.**

Let W = Actual weight of dry flue gas per kg of coal

$$W = \frac{11CO_2 + 8O_2 + 7\,(CO + N_2)}{3\,(CO_2 + CO)} \times \left(C + \frac{S}{1.83}\right)$$

$$= \frac{11 \times 12.5 + 8 \times 6 + 7\,(0.4 + 81.1)}{3\,(125 + 0.4)} \times \left(0.64 + \frac{0.007}{1.83}\right)$$

= 12.6 kg

W_1 = Total weight of flue gas per kg of coal

= Actual weight of dry flue gas

+ Moisture evaporated from coal

+ Water produced from H

$= 12.6 + 0.14 + 9\ (0.045) = 13.14$ kg.

Now ash content = 9.8%

W_2 = Weight of fuel burnt

$\therefore \quad = 1 - 0.098 = 0.902$

W_3 = Weight of air supplied per kg of coal fired

$W_3 = W_1 - W_2 = 13.14 - 0.902 = 12.238$ kg

W_4 = Weight of water evaporated per kg of fuel fired

$$= \frac{300{,}000}{30{,}000} = 10 \text{ kg.}$$

(*ii*) **To Calculate Heat Absorbed :**

H_1 = Heat absorbed by air preheater per kg of coal fired

= Weight of air × Temperature rise × Specific heat

$= W_2 \times (90 - 45) \times 0.24$

$= 12.238 \times 45 \times 0.24 = 132$ kg cal.

H_2 = Heat absorbed by boiler

= Weight of water evaporated per kg of coal × (Total heat in 1 kg of steam − Heat in feed water − Heat in air)

$= 10\ [666 - (120 - 0) - 132]$

$= 4140$ kg cal.

H_3 = Heat absorbed by economiser

= Weight of water evaporated × Temperature rise

$= 10\ [120 - 50] = 700$ kg cal.

H_4 = Heat absorbed by superheater

= Weight of water evaporated × [Super heat temperature − saturated temperature] × Specific heat

$= 10\ [300 - 190] \times 0.5$

$= 10 \times 110 \times 0.5 = 550$ kcal.

(*iii*) **To Calculate Heat Lost :**

H_5 = Heat lost in dry flue gases

= Weight of dry flue gases per kg of coal

× Temperature rise × Specific heat

$= W \times (115 - 25) \times 0.25$

$= 12.6 \times 90 \times 0.25 = 283.6$ kg cal

H_6 = Heat loss due to moisture in fuel

$= w\,(100 - t) + L + k\,(T - 100)$

where w is the weight of moisture evaporated from coal

$= 0.14\,[(100 \times 25) + 539 + (115 + 100) \times 0.47]$

= 16 kg cal

(Assuming specific heat as 0.47)

H_7 = Heat lost due to water formed by

combustion of hydrogen

$= 9H\,[(100 - t) + L + k\,(T - 100)]$

where H is weight of hydrogen per kg of fuel, t is the atmospheric temperature, T is exist gas temperature and k is the specific heat of steam and L is latent heat of evaporation

$= 9 \times 0.045\,[(100 - 25) + 539 + (115 - 102) \times 0.47]$

$= 0.4 \times 621 = 248.4$ kg cal

H_8 = Heat lost due to incomplete combustion of carbon

$$= C \times C.V. \left(\frac{CO}{CO + CO_2} \right)$$

where C is the weight of carbon per kg of fuel, and CO and CO_2 represent the per cent of volume of carbon monoxide and carbon dioxide in flue gases respectively and C.V. is the calorific value of coal

$$= 0.64 \times 6800 \left[\frac{0.4}{12.6 \times 0.4} \right] = 130 \text{ kg cal}$$

H_9 = Heat unaccounted for losses

$= 6800 - [H_1 + H_2 + H_3 + H_4 + H_5 + H_6 + H_7 + H_8]$

$= 6800 - 6170 = 630$ kcal.

Example 3.12. *A boiler with maximum continuous steam rating of* 1.2×10^5 *kg per hour is fired with bituminous coal having 10% moisture and 10% ash and a higher calorific value of 7500 kcal per*

kg. If it takes 1000 kcal to evaporate 1 kg of feed water entering the boiler and superheat it to final temperature and if overall efficiency of boiler is 80% determine the following :

(i) Hourly coal supply.

(ii) Grate length of building dimensions limit grate width to 6 metre. Given that the maximum heat produced is 3×10^6 kcal per square metre per hour.

Solution. H = Heat required to convert water into steam

$$= 1.2 \times 10^5 \times 1000 = 1.2 \times 10^8 \text{ kcal per hour}$$

Efficiency (η) or boiler = 0.8

Heat to be produced by the fuel $= \frac{H}{0.8}$

$$H_1 = \frac{1.2}{0.8} \times 10^8$$

$$H_1 = 1.5 \times 10^8 \text{ kcal per hour}$$

Coal required $= \frac{1.5 \times 10^8}{7500}$ kg $= \frac{1.5 \times 10^8}{7500 \times 10^3}$ tonnes

$= 20$ tonnes per hour

Grate area $= \frac{H}{3 \times 10^6} = \frac{1.5 \times 10^8}{3 \times 10^6} = 50$ square metres

Grate length $= \frac{50}{6} = 8.33$ metres. **Ans.**

3.83 Useful Life of Components

Approximate useful life of some of the components of a steam power plant are mentioned in Table 3.2

Table 3.2

Component	*Life (years)*
(*i*) Boiler (Water tube)	20
(*ii*) Coal and ash machinery	10 to 20
(*iii*) Turbines	15 to 20
(*iv*) Condensers	20
(*v*) Turbo-generators	10 to 20
(*vi*) Feed water heater	30
(*vii*) Pumps	15 to 20
(*viii*) Transformers	15 to 20
(*ix*) Motors	20
(*x*) Buildings	50
(*xi*) Air Compressors	20 to 25

3.83.1 Power Plant Pumps

In a steam power plant 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.

Power plant pumps are classified as follows :

Class	*Type*
(*i*) Reciprocating	(*a*) Direct acting (*b*) Power (*a*) Vane
(*ii*) Rotary	(*b*) Screw (*c*) Gear (*d*) Lobe
(*iii*) Centrifugal	(*a*) Volute (*b*) Diffuser (*c*) Axial flow (*d*) Mixed flow

3.84 Plant Layout

Fig. 3.99 shows the layout of power plant. The turbine room should be sufficiently wide to accommodate various auxiliaries. In boiler room enough space should be left for repairs and maintenance. Various equipment should be so placed that access to all the parts is easy.

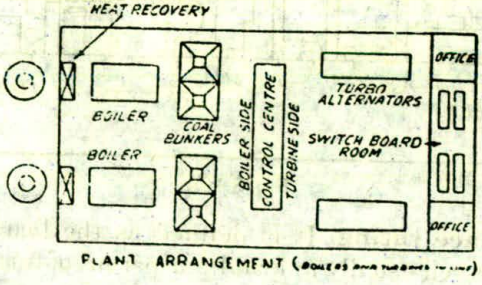


Fig. 3.99

Basic arrangements of various equipments used in power station differ from station to station. The following factors should be considered while installing various components :

1. All similar items such as turbines, boiler, transformers, bunker bays and other mechanical and electrical com-

ponents are arranged in parallel lines and at right angles rows individual boiler, turbo-generator, transformers etc.

2. Chimneys should be erected independently of the station building with chimney serving two or more boilers.
3. Main flue, draft fans and outdoor precipitators should be located behind the boiler house.
4. Circulating water supply, coal supply to bunkers and lifting equipment should be properly placed.
5. Outdoor generator and unit transformers should be in front of the turbine house.

Fig. 3.100 shows the cross-section of a typical station housing of about 60 MW capacity with unit boilers.

3.85 Terms and Definitions

(*i*) **Load Shedding.** Power load on the system in shed if insufficient generating power plant is available to meet the demand for current load.

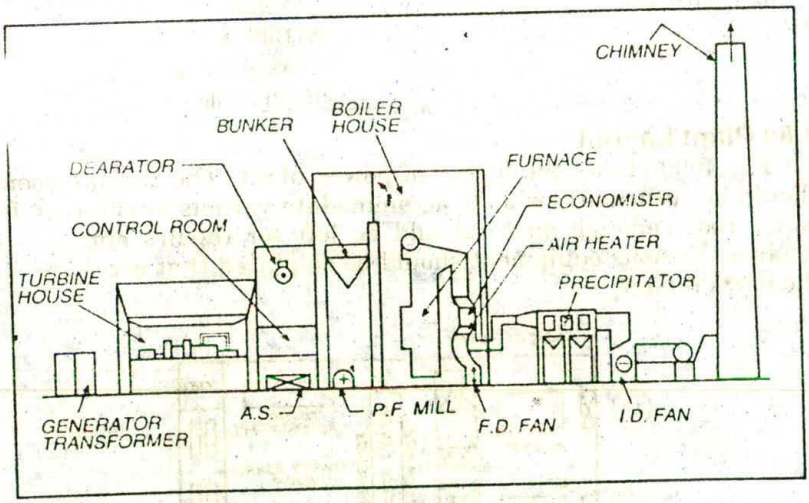


Fig. 3.100

(*ii*) **Furnace rating.** It is defined as the heat input to the furnace expressed usually in kcal/hour per m^3 of furnace volume.

(*iii*) **Lagging.** It is process of applying insulating material to the outer parts of equipment (in which some hot fluid is flowing) to prevent heat loss and distortion due to unequal temperatures.

(*iv*) **Inhibitor.** These are the chemical substances as added to the turbine oil which check or retard the occurrence of undesirable properties.

(*v*) **Grit Arrestor.** It is the device used for removing grit from boiler gases before they flow to chimney. The removal of grit and dust from flue gases is called flue gases treatment.

(*vi*) **Electrostatic Precipitator.** The equipment is used for cleaning boiler flue gases. In this the dust particles of flue gases are electrically attracted to the metal tubes placed in the path of flue gases.

(*vii*) **Feed water.** Water suitable for feeding to a boiler for steam generation.

(*viii*) **Make up Water.** It is the purified water (distilled or chemically treated) for replacing losses from the feed system.

(*ix*) **Raw Water.** It is the unpurified water obtained directly from a natural source. This can be used as boiler water after proper purification.

3.86 Modern Steam Power Station

Central steam power station of larger capacities use higher boiler pressure with super-heated steam as the super heated steam contains more heat energy than saturated steam at the same pressure and provides more energy to the turbine for conversion into electric energy. They use large capacity boilers, and improved methods of coal firing such as stoker firing or pulverised coal firing. The coal used is of good quality as low grade coal such as those having high ash contents (about 18–20% and above) and higher moisture contents (about 30% or more) are not preferred. High ash contents in coal reduce the heating value of coal and more labour is required for the removal of ash from the furnace. Ash with low fusing, or melting temperature forms clinkers when subjected to high temperatures of fuel bed. The clinkers so formed interfere with the movement of fuel on the stokers. The coal to be burnt on hand fired grates and on the stokers should have a minimum of about 4 to 6% of ash. Moisture also reduces the heat value of coal. Coals with 7 to 12% moisture are generally burnt on chain grate and travelling grate stokers. Coal analysis is done to know its composition.

Small size of coal have greater tendency to hold the moisture. Efficient combustion control equipment is used. The shape, size and temperature of the furnace used depends on the type of coal to be burnt, type of burner and its location and type of boiler used. Furnace may be air cooled or water cooled. Induced draft fans and forced draft fans are used to regulate the flow of air to the furnace and for exhaust of flue gases. In larger power stations heat recovery equipment such as economiser and air preheater are used. The flue gases are made to pass through these devices so that some of their heat energy may be recovered by heating feed water in the economiser and air supply to the furnace in the air preheater. For

efficient operation of the plant it is essential that the water to be used in boiler should be free from impurities as improperly treated water causes corrosion and scale formation etc. which may lead to failure of the plant. Circulating and feed pump may be reciprocating or centrifugal type. Multi-stage centrifugal pumps are commonly used for high pressure. Regenerative feed water heating increases the thermal efficiency of the plant. In regenerative feed heating steam is bled from the turbine at different pressure and is used to heat feed water in the feed water heaters. Condensers are used to increase the horse power and efficiency of the plant. Air removal from the condenser is very essential as presence of air in the condenser reduces the heat transfer action in surface condenser. In steam turbine plant using surface condenser the air leakage should not be more than 5 kg for 10000 kg of steam condensed. The main sources of air in the condenser are :

1. Air dissolved in boiler feed water is carried by the steam to the turbine and from there it enters the condenser with exhaust steam.
2. Injection water of jet condensers may bring some amount of air dissolved into it.
3. Air may leak in through the joint; turbine packing gland or exhaust nozzle connections.
4. Condensing water leakage through tubes is another source.

Feed regulator is employed to maintain the level of water in the boiler. In such plants back pressure or extraction turbines are used.

3.87 Ways of Increasing Thermal Efficiency of a Steam Power Plant

The thermal efficiency of a steam power plant can be increased by the following ways :

(*i*) An increase in the initial pressure of steam raises the thermal efficiency.

(*ii*) The thermal efficiency can be increased by raising the initial temperature of the steam without changing the pressure.

(*iii*) Intermediate reheating of steam improves the thermal efficiency of the plant. As already mentioned an increase in the initial pressure of steam improves the thermal efficiency of steam power plant but the wetness fraction of such steam also grows at the end of expansion. The wetness is so high that it causes wear of the blades of the last stages of a steam turbine. This shortcoming is eliminated by intermediate reheating of the steam. The steam from boiler after partial expansion in the first stage

turbine is fed into super heater, where it is reheated at a constant pressure either to the temperature of live steam or to a temperature slightly below that one. The reheated steam then flows to the last stages of the turbine where the process of expansion is completed (Fig. 3.101).

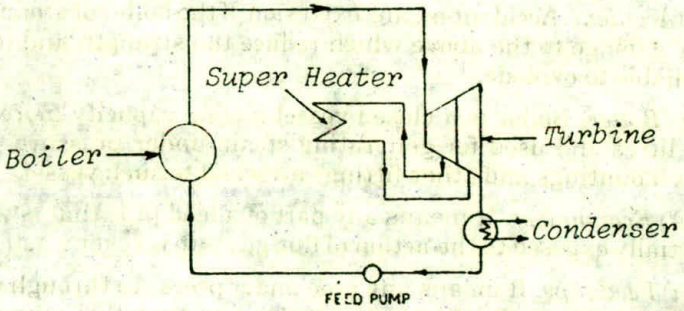


Fig. 3.101

(*iv*) Thermal efficiency of steam power plant can be improved by carrying out regenerative heating of the feed water. Such heating of the water is carried out by using the heat of steam partly tapped from the turbine. In this method (Fig. 3.102) the steam from boiler flows into steam turbine. After partial expansion some of the steam is tapped from the first stage of the turbine and directed to feed water heater and then to feed tank. The remaining steam enters the second stage of the turbine where it continues to expand. At the outlet from the second stage some of the steam is directed into water heater and then to feed tank. The other part of steam goes to the third stage of the turbine and expands there to the final pressure and enters the condenser. The condensate is delivered by pump to feed tank.

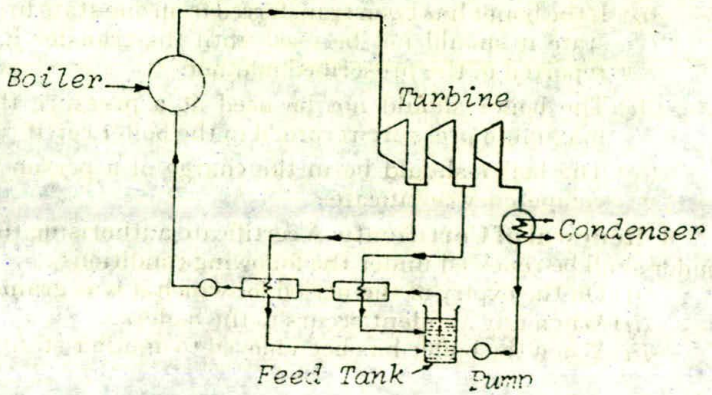


Fig. 3.102

3.88 Indian Boiler Act

The Indian Boiler Act was passed in 1923 and later amended in 1953. Some of its clauses are as follows :

1. **Definitions.** Following are some of the important definitions mentioned in the act :

(*i*) *Accident.* Accident means explosion of the boiler or steam pipe or any damage to the above which reduce the strength and makes them liable to explode.

(*ii*) *Boiler.* Boiler is a closed vessel having capacity more than 22.75 litres and used for generating steam under pressure. It includes mountings and other fittings attached to such vessel.

(*iii*) *Economiser.* It means any part of a feed pipe that is wholly or partially exposed to the action of flue gases to recover waste heat.

(*vi*) *Feed pipe.* It means any pipe under pressure through which feed water passes directly to the boiler and that this pipe is not integral part of the boiler.

(*v*) *Steam pipe.* It is any pipe through which steam passes from the boiler to the prime mover and the steam pressure exceed 3.5 kg/cm^2.

2. **Boiler Registration.** The boiler cannot be fixed unless it has been registered. The owner of the boiler has to apply for the registration of boiler to the chief inspector of the boiler. The inspector will then examine the boiler and submit the report to the chief inspector. If the boiler is approved for registration a certificate is issued to the owner for the use of boiler for a period of 12 months at a given maximum pressure. The boiler registration number is mentioned in the certificate.

3. **Restriction on Use of Boiler.** Restriction on the use of boiler are as follows :

(*i*) No owner of a boiler shall use unless it has been registered.

(*ii*) If the boiler has been transferred from one state to another state it should not be used until the transfer has been reported in the prescribed manner.

(*iii*) The boiler should not be used at a pressure than the maximum pressure recorded in the boiler certificate.

(*iv*) The boiler should be in the charge of a person holding competency certificate.

4. **Renewal of Certificate.** A certificate authorising the use of boiler shall be renewed under the following conditions :

(*i*) On the expiry of the period for which it was granted.

(*ii*) When any accident occurs to the boilers.

(*iii*) When the boiler has been moved to another state.

(*iv*) When any structural alteration, addition or renewal is made in or to the boiler.

(*v*) When the steam pipe or pipes of the boiler are found to be in dangerous conditions.

5. **Transfer of a Boiler.** When a boiler is transferred from one state to another state, the fact is noted in the register. The new owner of the boiler shall apply to the chief inspector of the state in which the boiler is to be installed for the registration of transfer. The chief inspector then obtains the necessary records from the state from which the boiler was transferred. On receipts of the record, entry is made in the registers of inspector and chief inspector.

6. **Report of Accident.** If some accident occurs to the boiler owner or person incharge thereof shall, within 24 hours of accident, inform to the inspector in writing giving full details about it and injuries, if any caused to the boiler or to the steam pipe or to any person. The inspector will then investigate the matter and decide whether the boiler can be reused at the original or reduced pressure without repairs or pending the completion of any repair or alteration. At the time of investigation the inspector can ask questions from any body and every person shall be bound to answer truely to the best of his knowledge and ability.

7. **Repairs of Boiler.** Sanction of the chief inspector should be obtained before taking a repair in hand. However a few water tubes or smoke tubes may in emergency condition be renewed pending the sanction of the chief inspector. Extensive repairs such as renewal of furnace, plate and fire boxes etc. should be carried out under the supervision of the inspector.

8. **Alterations and Renewals to Boilers.** No structural alteration, addition or renewal be made in or to any boiler unless such alterations, additions or renewal have been permitted in writing by the chief inspector.

9. **Penalties**

(*a*) **Minor Penalties.** The Act provides penalties up to Rs. 100 for the following offences :

(*i*) To use a boiler without obtaining certificate or a provisional order.

(*ii*) To refuse to surrender a certificate.

(*iii*) To use a boiler which has been transferred from one state to another state without such transfer having been reported.

(*b*) **Penalties for illegal use of boiler.** If the owner of the boiler runs the boiler without certificate or runs the boiler at a higher pressure than the allowed shall be liable to the fine up to Rs. 500

and in the case of continuing the offence he may be fined further at the rate of Rs. 100 for each day after the first day on which he is convicted of the offence.

(*c*) **Other Penalties.** A person can be fined up to Rs. 500 for the following offences :

(*i*) To use boiler after alterations without informing about such alteration.

(*ii*) To fail to mark the registration number of the boiler.

(*iii*) To make alterations in a boiler or its steam pipe without obtaining prior permissions.

(*iv*) To fail to report any accident to a boiler or steam pipe that might have occurred.

(*v*) To tamper with a safety valve of the boiler having a malafide intention..

(*d*) **Penalty for tempering with registration number**

(*i*) The owner can be fined up to Rs. 500 if he removes, changes, defaces, or renders invisible the registration number of the boiler.

(*ii*) The owner of the boiler can be fined up to two years imprisonment or fined or both if he marks a fraudulent registration number on the boiler.

10. **Boiler Mountings.** The following mountings shall be fitted on the boiler for the safety of the boiler :

(*i*) Safety valve–Two

(*ii*) Water level indicators–Two

(*iii*) Steam pressure gauges–Two

(*iv*) Steam stop valve–one

(*v*) Feed check valve–one

(*vi*) Blow off cock–one

(*vii*) Feed pump–one

(*viii*) Fusible plug–one

(*ix*) Valve after super heater–one

(*x*) For cleaning of boiler manholes, hand holes and sight holes shall be provided as necessary.

11. **Hydraulic Test of Boiler.** Each boiler is tested hydraulically in the presence of the inspector. The hydraulic test pressure is twice the approved working pressure or one and a half times working pressure or one and a half time working pressure plugs 4 kg/cm^2 whichever is less. Each piece before it is fitted in its position is subjected to a hydraulic test at a pressure of the boiler. The boiler drum after welding is subjected to a hydraulic test pressure of one and a half times the working pressure for a time (not less than half an hour) sufficient to inspect various seams and connections. If there

is no leakage the inspector allows to use the boiler up to the working pressure.

3.89 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	Kothagudam	240
2.	Assam	Gauhati	42
3.	Bihar	(*i*) Barauni	145
		(*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	195
		(*ii*) Panipat	220
7.	Madhya Pradesh	(*i*) Korba	420
		(*ii*) Satpura	300
		(*iii*) Amarkantak	180
8.	Maharashtra	(*i*) Nagpur (located at Koradi)	480
		(*ii*) Nasik	280
		(*iii*) Paras	90
9.	Orissa	Talcher	254
10.	Tamil Nadu	(*i*) Neyveli	600
		(*ii*) Ennore	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

3.90 Super Thermal Power Stations

In view of the persisting power crisis in the country and the resulting acute power shortage the Government of India has placed emphasis on constructing large super thermal power stations preferably near mine heads, with ultimate installed capacity of 2000-3000 MW each. The major super thermal power stations planned in the initial stage are Singrauli, Korba, Ramagudam, Neyveli, Talcher and Farakka.

3.90 (*a*) Singrauli Super Thermal Power Plant

The first of these super thermal power station is Singrauli in Mirzapur district in the South East Uttar Pradesh. This station conveniently located near the coal belt thus reducing its dependency on coal transport, one of the biggest bottle-necks in the power generation. The first stage of Singrauli thermal power station foresees installation of 3×200 MW and 2×200 MW turbo alternator sets which will be supplied by BHEL.

There are two units each of 500 MW capacity. The plant has a total capacity of 2000 MW. It will supply power to U.P., Rajasthan, Punjab, Haryana, H.P., and J & K. This project has been executed by National Thermal Power Corporation (NTPC).

3.91 Korba Super Thermal Power Station

This power station will have a total capacity of 2100 WM. The first 200 MW unit of this power station has started generating power from December 1982. The next two units each of 200 MW capacity has been commissioned by the end of 1983, Korba super thermal power station is being constructed by National Thermal Power Corporation (NTPC) near coalpit heads in the central sector. It is located two kilometres down steam of Darri Barrage to the right of right bank canal of the Hasdep river in Katghora Tehsil of Bilaspur district. This power station will supply power to Madhya Pradesh, Maharashtra, West Gujarat and Goa. For transmitting power 1960 km long 400 KV AC transmission lines will be established. In the first phase four transmission lines Korba, Bhillai-I, 15 km long Korba-Korba (West), 190 km long Korba Bhillai-II and 262 km long Bhillai-Koradi will be constructed. About 8 km away from the power station site are the Kusumunda mines which will supply coal for the power station. When the first three 100 MW units of this power station come up they will use up 8000 tonnes of coal per day and when the next three 500 MW units start power generation by December 1988 it will require 2800 tonnes of coal everyday. For transportation of this huge quantity of coal, a completely automatic system called merry-go round rail system will be used.

3.92 Thermal Power Plants Environmental Control

Fuel burnt at thermal power plants contain harmful impurities which are ejected into the environment as gaseous and solid components of combustible products and can adversely affect the atmosphere and water. Toxic substances contained in the flue gases discharge from chimneys of thermal power plants can produce harmful effects on the whole of complex of living nature. The flue gases may contain the following :

(*i*) oxides of carbon and hydrogen.

(*ii*) fly ash.
(*iii*) solid particles of unburnt fuel.
(*iv*) oxides of sulphur and nitrogen.

Thermal power plants consume more than $\frac{1}{3}$ of all the fuels produced and thus can significantly affect the local environment and the whole of bio-sphere comprising the atmospheric layer near the earth's surface and upper layers of soil and water basins. The influence of thermal power plants on the surroundings is determined by following factors :

(*i*) Ejection of the flue gases, heat and contaminated water.
(*ii*) Type of fuel used.
(*iii*) Method of combustion.
(*iv*) Type of furnace used.

The fraction of solid particles carried off from the furnace with the flue gases (K) depends on the type of furnace as indicated below :

Type of Furnace	*K(%)*
Horizontal cyclone furnace	0.1—0.15
Furnace with vertical primary chambers	0.2—0.4
Two chamber furnaces	0.5—0.55
Open furnaces with hydraulic ash disposal	0.7—0.85
Chamber furnaces with dry ash disposal	0.94

(*v*) Devices used for ejection of flue gases into the atmosphere.
(*vi*) Efficiency of dust collecting and gas cleaning plants.

The basic characteristic for calculation of environmental effects of effluents from power generating power plants is the emission of a particular pollutant per unit time. The toxic substances present in the flue gases may have harmful effects on vegetation, animals, people, buildings and structures. For example vegetables are most sensitive to the content of SO_2 gas in the atmosphere. The toxic effect of SO_2 gas is associated with deterioration of the surfaces of leaves. People living in NO_2 contaminated areas suffer from reduced respiratory function, have a higher incidence of respiratory diseases and exhibit certain changes in the peripheric blood.

The environmental control of the atmosphere at thermal power plants is mainly aimed at minimising the discharge of toxic substances into the atmosphere. This will preserve the purity of atmosphere and water basins.

This can be achieved as follows :

(*i*) By decreasing the discharge of solid ash particles. Ash contents of various fuels is different. Modern ash collec-

tors used in steam power plants have a high degree of ash collection and can thus reduce to a great extent the ash particles ejected into the atmosphere.

(*ii*) Contamination of the atmosphere with sulphur oxide can be prevented both by removing sulphur from fuel and applying means to clean the flue gases from sulphurous compounds.

(*iii*) By properly burning the fuel in the furnace so that complete combustion takes place.

(*iv*) The impurities should be diluted to concentrations which can do virtually no harm to both nature and man.

(*v*) By using better quality of fuel.

(*vi*) By selection proper equipment like ash collectors, chimneys etc. and to ensure proper operation of the equipment so that discharge of effluents to the surroundings is minimum.

The control of the atmosphere at thermal power plants is mainly aimed at minimising the discharge of toxic substances into the atmosphere.

3.93 Commissioning of Plants

The present trend is towards the commissioning of entire mechanical section as well as electrical section simultaneously. Commissioning of plant is done in the presence of the representatives of manufacturers. Procedure for commissioning of steam power plants is as follows.

(*i*) **Boiler.** Before putting a new boiler on load it is desirable as per Indian Boilers act to conduct a hydraulic test of the boiler. Hydraulic test for low pressure boilers is carried out at one and half times the rated pressure of the boiler plus 3.3 kg/cm^2. A pressure gauge supplied by the Boiler Inspector is mounted on the boiler. Checks for proper functioning of outlet of steam blow off, water treatment plant, valves etc. are made. A heat balance sheet is prepared to check the performance of boiler.

(*ii*) **Turbine.** Steam is admitted to the turbine to turn it slowly. Turbine speed is then gradually increased with a close watch being kept on bearing temperature until full speed is reached. Adjustments in lubrication system and governing system are made, checks for reading of turbine stage pressures are carried out.

(*iii*) **Condensers.** Exhaust outlet of turbine is connected to the condenser. Various auxiliaries of condenser are checked for proper functioning.

(*iv*) **Coal conveying system.** The coal conveying system should be checked for smooth running and for its capacity to deliver the required quantity of coal.

(*v*) **Circulating water system.** Water distribution system for cooling towers is checked and adjusted for even flow. The service feed water may be put in operation and performance of pumps may be checked for pressures and output.

(*vi*) **Alternators.** The drying out test is carried out until the insulation resistance is steady at constant temperature as specified by the manufacturer. Other tests such as test for insulation of rotor, over voltage test, phase rotation test, testing of exciters, ventilating system etc. are carried out.

(*vii*) Water level floats, alarms, automatic controls and other auxiliary equipment should be checked for proper operation.

(*viii*) Foundations for boiler, turbine condenser alternator etc. should be of proper materials with suitable arrangements for preventing the vibrations.

In our country National Thermal Power Corporation (NTPC) is the largest producer of electric power with a commissioned capacity of about 10335 MW and a transmission net work of more than 16000 circuit kms. till 1991.

NTPC has set up five super thermal power plants namely

(*i*) Singrauli (*ii*) Korba
(*iii*) Ramagundam (*iv*) Vindhachal
(*v*) Rihand

and two gas based combined cycle power plants at

(*i*) Ahta (*ii*) Auraiya

At Farakha stage I of three 200 MW units is completed and work for setting up two 500 MW units is in progress. First unit of 210 MW of National Capital Thermal Power project at Dadri (Ghaziabad, U.P.) has been completed and this power plant when fully commissioned will have a total coal based capacity of 840 MW. The 720 MW Badarpur thermal power plant at New Delhi and 270 MW BALCO captive power plant at Korba in Madhya Pradesh are also being managed by NTPC.

Power generation must be in tune with the times and NTPC is planning to enter Solar Thermal power era. It is presently working on a solar power plant to be located in Rajasthan.

NTPC has adopted numerous new technologies such as

(*i*) High voltage direct current (HVDC) transmission system.
(*ii*) Use of fly ash for construction of dykes.
(*iii*) Distribution digital control system.
(*iv*) Micro-processor based system for boilers and turbines.

(*v*) Combined cycle for gas based power plants.

Environmental planning and preservation of ecological balance continues to be a matter of priority for NTPC. Effluents from power plants are neutralised to ensure that the unacceptable levels of effluents are not discharge into the surrounding eco-system.

Some of the power plants commissioned and managed by NTPC are as follows :

	Power Plant	*Location*	*Capacity (MW)*
1.	Singrauli	Sonebhadra (U.P.)	2000
2.	Korba	Bilaspur (M.P.)	2100
3.	Ramagundam	Karimnagar (A.P.)	2100
4.	Farakka	Murshidabad (W.B.)	600
5.	Rihand	Sonebhadra (U.P.)	1260
6.	Dadri	Ghaziabad (U.P.)	210
7.	Badarpur	New Delhi	720
8.	Balco	Bilaspur (M.P.)	270

Some of the other thermal power plants in construction stage being looked after by NTPC are as follows :

(*i*) Kahalgaon (Bhagalpur, Bihar)
It is a coal based plant.

(*ii*) Talcher (Dhenkanal, Orissa)
It is also a coal based plant.

(*iii*) Kawas (Surat, Gujrat)
It is a gas based plant of 630 MW capacity.

(*iv*) Dadri (Ghaziabad, U.P.)
It is a gas based plant.

Gas based power plants in operation and managed by NTPC are as follows :

(*i*) Dadri (U.P.) of 131 MW capacity. Its total capacity will be 817 MW on completion.

(*ii*) Anta (Rajasthan) of 413 MW capacity.

(*iii*) Auraiya (U.P.) of 652 MW capacity.

Example 3.13. *The following data is supplied for a boiler plant :*

(*i*) *Boiler*
Mass of coal supplied = 220 kg / hr.
Calorific value of coal = 7200 k cal / kg
Mass of feed water = 200 kg / hr
Enthalpy of steam produced = 670 k cal / kg

(*ii*) *Economiser*
Inlet temperature of feed water = 18°C
Outlet temperature of feed water = 88°C
Atmospheric temperature = 19 C
Temperature of flue gas entering = 350°C
Mass of flue gases = 4150 kg/hr.

Determine the following :

(*a*) *Efficiency of boiler*

(*b*) *Efficiency of economiser*

(*c*) *Efficiency of whole boiler plant.*

Solution. (*a*) W = Mass of coal supplied = 220 kg/hr

C = Calorific value of coal

= 7200 kcal/kg.

H_1 = Heat obtained by combustion of coal

$= W \times C_v = 220 \times 7200$

$= 1584 \times 10^3$ k. cal/hr.

W_1 = Mass of feed water = 2000 kg/hr.

H_2 = Heat utilised in evaporation of steam

$= W_1 (h - h_1)$

where h = Enthalpy steam = 670 k. cal/kg.

h_1 = Enthalpy of feed water = 88 k. cal/kg.

$H_2 = 2000 (670 - 88)$

$= 2000 \times 582 = 1164 \times 10^3$ k cal/hr

$= 1164 \times 10^3$ k cal.

$$\text{Boiler Efficiency} = \frac{H_2}{H_1} \times 100 = \frac{1164 \times 10^3}{1584 \times 10^3} \times 100$$

= 73.5%. **Ans.**

(*a*) T_1 = Inlet temperature of feed water = 18°C

T_2 = Outlet temperature of feed water = 88°C

H_3 = Heat utilised by economiser

$= W_1 (T_2 - T_1) = 2000 (88 - 18)$

$= 14 \times 10^4$ k. cal/hr.

W_2 = Mass of flue gases = 4150 kg/hr.

T_3 = Temperature of flue gases = 350°C

T_4 = Atmospheric temperature = 19°C

K_p = Specific heat of flue gases = 0.24

H_4 = Heat supplied to economiser

$= W_2 (T_3 - T_4) \times K_p = 4150 (350 - 19) \times 0.24$

$= 4150 \times 331 \times 0.24 = 329 \times 10^3$ k cal/hr.

Economiser efficiency

(*b*) $= \frac{H_3}{H_4} \times 100 = \frac{14 \times 10^4}{329 \times 10^3} \times 100$

$= 42.5\%$. **Ans.**

(*c*) H = Total heat utilised

$= H_2 + H_3 = 1164 \times 10^5 + 14 \times 10^4$

$= 1304 \times 10^4$ kcal/hr

η = Over all efficiency

$= \frac{H}{H_1} \times 100$

$= \frac{1304 \times 10^3}{1584 \times 10^3} \times 100 = 82.3\%$. **Ans.**

This shows that by installing economiser the efficiency of the boiler plant is increased.

Example 3.14. *Determine the quantity of air required per kg of coal burnt in a steam power plant furnace fitted with a 62 m high stack. The draft produced is 38 mm of water and temperature of flue gases is 419°C. Boiler house temperature is 29°C.*

Solution. h = Draught = 38 mm of water

W = Weight of air required per kg of coal burnt

T_1 = Absolute temperature of air outside the chimney

$= 29 + 273 = 302°K$

T = Average absolute temperature of chimney (stack) gases.

$= 410 + 273 = 683°K$

H = Height of chimney = 62 m.

$$h = 353\, H \left[\frac{1}{T_1} - \left(\frac{W+1}{W} \right) \times \frac{1}{T} \right]$$

$$38 = 353 \times 62 \left[\frac{1}{302} - \left(\frac{W+1}{W} \right) \times \frac{1}{683} \right]$$

$W = 16$ kg.

Example 3.15. *The following observations refer to a surface condenser :*

Weight of condensate	*= 1200 kg / hr.*
Weight of cooling water	*= 48,000 kg / hr*
Mean temperature of condensation	*= 35°C*
Condenser vacuum	*= 700 mm*
Barometer reading	*= 760 mm*
Inlet temperature of cooling water	*= 20°C*
Outlet temperature of cooling water	*= 30°C*
Temperature of hot well	*= 29°C*

Calculate the following :

(*a*) *Weight of air per m^3 of condenser volume*

(*b*) *State of steam entering condenser*

(*c*) *Vacuum efficiency.*

Solution. P = Absolute pressure in condenser

$= 760 - 700 = 60$ mm

$= 0.8$ kg/cm^2

T_1 = Mean temperature of condensation

$= 35$°C

P_1 = Partial pressure of steam at 35 °C

$= 0.057$ kg/cm^2

P_2 = Partial pressure of air

$= P - P_1 = 0.08 - 0.057 = 0.023$ kg/cm^2

Let V = Volume of condenser

m = Weight of air present in condenser

Using gas equation

$$P_2V = mRT_1$$

$$\frac{m}{V} = \frac{P_2}{RT} = \frac{0.023 \times 10^4}{29.27 \times (273 + 35)}$$

$= 0.025$ kg/m^3. **Ans.**

q = Dryness fraction of steam entering the condenser

W_1 = Amount of cooling water

H_1 = Heat gained by cooling water

$= W_1 (T_2 - T_3) = 48{,}000\ (30 - 20)$

$= 48 \times 10^4$ kcal

W_2 = Amount of steam entering the condenser

= 1200 kg/hr

L = Latent heat of steam at 0.08 kg/cm^2

= 574 kcal/kg (From steam tables)

T = Temperature of steam at 0.08 kg/cm^2

= 41.16°C

T_4 = Temperature of hot well = 29°C

H_2 = Heat lost by steam

$= W_2 [qL + T - T_4]$

$= 1200 [q \times 574 + 41.16 - 29]$

$H_1 = H_2$

$48 \times 10^4 = 1200 [q \times 574 + (41.16 - 29)]$

$q = 0.67$

$$\text{Vacuum efficiency} = \frac{700}{760 - 0.057 \times 760} = 0.976 = 97.6\%.$$ **Ans.**

Example 3.16. *The data given below refers to a simple steam power plant (Fig. 3.103).*

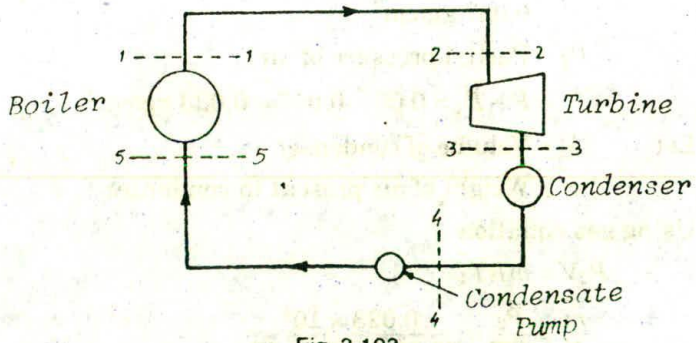


Fig. 3.103

Power of pump = 400 H.P.

Rate of steam flow = 8×10^4 kg/hr.

The enthalpy and velocity for the fluids at different points of cycle are indicated in table 3.2 (A) :

Table 3.2 (A)

Location	*Enthalpy (k.cal/kg)*	*Velocity (m/sec.)*
Steam leaving the boiler (1-1)	780	80
Steam entering the turbine (2-2)	776	80

Steam leaving the turbine and entering the condenser (3–3)	550	160
Water leaving condenser and entering pump (4–4)	70	

The enthalpy and velocity of hot water leaving the pump and entering the boiler (5-5) are negligible. Heat loss from the turbine to the atmosphere is 40000 kcal / hr.

Calculate the following :

(*a*) *Heat transfer per hour in pipe line joining boiler and turbine.*

(*b*) *Heat transfer per hour in pipe line joining boiler and condenser.*

(*c*) *Power output of turbine.*

Assume all the items to be working at the same level.

Solution. (*a*) Q_1 = Heat transfer in pipe line between boiler and turbine

$= (H_1 - H_2) \times m$

where $H_1 = 780$ kcal/kg

$H_2 = 776$ kcal/kg

m = Rate of steam flow $= 8 \times 10^4$ kg/hr

$Q_1 = (780 - 776) \times 8 \times 10^4$

$= 32 \times 10^4$ kcal/hr

(*b*) W_1 = work done by pump

$= 400$ H.P. $= 400 \times 75 \times 3600$ kgm/hr

$= \dfrac{400 \times 75 \times 3600}{427}$ kcal/hr.

$= 25 \times 10^4$ kcal/hr

H_1 = Enthalpy of water entering the boiler

$= W_1$ + Enthalpy of water leaving the pump

$= 25 \times 10^4 + 70 \times 8 \times 10^4$

$= 585 \times 10^4$ kcal/hr

H_1 = Enthalpy of steam leaving the boiler

$= 780 \times 8 \times 10^4 = 624 \times 10^5$ kcal/hr

H = Heat supplied by the boiler

$= H_1 - H_5 = 624 \times 10^5 - 585 \times 10^4$

$= 3655 \times 10^4$ kcal/hr

(c) Q = Heat loss from turbine to atmosphere

$$= -\frac{40,000}{8 \times 10^4} = -0.5 \text{ kcal/kg of steam flow.}$$

Applying general energy equation

$$\frac{H}{J} + H_3 + \frac{v_3^2}{2gJ} + Z_3 = Q + H_3 + \frac{v_2^2}{2gJ} + Z_2$$

As all the items work at the same level

$Z_2 = Z_3$

$v_2 = 80$ m/sec

$v_3 = 160$ m/sec

$H_2 = 776$ kcal/kg

$H_3 = 550$ kcal/kg

W = work done

$$\frac{W}{J} = (H_2 - H_3) + \frac{v_2^2}{2gJ} - \frac{v_3^2}{2gJ} - Q$$

$$= (776 - 550) + \frac{(80^2)}{2 \times 9.81 \times 427} - \frac{(160)^2}{2 \times 9.8 \times 427} - 0.5$$

$$= 226 + \frac{(80)^2 - (160)^2}{2 \times 9.81 \times 427} - 0.5$$

$= 223$ kcal/kg

$= 223 \times 427 = 95,221$ kgm/kg

$= 95,221 \times 8 \times 10^4$ kgm/hour

$$\text{H.P.} = \frac{95.221 \times 8 \times 10^4}{75 \times 3600} = 28,213.$$

Example 3.17. *In a steam power plant an endless rope haulage raises 300 tonnes of coal through a vertical distance of 80 metres in one hour. If the efficiency of the haulage system is 40% and the system runs for 8 hours per day for 5 days, calculate the following :*

(a) H.P. output of system

(b) Power input

(c) Weekly cost of coal raising. The charge for electricity is 25 paise per kWh.

Solution. t = Time = 1 hour = 3600 sec.

P = Power output

$= mgh = 300 \times 1000 \times 9.8 \times 8$

$$= 2352 \times 10^5 J$$

$$= \frac{2352 \times 10^5}{t} = \frac{2352 \times 10^5}{3600} = 65 \times 10^3 \text{ W}$$

(As 1 W = 1 J per sec)

$$\text{Power output (H.P.)} = \frac{65 \times 10^3}{735.5} = 88$$

η = Efficiency = 0.4

$$\text{Power input} = \frac{88}{0.4} = 220 \text{ H.P.}$$

Hours per week $= 8 \times 5 = 40$

$$\text{Power input} = \frac{\text{Power output}}{\eta} = \frac{65 \times 10^3}{0.4}$$

$$= 162 \times 10^3 \text{ W}$$

E = Energy consumed

$$= \frac{162 \times 10^3}{1000} \times 40 = 6480 \text{ kWh.}$$

Rate per kWh = 25 paise

$$\text{Cost} = 6480 \times \frac{25}{100} = \text{Rs. } 1620.$$

Example 3.18. *A steam power plant uses coal 5000 kg/hr. The heat conversion efficiency is 30% and calorific value of coal is 7000 k. cal/kg, calculate the electric energy produced per day.*

Solution. W_1 = Amount of coal used = 5000 kg/h

C = Calorific value of coal

= 7000 kcal/kg

and Conversion efficiency = 0.3

H_1 = Net heat utilised

$= W.C. \eta = 5000 \times 7000 \times 0.3$

$= 10.5 \times 10^6$ kcal/hr

E = Energy produced per hour

$$= \frac{H}{860} \text{ kWh}$$

(As 1 kWh = 860 kcal)

$$E = \frac{10.5 \times 10^3}{860} = 12{,}210 \text{ kWh.}$$

Energy produced per day

$$= E \times 24 = 12.210 \times 24$$

$$= 293 \times 10^3 \text{ kWh} = 293 \text{ MWh.}$$

Example 3.19. *Find the rate of flow of cooling water and the cooling ratio for a surface condenser with the following data :*

Total amount of condensing steam = 17 kg / sec.

Temperature of condensate = 25°C

Inlet temperature of cooling water = 12°C

Outlet temperature of cooling water = 20°C

Enthalpy of steam at inlet to condenser = 2400 KJ / kg

Solution. W_1 = Amount of steam = 17 kg/sec

W = Weight of cooling water

T = Temperature of condensate

T_1 = Inlet temperature of cooling water

= 12°C

T_2 = Outlet temperature of cooling water

= 20°C

H = Enthalpy of steam at inlet to condenser

H_1 = Enthalpy of condensate

C = Heat capacity of water

= 4.19 KJ/kg deg.

Heat lost by steam = Heat gained by water

$$W_1 (H - H_1) = W (T_2 - T_1) C$$

$$17 (2400 - 4.19 \times 25) = W (20 - 12) \times 4.19$$

$$W = 1164 \text{ kg}$$

$$\text{Cooling ratio} = \frac{W}{W_1} = \frac{1164}{17} = 68.4 \text{ kg/kg.}$$

Example 3.20. *A steam power plant of 150 kW capacity uses gas of calorific value 1200 kcal/m³.*

Determine the volume of gas required per hour when the plant is running at full load conditions.

Take the overall efficiency of the plant as 30%.

Solution. E = Energy generated per hour

$= 150 \times 1 = 150$ kWh

H_1 = Heat required for E

$= E \times 860 = 150 \times 860$ kcal

(As 1 kWh = 860 kcal)

Let V = volume of gas required per hour

C.V. = Calorific value of gas

$= 1200$ kcal/m^3

η = Efficiency of plant = 0.3

H_2 = Heat produced by burning the gas

$H_2 = V \times \text{C.V.} \times \eta = V \times 1200 \times 0.3$

$H_1 = H_2$

$150 \times 860 = V \times 1200 \times 0.3$

$V = 358$ m^3.

Example 3.21. *Two boilers one with a super heater and the other without a super heater are supplying equal quantities of steam into a common main. The temperature of steam from the boiler with super heater is 330°C and that of steam in the main is 260°. If the pressure in the boiler and the main is 15 kg/cm^2 and specific heat of superheated steam is 0.54 determine the quality of steam supplied by boiler without super heater.*

Solution.

Let q = Dryness fraction of steam supplied by boiler without super heater

At 15 kg/cm^2 (From steam tables)

t = Saturation temperature of steam

$= 197.4$°C

L = Latent heat

$= 466.7$ kcal

$H_w = 200.7$ kcal

Let us assume that each boiler supplies one kg of steam into the common main.

H' = Heat of steam

$= H_w + qL$

$= 200.7 + q \times 466.7$ kcal.

Now t_s = Temperature of super-heated steam

$= 330$ C

$C_p = 0.54$

H_s = Heat of super heated steam

$= H + C_p (t_s - t)$

$= 667.4 + 0.54 (330 - 197.4)$ k.cal

$= 739$ k.cal

$H_1 = H' + H_s$

$= 200.7 + q \times 466.7 + 739$ k.cal.

Since the temperature of steam in the common main is 260°C and saturation temperature is 197.4°C it is obvious that steam is still in super heated condition.

H_2 = Heat of 2 kg of steam in the main

$= [H + C_p (t_s - t)] \times 2$

$= [667.4 + 0.54 (260 - 197.4)] \times 2$

$= 1402.4$ k.cal.

Now $H_1 = H_2$

$200.7 + q \times 466.7 + 739 = 1402.4$

$q = 0.91.$

Example 3.22. *Calculate the efficiency of a boiler in which coal consumption is 65 kg per hour and which generates 370 kg of steam per hour at 0.93 dryness fraction and at a pressure of 8 bar ablso lute. Coal used has the following composition per kg.*

Carbon	*= 0.71*
Hydrogen	*= 0.05*
Oxygen	*= 0.11*
Sulphur	*= 0.02*
Ash	*= 0.11*
Feed water temperature	*= 24°C.*

Solution.

P = Pressure of steam

$= 8$ bar

From steam tables

hf = sensible heat

= 721 kJ/kg

hfg = Latent heat of steam

= 2046.5 kJ/kg

x = Dryness fraction

H = Heat of 1 kg of steam

$= hf + x \cdot hfg$

$= 721 + 0.93 \times 2046.5$

= 2624.3 kJ/kg

H_1 = Heat supplied to steam per kg

= H – heat contained in 1 kg of feed water

$= 2624.3 - 1 \times 4.18 \times (24 - 0)$

= 2524 kJ/kg

W = weight of steam produced per hour = 370 kg

H_2 = Heat of steam

$= W \times H_1 = 370 \times 2524$

= 933880

C_V = Calorific value of coal

$$= 3380°C + 144000\left(H - \frac{0}{8}\right) + 9270\,S$$

where C = Amount of carbon per kg of coal

= 0.71

H = Amount of carbon per kg of coal

= 0.05

O = Amount of oxygen per kg of coal

= 0.11

S = Amount of sulphur per kg of coal

= 0.02

$$C_V = 33800 \times 0.71 + 144000\left(0.05 - \frac{0.11}{8}\right) + 9270 \times 0.02$$

= 29367.4 kJ/kg

W_1 = Amount of coal burnt per hour

$= 65$ kg

H_3 = Total heat input

$= C_v \times W_1$

$= 29367.4 \times 65$

$= 1908855$ kJ

η = Boiler efficiency

$$= \frac{H_2}{H_3} \times 100$$

$$= \frac{933880}{1908855} \times 100$$

$= 49\%$.

Example 3.23. *A boiler working at a pressure of 10 bar generates 2100 kg of dry and saturated steam per hour. The feed water is heated by an economiser to a temperature of 105°C. Coal consumed is 208 kg and calorific value of coal is 30200 kJ / kg. If 12% of coal remains unburnt determine :*

(a) thermal efficiency of boiler

(b) thermal efficiency of boiler and grate combined.

Solution. x = Dryness fraction = 1

m = Rate of production of steam

$= 2100$ kg/h

ΔT = Feed water temp. rise

$= 105°C$

P = Pressure

$= 10$ Bar

h = Heat of steam at 10 bar pressure

$= hg$

$= 2776$ kJ/kg

h_{f1} = Heat contained in feed water

$= 1 \times 4.18 \times \Delta T$

$= 1 \times 4.18 \times 105$

$= 439$ kJ/kg

h_1 = Heat used to produce 1 kg of steam in boiler.

$= h - h_{f1}$

$= 2776 - 439$

$= 2337$ kJ/kg

Unburnt coal = 10%

W = Coal consumed = 208 kg

m_1 = Mass of coal actually burnt

$$= 208 \times \frac{90}{100}$$

$= 187.2$ kg

m_2 = mass of steam produced per kg of coal actually burnt.

$$= \frac{m}{m_1}$$

$$= \frac{2100}{187.2}$$

$= 11.2$ kg

H_1 = Total heat of steam

$= m_2 \times h_1$

$= 11.2 \times 2337$

$= 26174.4$ kJ

C_v = Calorific value of coal

$= 30200$

η_b = Boiler efficiency

$$= \frac{H_1}{C_v} \times 100$$

$$= \frac{26174.4}{30200} \times 100$$

$= 86.6\%$

η_g = Efficiency of boiler and grate

$$= \frac{\frac{m}{w} \times (h_1)}{C_v} = \frac{2100}{208} \times \frac{2337}{30200} = 0.78 = 78\% \text{ . Ans.}$$

Example 3.24. *Sketch and describe a steam power plant indicating various parts of the plant.*

Solution. In a steam power plant, fuel and air enter the power plant and products of combustion leave the unit. There is a transfer of heat to the cooling water, and work is done in the form of the electrical energy leaving the power plant. The overall objective of a

power plant is to convert the availability (to do work) of the fuel into work (in the form of electrical energy) in the most effcient manner, taking into consideration cost, space, safety, and environmental concerns.

A schematic diagram of a steam power plant is shown in Fig. 3.104. High-pressure superheated steam leaves the boiler, which is also referred to as a steam generator, and enters the turbine. The steam expands in the turbine and, in doing so, does work, which enables the turbine to drive the electric generator. The low-pressure steam leaves the turbine and enters the condenser, where heat is transferred from the steam (causing it to condense) to the cooling water.

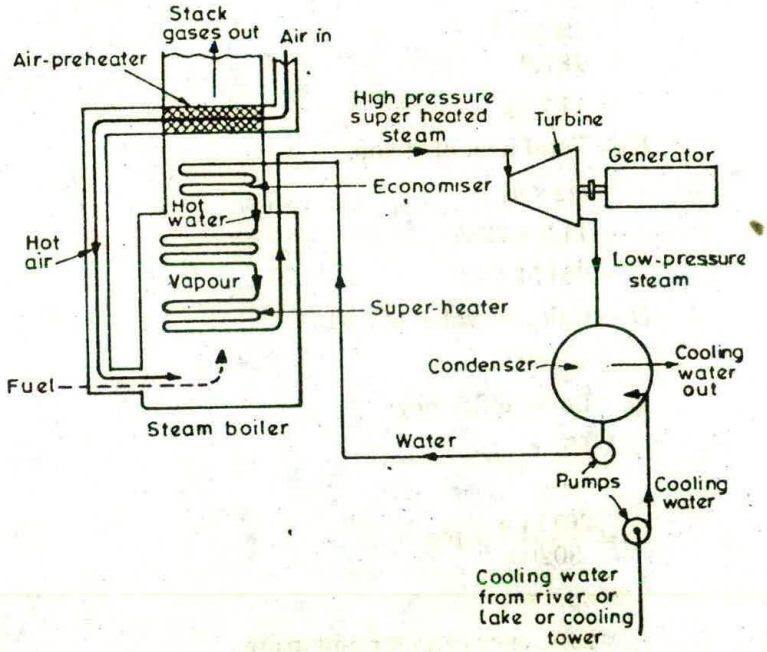


Fig. 3.104

PROBLEMS

3.1. (*a*) What are the different types of coal conveyors ? Describe the construction and operation of belt-conveyor and screw conveyor.

(*b*) Describe a grab bucket elevator.

3.2. (*a*) What is meant by 'over feed' and 'under feed' principles of firing coal ?

(*b*) What are the different methods of firing coal ? Discuss the advantages of mechanical methods of firing coal.

(*c*) Make neat sketch and explain the working of :
(*i*) Chain grate stoker. (*ii*) Spreader stoker.
(*iii*) Multi retort stoker.

(*d*) What is Fluidised Bed Combustion system. Sketch and describe a Fluidised Bed Combustion (FBC) system. State the advantages of FBC system.

3.3. Describe the various types of grates used with hand fired furnaces.

3.4. Name the various methods of ash handling. Describe the pneumatic system of ash handling. Why it is essential to quench the ash before handling ?

3.5. (*a*) Describe the various methods used to fire pulverised coal.

(*b*) Make a neat sketch of ball and Race mill and explain its working.

(*c*) State the advantages of pulverised fuel firing.

3.6. Name the different types of coal-pulverising mills. Describe Ball-Mill.

3.7. Describe the various types of burners used to burn pulverised coal.

3.8. Name various draught systems. Describe the operation of a balanced draught system.

3.9. What is the cause of smoke ? State the factors necessary for its prevention.

3.10. Name the different types of chimneys used. State the advantages of steel chimney. Derive an expression for the height of chimney.

3.11. (*a*) What are the harmful effects caused by using impure water in boilers ? Describe the various methods of purifying feed water.
(*b*) What is meant by make up water of boiler and how is this water fed into a boiler ?

3.12. Describe the various methods used to control the degree of superheat. Name the advantages gained by using super-heat steam.

3.13. What is condenser ? Name the different types of condenser. Describe the operation of (*i*) Surface condenser (*ii*) Jet condenser.

3.14. What are the different types of cooling towers used in a steam power plant. Discuss their specific advantages.

3.15. What is a steam trap ? Where it is located ? Describe Ball Float steam trap.

3.16. What are the requirement of a well designed pipe line in a steam power plant. Name and describe the various expansion bends used in piping steam.

3.17. What are the advantages of using large capacity boilers ? Describe the operation of :

(*i*) Velox Boiler (*ii*) Benson Boiler (*iii*) Loeffler Boiler.

3.18. State the advantages and disadvantages of a steam power station as compared to hydro-electric power station and nuclear power station.

3.19. Describe the various factors which determine the location of a steam power station.

3.20. Write short notes on the following :
(*a*) Cyclone and collector
(*b*) Industrial steam turbines
(*c*) Hydraulic test of boiler
(*d*) Draught fans
(*e*) Steam separator
(*f*) Economiser
(*g*) Cyclone fired boilers
(*h*) Pressure Filter.
(*i*) Air preheater
(*j*) Pipe fittings
(*k*) Heat flow in steam plant.

3.21. What is the difference between water-tube and fire tube boilers ? Describe the working principle of Cochran Boiler or Lancashire Boiler.

3.22. (*a*) How will you classify various types of boilers ?
(*b*) Write short notes on the following :
(*i*) Efficiency of boiler
(*ii*) Maintenance of boiler
(*iii*) Accessories of a boiler
(*iv*) Overall efficiency of steam power plant
(*v*) Steam turbine specifications
(*vi*) Feed water control
(*vii*) Causes of heat loss in boiler.

3.23. What is a superheater ?
(*a*) Describe three types for superheaters ?
(*b*) State the advantages of superheated steam.

3.24. (*a*) What is a steam turbine ?
(*b*) How are steam turbines classified ?
(*c*) Explain three methods of steam turbine governing.

3.25. Explain the methods used to increase thermal efficiency of a steam power plant.

3.26. Write short notes on the following :
(*a*) pH value of water.
(*b*) Power plant pumps.
(*c*) Steam turbine capacity.
(*d*) Comparison of forced and induced draft system for boiler.
(*e*) Principles of steam power plant design.
(*f*) Korba super thermal power station.
(*g*) Singrauli super thermal power plant.

3.27. Determine the quantity of air per kg of coal burnt in a furnace if the stack height is 58 m and draught produced is 35 mm of water. The temperature of flue gases is 380°C.

Also calculate the draught produced in terms of height of a column of hot gases if the boiler house temperature is 27°C.

3.28. Discuss piping system of a power plant.
3.29. What is blowing down of a boiler ? How will you determine blow down ?
3.30. Describe a water tube boiler and a fire tube boiler.
3.31. Describe a feed water regulator.
3.32. In a boiler, give the flow diagram for
(*a*) Flue gas flow.
(*b*) Water steam flow.
3.33. State the advantages of high pressure boilers.
3.34. Write short notes on the following :
(*a*) Steam turbine performance
(*b*) Steam turbine generators.
3.35. Describe environmental control of steam power plants.
3.36. Write short notes on the following :
(*i*) Selection of boiler
(*ii*) Gas fired boilers
(*iii*) Modern trends in generating steam.
3.37. State the requirements of a fuel burning equipment.
3.38. State the factors to be considered while selecting a suitable combustion equipment for a fuel.
3.39. Describe the handling of liquid fuels and gaseous fuels.
3.40. Sketch and describe two types of gas b[illegible]ners.
3.41. Sketch and describe a pressure filter f[illegible]r feed water treatment.
3.42. State the effects of air leakage in cond[illegible]nser.
3.43. Write short notes on the following :
(*i*) Selection of a condenser
(*ii*) Sources of air in a condenser
(*iii*) Condenser auxiliaries.
3.44. Sketch and describe Edward's air extraction pump for a condenser.
3.45. Write short notes on the following :
(*i*) Boiler mountings.
(*ii*) Hydraulic test of boiler.
3.46. Sketch and describe a schematic arrangement of equipments of a steam power plant.
3.47. What are the principal requirements of ash handling plant.
3.48. Discuss commissioning of steam power plant.
3.49. Sketch and describe the following :
(*i*) Cyclone dust collector
(*ii*) Electrostatic precipitator
(*iii*) Cinder catcher.
(*iv*) Fly ash scrubber.
3.50. Write short notes on the following :
(*i*) Steam turbine testing
(*ii*) Choice of steam turbine.

4

Diesel Engine Power Plant

4.0 Introduction

Diesel engine power plant is suitable for small and medium outputs. It is used as central power station for smaller power supplies and as a standby plants to hydro-electric power plants and steam power plants.

The diesel power plants are commonly used where fuel prices or reliability of supply favour oil over coal, where water supply is limited, where loads are relatively small, and where electric line service is unavailable or is available at too high rates. Diesel power plants in common use have capacities up to about 5 MW.

Fig. 4.1 (*a*) shows various parts of an I.C. engine. The cylinder is the main body of the engine where in direct combustion of fuel takes place. The cylinder is stationary and the piston reciprocates inside it. The connecting rod transmits the force given by the piston to the crank, causing it to turn and thus convert the reciprocating motion of the piston into rotary motion of the crankshaft.

The valves may be provided

(*i*) at the top

or (*ii*) on the side of the engine cylinder.

Fig. 4.1 (*b*) shows a typical overhead valve assembly.

The cam lifts the push rod through cam follower and the push rod actuates the rocker arm lever at one end. The other end of the rocker arm then gets depressed and that opens the valve. The valve returns to its seating by the spring after the cam has rotated. The valve stem moves in a valve guide acts as a bearing.

On a four stroke engine, the inlet and exhaust valves operate once per cycle, *i.e.*, in two revolutions of the crankshaft. Consequently, the cam shaft is driven by the crankshaft at exactly half its rotational speed.

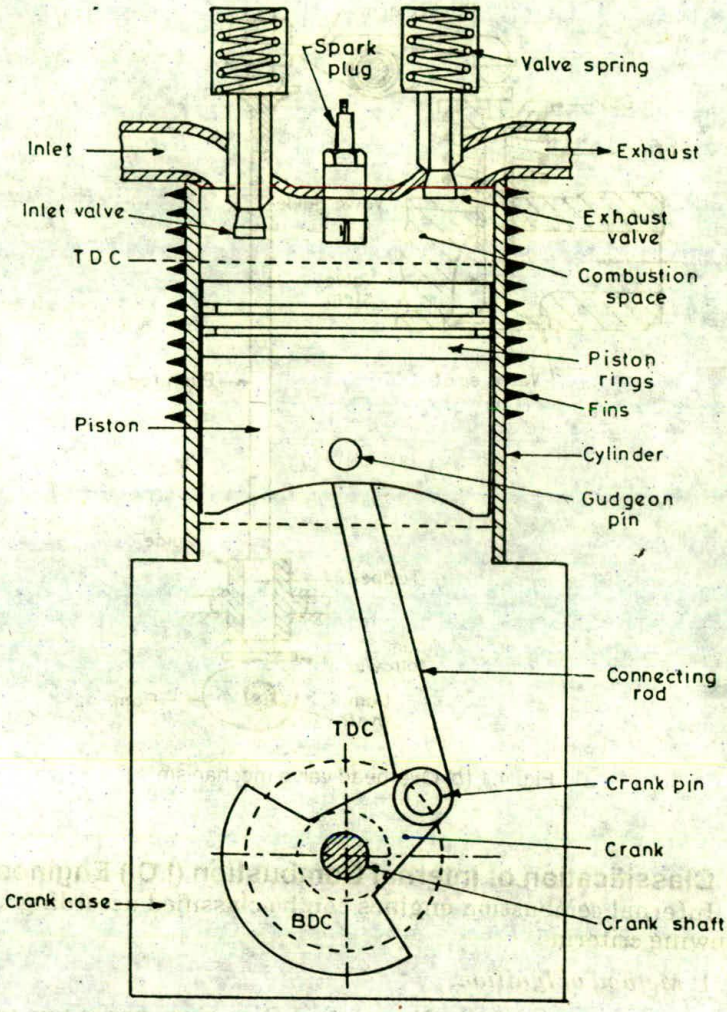

Spark plug
Valve spring
Inlet
Exhaust
Inlet valve
Exhaust valve
TDC
Combustion space
Piston rings
Fins
Piston
Cylinder
Gudgeon pin
Connecting rod
TDC
Crank pin
Crank
Crank case
BDC
Crank shaft

Fig. 4.1 (*a*)

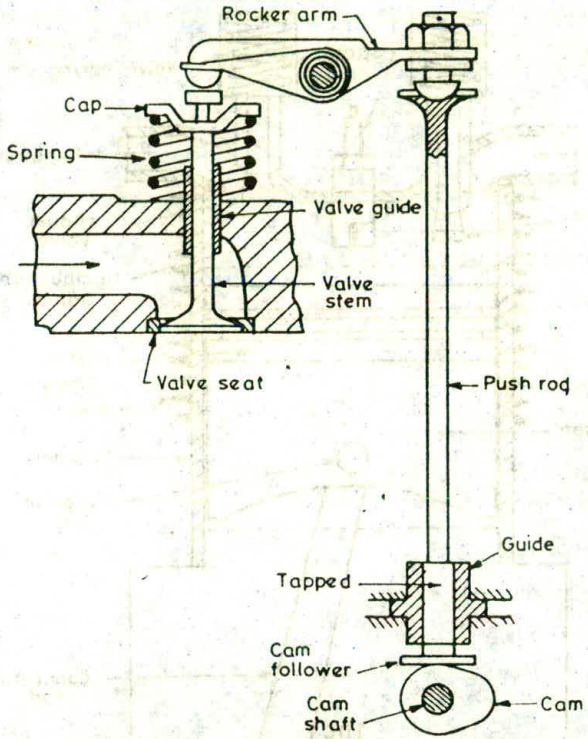


Fig. 4.1 (*b*) Overhead valve mechanism.

4.1 Classification of Internal Combustion (I.C.) Engines

Internal combustion engines can be classified according to the following criteria :

1. *Method of Ignition.*

According to method of ignition : I.C. engines are of two types :

(*a*) Spark ignition engines

(*b*) Compression ignition engines.

In spark ignition engines such as in petrol engines the air fuel mixture is compressed and ignited at the end of compression stroke by an electric spark. The compression ratio in such engines varies between 5 to 8. In compression ignition engines or diesel engines as they are often called air admitted into the cylinder is compressed. The compression ratio being nearly 12 to 20. The temperature of air becomes very high due to compression. At or near to the end of

compression stroke fuel is injected through an injection nozzle into the hot air in the engine cylinder. Due to high temperature of air the fuel oil burns. The burning gases expand do work on the piston and hence on the load coupled to the engine. The gases are then exhausted from the cylinder and this cycle is repeated. In I.C. engines the charge of fuel and air in correct proportions should be supplied and combustion products should be exhausted from the cylinder when air expansion is complete in order that fresh charge may enter the cylinder.

Usualiy well designed compression ignition engines shows greater efficiency than spark ignition engines because of their higher compression ratios. Part load efficiency of compression ignition engines is higher.

2. *Cycle of Operation.* According to cycle of operation I.C. engines are of two types :

(*a*) Two-stroke cycle engine.
(*b*) Four-stroke cycle engine.

The relative advantages and disadvantages of these engines are as follows :

(*i*) The working or power stroke is completed in two revolutions of the crank shaft in four stroke cycle engine whereas in two-stroke cycle engine the working stroke is completed in one revolution. Thus the power obtained from a two-stroke engine should be twice that of power obtained from four-stroke engine but due to charge loss and power needed to drive scavenge compressor the actual power obtained from a two-stroke engine is 50 to 60% more than four-stroke engine. As one working stroke is completed for every revolution of crankshaft the turning moment on crankshaft is more uniform in case of two stroke engine and, therefore, a lighter flywheel serves the purpose.

(*ii*) Two-stroke engine is lighter is weight and requires less space than a four-stroke engine of the same power. This makes it suitable for marine engines.

(*iii*) In two stroke engine the power needed to overcome frictional resistance during suction and exhaust stroke is saved.

(*iv*) In a two-stroke engine there is more noise and wear.

(*v*) The consumption of lubricating oil is greater in a two stroke engine due to large amount of heat generated.

(*vi*) Two stroke engine is simple and its maintenance cost is low.

(*vii*) Scavenging is better in four-stroke engine.

(*viii*) In two-stroke engine the exhaust port remains open for a very short time which results in incomplete scavenging and thus dilution of fresh change.

(*ix*) Construction of combustion chamber is better and simple in two-stroke engine.

3. *Number of Cylinders.* According to number of cylinders, they are classified as single cylinder and mutli-cylinder engines.

Internal combustion engines may have more than one cylinders such as 4, 6, 8 etc.

For any given engine the number of cylinders are fixed by the output desired, space available and balancing and torque considerations. With increase in number of cylinders the weight, cost, space occupied and number of working parts of the engine increase. The size of an engine is designated by the cylinder diameter (bore) stated first followed by the length of stroke.

4. *Arrangement of Cylinders.* According to the arrangement of cylinders the I.C. engines may be classified as Inline engines, V-engines, radial engines, horizontal engines etc. (Fig. 4.1).

5. *Speed.* According to speed I.C. engines may be classified as follows :

(*i*) Low speed (upto 350 R.P.M.)

(*ii*) Medium speed (From 350 to 1000 R.P.M.)

(*iii*) High speed (Above 1000 R.P.M.)

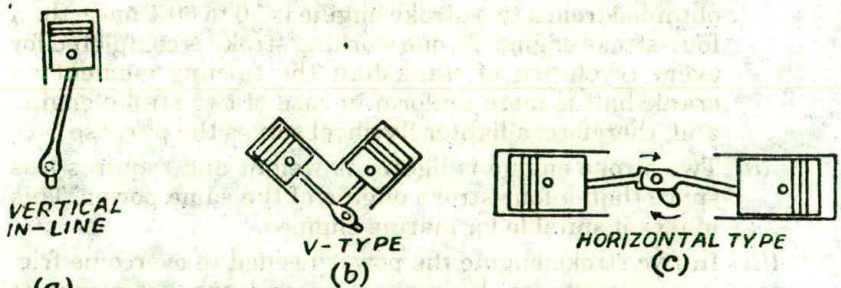


Fig. 4.1

6. *Method of Cooling the Cylinder.* According to the method of cooling the cylinder IC engines are of two types :

(*i*) Air cooled

(*ii*) Water cooled.

7. *Purpose.* According to the purpose for which to be used they are classified as stationary, mobile and special.

4.2 Four-stroke Diesel Engine

If four-stroke diesel engine the four operations are completed in two revolutions of crank shaft. The various operations are as follows:

(*i*) *Suction Stroke.* In this stroke in let valve (I.V.) remains open [Fig. 4.2 (*a*)] and exhaust valve (E.V.) remains closed. The descending piston draws in a fresh charge of air to fill the cylinder with it. The air taken in during suction stroke is nearly at atmospheric pressure. Line *ab* in the indicator diagram (Fig. 4.3) represents this stroke.

(*ii*) *Compression Stroke.* In this stroke I.V. and E.V. remain closed. Piston moves up and the air sucked in during suction stroke is compressed to high pressure and temperature (nearly 3.5 kg/cm^2 and 600°C). This stroke is represented by the line *bc* in indicator diagram.

(*iii*) *Expansion Stroke.* During the stroke Fig. 4.2 (*c*), I.V. and E.V. remain closed. Injection of fuel through the fuel valve starts just before the beginning of this stroke. Due to compression the temperature of air inside the cylinder become high enough to ignite the fuel as soon as it is injected. The fuel is admitted into the cylinder gradually in such a way that fuel burns at constant pressure. In Fig. 4.3, *cd* represents the fuel burning operation. The ignited mixture of air and fuel expands and forces the piston downward. Expansion stroke is represented by *de* in Fig. 4.3.

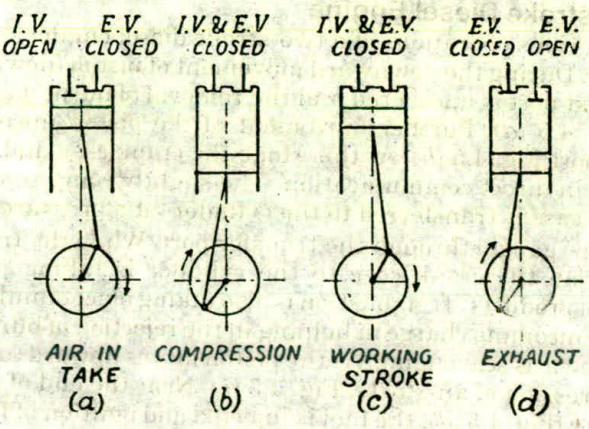


Fig. 4.2

(*iv*) *Exhaust Stroke.* This stroke is represented by *ea* in Fig. 4.3. In this stroke E.V. remains open, Fig. 4.2 (*d*) and the rising piston forces the burnt gases out of cylinder.

The exhaust of gases takes place at a pressure little above the atmospheric pressure because of restricted area of exhaust passages which do not allow the gases to move out of cylinder quickly. Fig. 4.4 shows the valve timing diagram for a four-stroke diesel engine. The approximate crank positions are shown when I.V., E.V., and fuel valves open and close. I.D.C. represents (inner dead centre) and O.D.C. (outer dead centre), I.V.O. represents (Inlet valve opens) and I.V.C. represents (Inlet valve closes). Similarly E.V.O. means exhaust valve open and E.V.C. means exhaust valve closes F.V.O. represents fuel valve opens and F.V.C. represents fuel closes and F.V.O. represents fuel valve opens.

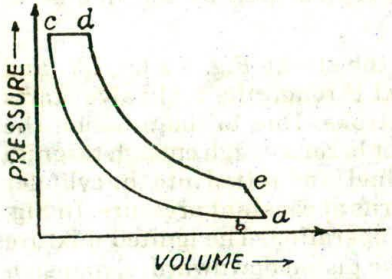


Fig. 4.3

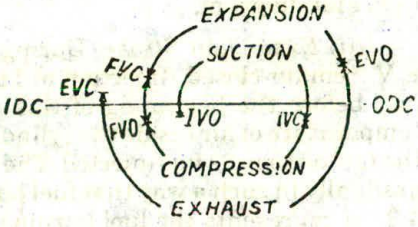


Fig. 4.4

4.3 Two-stroke Diesel Engine

The various operations of a two-stroke diesel engine are shown in Fig. 4.5. During the downward movement of piston (down stroke) the exhaust port is uncovered and the removal of burnt gases takes place Fig. 4.5 (*a*). Further movement of the piston uncovers the transfer port Fig. 4.5 (*b*). At this stage the crank case and cylinder space are in direct communication. The slightly compressed air in the crank case is transferred to the cylinder (at a pressure of about 0.05 kg/cm^2 gauge) through the transfer port. While the transfer of change from the crank case to the cylinder is taking place the removal of products of combustion is also taking place simultaneously, *i.e.* the incoming charge in helping in the rejection of burnt gases. this is known as scavenging. As the piston moves upward (up stroke) the compression of air starts, Fig. 4.5 (*c*). Near the end of compression stroke [Fig. 4.5 (*d*)] the fuel is injected and ignition of fuel takes place due to heat of compressed air. Then due to expansion of products of combustion the piston moves downward. As the inlet port is uncovered a fresh change of air gets entered in the crank case.

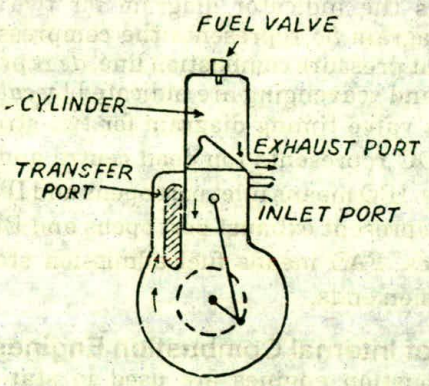


Fig. 4.5 (a)

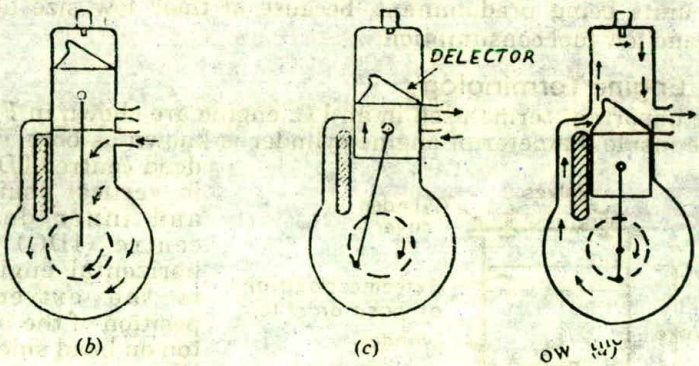


Fig. 4.5

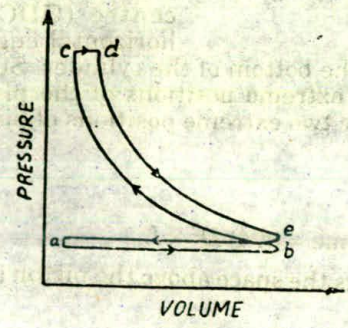


Fig. 4.6

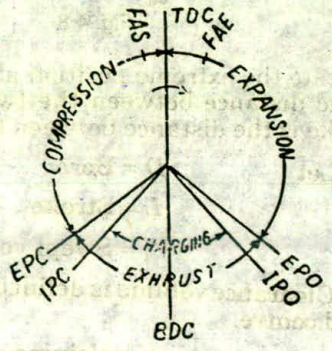


Fig. 4.7

Fig. 4.6 shows the indicator diagram for two stroke diesel engine. In this diagram *bc* represents the compression of air, *cd* represents constant pressure combustion line, *de* represents expansion and exhaust and scavenging are indicated by *eab*.

Fig. 4.7 shows valve timing diagram for two-stroke diesel engine. TDC and BDC represents top dead centre and bottom dead centre respectively. IPO means inlet port opens and IPC means inlet port closes, EPO represent exhaust port opens and EPS represents exhaust port closes. FAS means fuel admission starts and FAE means fuel admission ends.

4.4 Application of Internal Combustion Engines

Internal combustion engines are used in stationary plants, marine power plants, in various vehicles and aircrafts, their use in mobile units being predominant, because of their low size and weight and low fuel consumption.

4.5 I.C. Engine Terminology

The important terms used in an I.C. engine are shown in Fig. 4.8. The inside diameter of engine cylinder is known as bore Top dead centre (TDC) in vertical engine and inner dead centre (IDC) in horizontal engine is the extreme position of the piston on head side of the engine. Whereas bottom dead centre (BDC) in vertical engine and outer dead centre (ODC) in horizontal engines indicate the extreme position at the bottom of the cylinder. Stroke is the distance between the two extreme positions of the piston. Stroke is the distance between the two extreme positions of piston.

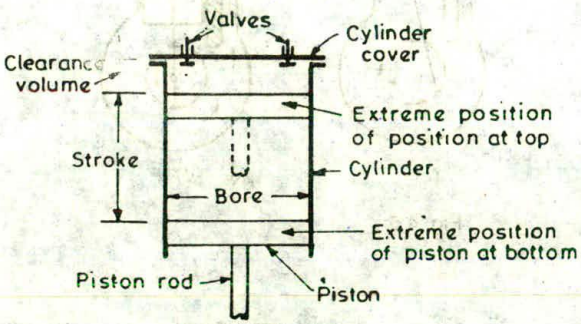


Fig. 4.8

Let D = Bore

L = Stroke

V_1 = Swept volume = $(\pi/4)\, D^2 \times L$.

Clearance volume is defined as the space above the piston at top dead centre.

V = Volume of cylinder = $V_1 + V_c$

where V_c is the clearance volume.

4.6 Engine Performance

(*i*) **IMEP.** In order to determine the power developed by the engine, the indicator diagram of engine should be available. From the area of indicator diagram it is possible to find an average gas pressure which while acting on piston throughout one stroke would account for the network done. This pressure is called indicated mean effective pressure (I.M.E.P.).

(*ii*) **IHP.** The indicated horse power (I.H.P.) of the engine can be calculated as follows :

$$\text{I.H.P.} = \frac{P_m L A N. n}{4500 \times k}$$

where P_m = I.M.E.P. in kg/cm^2

L = Length of stroke in metres

A = Piston areas in cm^2

N = Speed in R.P.M.

n = Number of cylinders

k = 1 for two stroke engine

= 2 for four stroke engine.

(*iii*) **Brake Horse Power (B.H.P.).** Brake horse power is defined as the net power available at the crankshaft. It is found by measuring the output torque with a dynamometer.

$$\text{B.H.P.} = \frac{2\pi NT}{4500}$$

where T = Torque in kg.m.

N = Speed in R.P.M.

(*iv*) **Frictional Horse Power (F.H.P.).** The difference of I.H.P. and B.H.P. is called F.H.P. It is utilised in overcoming frictional resistance of rotating and sliding parts of the engine.

$$\text{F.H.P.} = \text{IHP} - \text{BHP.}$$

(*v*) **Indicated Thermal Efficiency** (η_i). It is defined as the ratio of indicated work to thermal input.

$$\eta_i = \frac{\text{I.H.P.} \times 4500}{W \times C_v \times J}$$

where W = Weight of fuel supplied in kg per minute.

C_v = Calorific value of fuel oil in kcal/kg.

J = Joules equivalent = 427.

(*vi*) **Brake Thermal Efficiency (Overall Efficiency).** It is defined as the ratio of brake output to thermal input.

$$\eta_b = \frac{\text{B.H.P.} \times 4500}{W \times C_v \times J}$$

(*vii*) **Mechanical Efficiency** (η_m). It is defined as the ratio of B.H.P to I.H.P. Therefore, η_m = B.H.P./I.H.P.

4.7 Heat Balance Sheet

Heat balance sheet is a useful method to watch the performance of the plant. Of all the heat supplied to an engine only part of it is converted into useful work, the remaining goes as waste. The distribution of the heat imparted to an engine is called as its heat balance. The heat balance of an engine depends on a number of factors among which load is primary importance. The heat balance of an internal combustion engine shows that the cooling water and exhaust gases carry away about 60-70% of heat produced during combustion of fuel. In order to draw the heat balance sheet of internal combustion engine, the engine is run at constant load and constant speed and the indicator diagram is drawn with the help of indicator. The following quantities are noted :

1. The quantity of fuel consumed during a given period.
2. Quantity of cooling water and its outlet and inlet temperatures.
3. Weight of exhaust gases.
4. Temperature of exhaust gases.
5. Temperature of flue gases supplied.

To calculate the heat in various items proceed as follows.

Heat is Fuel Supplied

Let W = Weight of fuel consumed per minute in kg.

C_v = Lower calorific value of fuel, kcal per kg.

Then heat in fuel supplied per minute = WC_v kcal.

The energy supplied to I.C. engine in the form of fuel input is usually broken into following items :

(*a*) *Heat energy absorbed in I.H.P.*

The heat energy absorbed in indicated horse power, I.H.P. is found by the following expression :

Heat in I.H.P per minute

$$= \frac{\text{I.H.P.} \times 4500}{J} \text{ kcal.}$$

(*b*) *Heat rejected to cooling in water*

Let W_1 = Weight of cooling water supplied per minute (kg)

T_1 = Inlet temperature of cooling water in °C

T_2 = Output temperature of cooling water in °C

Then heat rejected to cooling water = $W_1 (T_2 - T_1)$

(*c*) *Heat carried away by exhaust gases*

Let W_2 = Weight of exhaust gases leaving per minute in kg.

(sum of weight of air and fuel supplied)

T_3 = Temperature of flue gases supplied per minute °C.

T_4 = Temperature C of exhaust gases.

K_P = Mean specific heat at constant pressure of exhaust gases

The heat carried away by exhaust gases

$$= W_2 \times K_p \times (T_4 - T_3) \text{ kg cal.}$$

(*d*) *Heat unaccounted for* (Heat lost due to friction, radiation etc.)

The heat balance sheet is drawn as follows :

Item	*Head units kcal*	*Per cent*
Heat in fuel supplied		
(*a*) Heat absorbed by I.H.P.		
(*b*) Heat rejected to cooling water.		
(*c*) Heat carried away by exhaust gases.		
(*d*) Heat unaccounted for (by difference)		
Total		

A typical heat balance sheet at full load for Diesel cycle (compression ignition) is as follows :

(*i*) Useful work = 30%
(*ii*) Heat rejected to cooling water = 30%
(*iii*) Heat carried away by exhaust gases = 26%
(*iv*) Heat unaccounted (Heat lost due to friction, radiation etc.) = 10%.

Example 4.1. *In a gas engine the mean effective pressure (m.e.p.) is 48 kg/cm² and the ratio of diameter of piston to stroke is* $\frac{2}{3}$. *Calculate the size of four stroke cycle gas engine if it runs at 250 P.P.M. and its B.H.P. is 16. The mechanical efficiency of the engine is 80%.*

Solution. Mechanical efficiency,

$$\eta_m = \frac{\text{B.H.P.}}{\text{I.H.P.}}$$

$$0.8 = \frac{16}{\text{I.H.P.}}$$

$$\text{I.H.P.} = \frac{16}{0.8} = 20.$$

Let D = Diameter of piston

L = Stroke

$$\text{I.H.P.} = \frac{P_m L.A.N.}{4500 \times k}$$

$$20 = \frac{4.8 \times L.A. \times 250}{4500 \times 2}$$

$$L.A. = 150$$

where L is in metres and A (area) is in cm^2.

Now $$\frac{D}{L} = \frac{2}{3}$$

If D is in centimetres.

$$L = \frac{3}{2} D = \frac{3}{2} D \times \frac{1}{100} \text{ metres}$$

Now $L.A. = 150$

$$\therefore \quad 150 = \frac{3}{2} \times D \times \frac{1}{100} \times \frac{\pi}{4} D^2$$

$$150 = \frac{3\pi D^3}{800}$$

$$D^2 = \frac{150 \times 180}{3 \times \pi} = 12{,}727$$

$$D = 22.7 \text{ cm.} \quad \textbf{Ans.}$$

and $$L = \frac{3}{2} \times D = \frac{3}{2} \times 22.7$$

$$= 3 \times 11.35 = 34 \text{ cm.} \quad \textbf{Ans.}$$

Example 4.2. *The following observations refer to trial on a four-stroke cycle gas engine :*

Mean effective pressure = 7 *kg/cm*^{2}
Fuel gas supplied = 0.24 *m*^{3}*/minute*
Calorific value of the gas = 4400 *kcal/m*^{3}

Stroke = 50 *cm.*
Bore = 20 *cm.*
Speed = 300 *R.P.M.*
Brake load = 70 *kg.*
Radius of brake drum = 0.8 *metres*

Determine the following :

(*a*) *I.H.P.*
(*b*) *B.H.P.*
(*c*) *Mechanical efficiency.*
(*d*) *Thermal efficiency.*

Solution. L = Stroke length = 0.5 m,

D = Bore = 20 cm.

Area $(A) = \frac{\pi}{4} \cdot (20)^2 = 314 \text{ cm}^2$.

P_m = mean effective pressure = 7 kg/cm^2.

$$\text{I.H.P.} = \frac{P_m L A N}{4500 \times k} \quad \text{where } k = 2$$

$$= \frac{7 \times 0.5 \times 3.14}{4500} \times \frac{300}{2} = 36.6.$$

$$\text{B.H.P.} = \frac{2\pi NT}{4500} = \frac{2\pi \times 300 \times 56}{4500} = 23.4$$

where T = Torque in kgm = $70 \times 0.8 = 56$ kgm.

Mechanical efficiency (%)

$$= \frac{\text{B.H.P.}}{\text{I.H.P.}} \times 100 = \frac{23.4}{36.6} \times 100 = 63.8\%$$

Heat supplied in fuel/minute

$$= 0.24 \times 4500 = 1080 \text{ kcal.}$$

Thermal efficiency on B.H.P. basis

$$= \frac{\text{B.H.P.} \times 4500}{1080 \times J} = \frac{23.4 \times 4500}{1080 \times 427} \times 100$$

$$= 22.7\%.$$

Example 4.3. *An internal combustion engine consumes 6 kg of fuel per hour and I.H.P. of engines is 27. It uses 12 kg of cooling water per minute and the inlet and outlet temperatures of water being 18°C and 48°C respectively. The exhaust gases raise the temperature of 3.40 kg of water through 32°C. The calorific value of fuel used is 10566 kcal per kg. Calculate the indicated thermal efficiency and draw heat balance sheet.*

Solution. Heat in fuel supplied per minute = WC_v

$$\frac{6}{60} \times 10{,}560 = 1056 \text{ kg cal.}$$

Indicated thermal efficiency

$$\eta_i = \frac{\text{I.H.P.} \times 4500}{W \cdot C_v \times J} \times 100$$

$$= \frac{27 \times 4500}{1056 \times 427} \times 100 = 27\%. \quad \textbf{Ans.}$$

Heat energy absorbed in indicated horse power

$$= \frac{\text{I.H.P.} \times 450}{J} = \frac{27 \times 4500}{427}$$

$$= 284 \text{ kcal}$$

Heat rejected to cooling water

$$= 12\,(48 - 18) = 12 \times 30 = 360 \text{ kcal.}$$

Heat carried away by exhaust gases

$$= 8.40 \times 32 = 368.8 \text{ kcal.}$$

Heat Balance Sheet

Item	*Heat unit (kcal)*	*(per cent)*
Heat supplied in fuel	1056	100%
Heat energy absorbed in I.H.P.	284	26.90
Heat rejected to cooling water	360	34.19
Heat carried away by exhaust gases	268.3	25.35
Heat unaccounted for (By Difference)	143.2	13.36
Total	1056	100%

Example 4.4. *A diesel power station is to supply power demand of 30 kW. If the overall efficiency of the power generating unit is 40% calculate the following :*

(a) Amount of diesel oil required per hour.

(b) The electric energy generated per tonne of the fuel oil.

The calorific value of fuel oil used is 12,000 kcal/kg.

Solution

(a) Efficiency = $\frac{\text{Output}}{\text{Input}}$

Output = 30 kW

Efficiency = 40%

$$\therefore \quad 0.4 = \frac{\text{Output}}{\text{Input}} = \frac{30}{\text{Input}}$$

$$= \frac{30}{0.4} = 75 \text{ kW}$$

Input per hour = $75 \times 1 = 75$ kWh.

Now 1 kWh = 860 kcal.

$\therefore$ Input per hour = $75 \times 860 = 64{,}500$ kcal.

$$\text{Fuel oil required} = \frac{64{,}500}{12{,}000} = 5.37 \text{ kg.}$$

(*b*) Input per tonne of fuel oil

$$= 1 \times 1000 \times 12{,}000 \text{ kcal} = 12 \times 10^6 \text{ kcal.}$$

$$= \frac{12 \times 10^6}{860} = 13{,}954 \text{ kWh}$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

Output = Efficiency × Input

$= 0.4 \times 13{,}954 = 5581$ kWh.

4.8 Diesel Engine Power Plant Auxiliaries

Auxiliary equipment consists of the following systems :

1. *Fuel supply system.* It consists of fuel tank for the storage of fuel, fuel filters and pumps to transfer and inject the fuel. The fuel oil may be supplied at the plant site by trucks, rail, road, tank, cars etc.

2. *Air intake and exhaust system.* It consists of pipes for the supply of air and exhaust of the gases. Filters are provided to remove dust etc. from the incoming air. In the exhaust system silencer is provided to reduce the noise.

Filters may be of dry type (made up of cloth, felt, glass, wool etc.) or oil bath type. In oil bath type of filters the air is swept over or through a bath of oil in order that the particles of dust get coated. The duties of the air intake systems are as follows :

(*i*) To clean the air intake supply.

(*ii*) To silence the intake air.

(*iii*) To supply air for super charging.

The intake system must cause a minimum pressure loss to avoid reducing engine capacity and raising the specific fuel consumption. Filters must be cleaned periodically to prevent pressure loss from

clogging. Silencers must be used on some systems to reduce high velocity air noises.

3. *Cooling system.* This system provides a proper amount of water circulation all around the engines to keep the temperature at reasonable level. Pumps are used to discharge the water inside and the hot water leaving the jacket is cooled in cooling ponds or other devices and is recirculated again.

4. *Lubricating system.* Lubrication is essential to reduce friction and wear of the rubbing parts. It includes lubricating oil tank, pumps, filters and lubricating oil cooler.

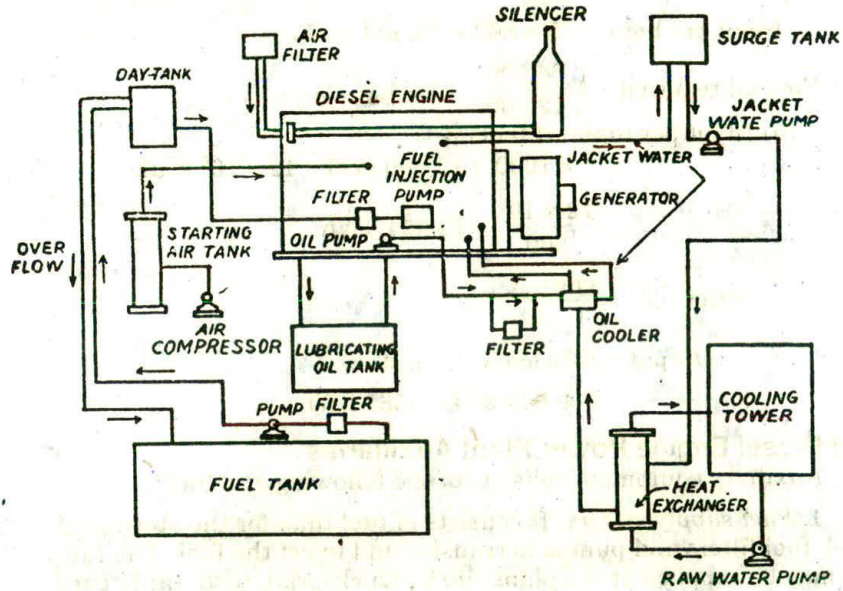


Fig. 4.9 (*a*)

5. *Starting system.* For the initial starting of engine the various devices used are compressed air, battery, electric motor or self starter. Fig. 4.9 (*a*) shows the auxiliary equipment of diesel engine power plant.

4.9 Internal Combustion Engine Cooling Methods

Due to combustion of fuel in the engine cylinder the temperature of burning gases is too high (nearly 1500° to 2000°C). This temperature may cause the distortion of some of the engine parts such as cylinder head and walls, piston and exhaust valves and may burn the lubricating oil. Thus a cooling arrangement is essential to carry

away some of the heat from the cylinder to avoid the over heating. A well designed cooling system should provide adequate cooling but not excessive cooling. A cooling system should :

(*i*) Absorb and dissipate the excess heat from the engine in order at prevent damage to the engine.

(*ii*) Maintain sufficient high operating temperature so that smooth and efficient operation of the engine take place.

It is observed that about 25 to 30% of the heat supplied is absorbed by the cooling medium. Fig. 4.9 (*b*) indicates a typical heat distribution for a reciprocating internal combustion engine.

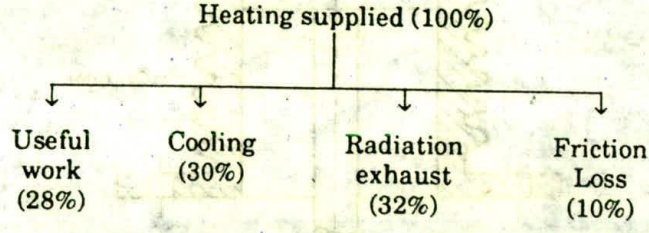


Fig. 4.9 (*b*)

The following points should be noted to achieve good cooling of diesel engine.

(*i*) Adequate quantity of water should continuously flow throughout the operation of the engine.

(*ii*) The cooling water should not be corrosive to metals.

(*iii*) The cooling water used for cylinder jackets should be free from scale forming impurities.

(*iv*) The temperature rise of cooling water should not be more than 11°C and the temperature of water leaving the engine should be limited to 60°C.

4.9.1 Cooling methods

There are two methods of cooling the I.C. Engines.

(*a*) Air cooling

(*b*) Water cooling.

Air Cooling. It is a direct method of cooling. In air cooled engines fins are cast on the cylinder head and cylinder barrel to increase its exposed surface of contact with air. Air passes over fins and carries away heat with it. Air for cooling the fins may be obtained from a blower or fan driven by the engine. Air moment relative to engine may be used to cool the engine as in case of motor cycle engine. About 13 to 15% of heat is lost by this method. Fig. 4.10 shows air cooling system. Simplicity and lightness are the advantages of air cooling. But this system is not as effective as water

cooling. The rate of cooling depends upon the velocity, quantity and temperature of cooling air and size of surface being cooled.

Fig. 4.10 (*a*) shows position of valves, Fins and head in air cooling system. This system is used in motor cycles, scooters and aeroplans.

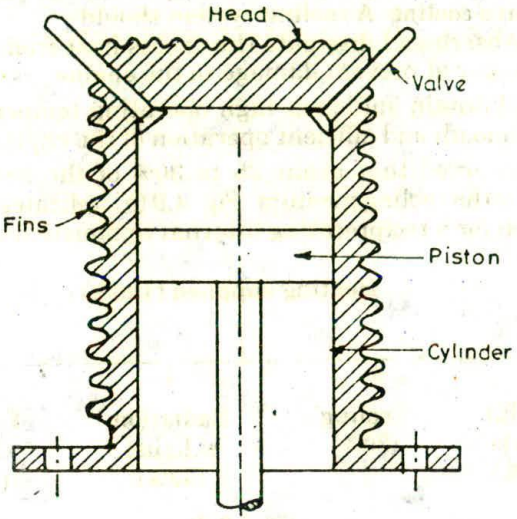


Fig. 4.10 (*a*) Air cooling system

Water Cooling. It is the indirect method of cooling the engine. The various cooling systems used are shown in Figs. 4.11 and 4.12. Water after circulating in water jackets (passages around the cylinder, combustion chamber valves etc.) goes as waste [Fig. 4.11] or in recirculating method of cooling [Fig. 4.12] water is continuously circulated through water jackets. Water takes up the heat and leaves for radiator where it is cooled for recirculation.

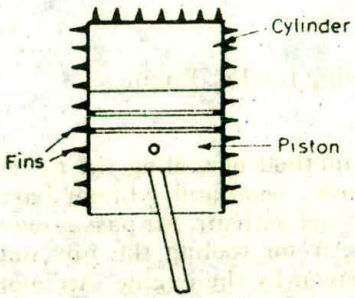


Fig. 4.10

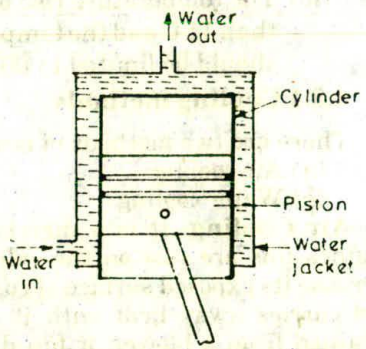


Fig. 4.11

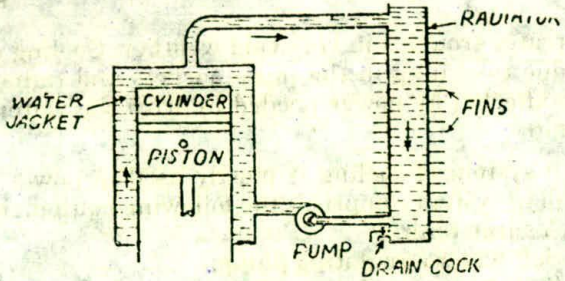


Fig. 4.12

In stationary diesel engine plants the water cooling systems used are as follows :

(*i*) *Open or Single Circuit System.* In this system [Fig. 4.13] pump draws the water from cooling pond and forces it into the main engine jackets. Water after circulating through the engine return to the cooling pond.

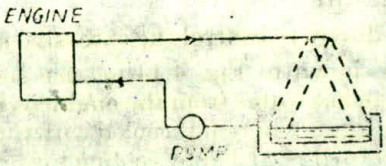


Fig. 4.13

(*ii*) *Closed or Double Circuit System.* In this system [Fig. 4.14] raw water is made to flow through the heat exchanger when it takes up the heat of jacket water and returns back to the cooling pond.

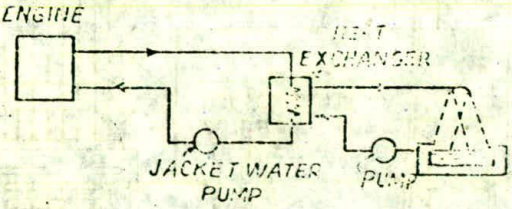


Fig. 4.14

Heat lost by water cooling is about 25 to 35%. The amount of heat lost is called jacket loss. The rate of flow of water should be so adjusted that the outlet temperature of cooling water does not exceed 60 C and rise in temperature of cooling water is limited to 11 C. The water used for cooling purposes should be free from impurities. Water cooling methods permit uniform cooling. Water

cooling creates troubles in very cold weather. Cooling efficiency is reduced due to scaling in the pipes, jackets and radiator. Engine efficiency affected by power needed to drive the water pump and radiator fan.

Closed system of cooling is mostly used in power stations. A closed cooling system comprises the following equipment.

(*i*) A surge tank.
(*ii*) Soft water circulating pump..
(*iii*) Soft water circulation pipe.
(*iv*) Soft water heat exchanger or cooler.
(*v*) Raw water softening plant.
(*vi*) Raw water circulation pump.
(*vii*) Raw water circulation pipe.
(*viii*) Raw water cooling arrangement such as cooling tower.
(*ix*) Thermometer for measuring inlet and outlet temperatures.
(*x*) Temperature regulator to control the excessive jacket temperature.
(*xi*) Safety device to control the excessive jacket temperature.

This system shown in Fig. 4.14 (*a*) use soft water for jacket cooling. The hot jacket water from the engine is passed through the cooler (heat exchanger) where it is cooled with the help of raw water. The raw water in turn is cooled by cooling towers.

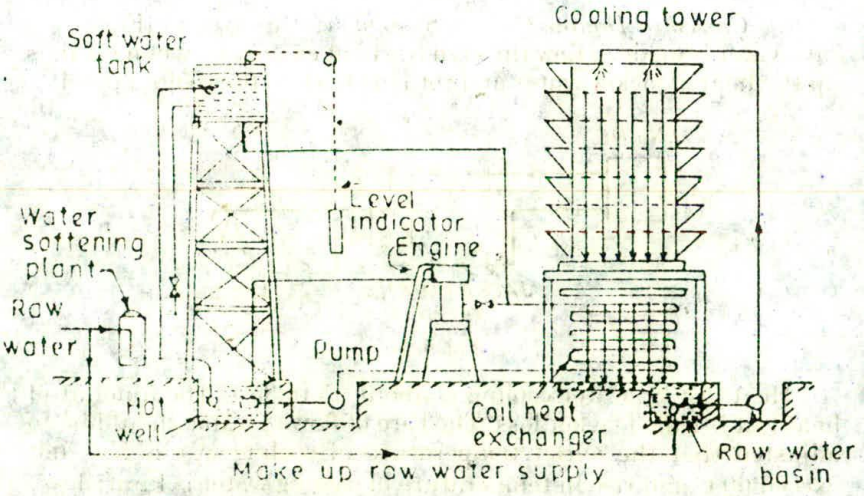


Fig. 4.14 (*a*)

4.10 Lubrication

Frictional forces causes wear and tear of rubbing parts of the engine and thereby the life of the engine is reduced. This requires that some substance should be introduced between the rubbing surfaces in order to decrease the frictional force between them. Such substance is called lubricant. The lubricant forms a thin film between the rubbing surfaces and prevents metal to metal contact. The various parts of an I.C. engine requiring lubrication are cylinder walls and pistons, big end bearing and crank pins small end bearing and gudgeon pins, main bearing cams and bearing valve tappet and guides and timing gears etc. The functions of a lubricant are as follows :

1. It reduces wear and tear of various moving parts by minimising the force of friction and ensures smooth running of parts.
2. It helps the piston ring to seal the gases in the cylinder.
3. It removes the heat generated due to friction and keeps the parts cool.

The various lubricants used in engines are of three types :

(*i*) Liquid Lubricants.
(*ii*) Solid Lubricants.
(*iii*) Semi-solid Lubricants.

Liquid oils lubricants are most commonly used. Liquid lubricants are of two types : (*a*) Mineral Oils (*b*) Fatty oils. Graphite, white lead and mica are the solid lubricants. Semi solid lubricants or greases as they are often called are made from mineral oils and fatty-oils.

A good lubricant should possess the following properties :

(*i*) It should not change its state with change in temperature.
(*ii*) It should maintain a continuous films between the rubbing surfaces.
(*iii*) It should have high specific heat so that it can remove maximum amount of heat.
(*iv*) It should be free from corrosive acids.
(*v*) The lubricant should be purified before it enter the engine. It should be free from dust, moisture, metallic chips, etc. The lubricating oil consumed is nearly 1% of fuel consumption.

The lubricating oil gets heated because of friction of moving parts and should be cooled before recirculation. The cooling water used in the engine may be used for cooling the lubricant. Nearly $2\frac{1}{2}\%$ of heat of fuel is dissipated as heat which is removed by the lubricating oil.

Lubricating oil is purified by following four methods :

(*i*) Settling,

(*ii*) Centrifuging,

(*iii*) Filtering,

(*iv*) Chemical reclaiming. The centrifuging widely used gives excellent purification when properly done.

Fig. 4.15 shows the lubricating oil external circuit.

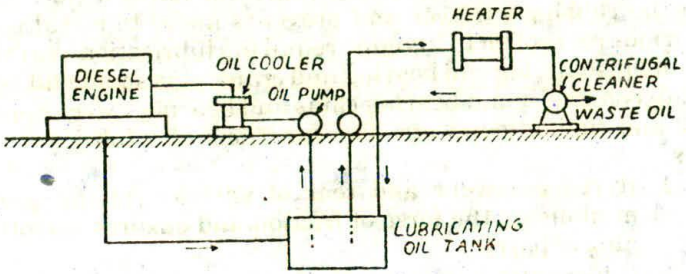


Fig. 4.15

4.11 Engine Starting Methods

Spark ignition engines (Petrol engines) are used mainly in smaller size where compression ratio to be our come in cranking is only 5 to 7. Hand and electric motor (6 – 12 V, d – C) cranking are practical. Diesel engines are difficult to be started by hand cranking because of high compression required and therefore mechanical cranking system is used.

The various methods used for the starting of diesel engine are as follows :

1. *Compressed Air System.* Compressed air system is used to start large diesel engines. In this system compressed air at a pressure of about 20 kg per sq. cm is supplied from an air bottle to the engine an inlet valve through the distributor or through inlet manifold. In a multi-cylinder engine compressed air enters one cylinder and forces down the piston to turn the engine shaft. Meanwhile the suction stroke of some other cylinder takes place and the compressed air again pushes the piston of this cylinder and causes the engine crank shaft assembly to rotate. Gradually the engine gains momentum and by supplying fuel the engine will start running.

2. *Electric Starting.* Electric starting arrangement consists of an electric motor which a drives pinion which engages a toothed rim on engine flywheel. Electric power supply for the motor is made available by a small electric generator driven from the engine. In

case of small plants a storage battery of 12 to 36 volts is used to supply power to the electric motor.

The electric motor disengages automatically after the engine has started. The advantages of electric starting are its simplicity and effectiveness.

3. *Starting by an Auxiliary Engine.* In this method a small petrol engine is connected to the main engine through clutch and gear arrangements. Firstly, the clutch is disengaged and petrol engine is started by hand. Then clutch is gradually engaged and the main engine is cranked for starting. Automatic disengagement of clutch takes place after the main engine has started.

4.12 Starting Procedure

Actual process of starting the engine differs from engine to engine. Some common steps for starting the engine are as follows:

1. Before starting the engine it is desirable to check fuel system, lubricating system and cooling water supply.
2. Depending upon the method of starting a check for the same is essential. If air starting is used the pressure of air should be checked and also the air system should be checked for possible leakage. The storage battery should be checked if electric motor is used for starting.
3. There should be no load on the engine.
4. Crank the engine and run it at slow speed for a few minutes and again check the working of various systems such as fuel, lubricating oil system etc.

The speed of the engine should be gradually increased till it synchronises with the bus bars. Then connect the generator to the bus bars and finally increase the engine speed so that it takes up the desired load.

4.12.1 Stopping the Engine

The engine should not be stopped abruptly. Top stop the engine the speed should be decreased gradually until no power is delivered by the alternator. Then the engine is disconnected from the bus bars and is allowed to run idle for some time.

4.13 Starting Aids

Starting aids may be used during cold weather to obtain quicker starting of the engine. Ethyl ether is mostly used as such aid. Glow plugs are another starting aid. Glow plug forms a local hot spot thus initiating the combustion of fuel even if the compression temperature of air is insufficient.

4.13.1 Warming up of Diesel Engine

The diesel engine should be allowed to warm up for four to five minutes after the engine has started. During this time the following points should be checked.

(*i*) To check whether the firing is correct in all cylinders
(*ii*) To check the operation of fuel pump
(*iii*) To check the cooling water system, circulating water pump etc.
(*iv*) To check the lubrication system
(*v*) To check the colour of exhaust gases etc. to know whether the combustion is proper.

After these checks the engine should be put on load. Then the speed of engine should be gradually increased in order to synchronise the incoming generator with the station bus bars.

4.14 I.C. Engine Fuel

The internal combustion engines use both oil and gas fuels, the former being predominant. The oils used are specified according to the following properties :

(*i*) Cetane number
(*ii*) Viscosity
(*iii*) Volatility
(*iv*) Pour point
(*v*) Flash and fire point
(*vi*) Heating value
(*vii*) Distillation test
(*viii*) Aniline point
(*ix*) Conradson Carbon
(*x*) Ash

Cetane number indicates the ease with which fuel ignites when injected whereas viscosity is significant in oil-handling, volatility is an index of ease with which the combustible fuel air mixture can be prepared and pour point indicates the temperature at which oil flows. Fire hazards of an oil depend on flash and the fire point. Heating value measures the thermal energy in fuel and the distillation test is carried out to indicate whether oil contains any heavy ends of the refining process which generally burn poorly. Aniline point of oil fuel is used in calculating the diesel index which measures ignition quality. Conradson carbon indicates fire extent of components in oil with a tendency to form carbon deposits and ash indicates the components of oil believed to cause cylinder wear.

4.15 Fuel Supply

The fuels used in I.C. engines are in liquid form. They are preferred because of their high calorific value and case of storage and handling. The storage of oil fuel is simpler than the solid fuel. The amount of fuel to be stored depends upon the service hours and varies for different installations. Bulk storage and engine day tanks hold the engine fuel. The fuel delivered to the power plant is received in storage tanks. Pumps draw the oil from storage tanks and supply

it to the smaller day tanks from where the oil is supplied to the engine as shown in Fig. 4.16.

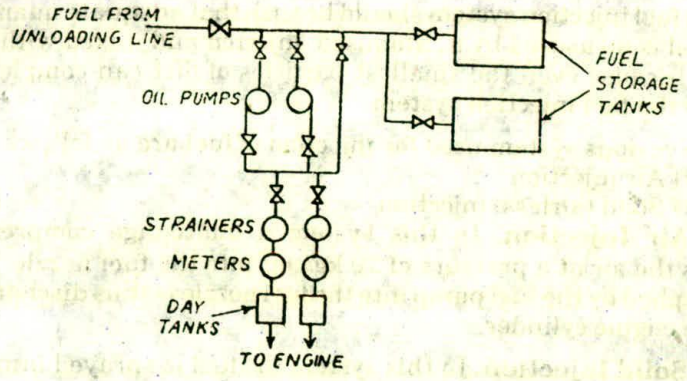


Fig. 4.16

The fuel oil used should be free from impurities. Efforts should be made to prevent contamination of the fuel. An important step is to reduce the number of times the fuel is handled. Greater amount of impurities settle down in the storage tank and remaining impurities are removed by passing the oil through filters. Storage tank may be located above the ground or underground. But underground storage tanks are preferred. Fig. 4.17 shows an underground storage tank. It is provided with coils, heated by steam or hot water to reduce the viscosity and to lower the pumping cost. Main hole is provided for internal access and repair. Vent pipe is provided to allow the tank to breathe as it is filled or emptied. Level indicator measures the quantity of oil in the tank, and an overflow line is provided to control the quantity of oil.

4.16 Diesel Engine Fuel Injection System

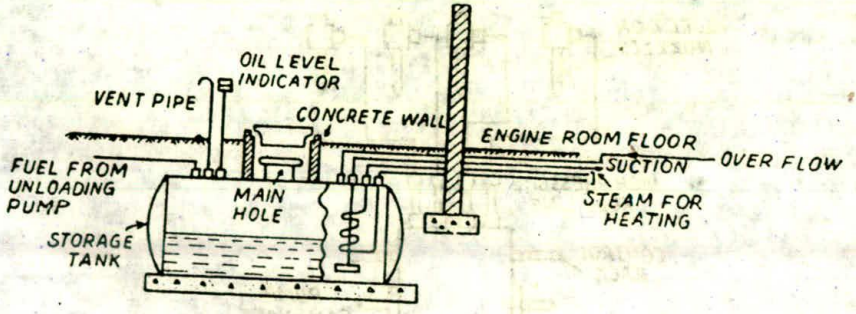


Fig. 4.17

The fuel injection system should be such that adequate quantity of fuel oil is measured by it, atomised, injected and mixed with the fuel oil because even the smallest particles of dirt can completely damage the fuel injection system.

The various system used for injection of fuel are as follows :

(*i*) Air injection

(*ii*) Solid (airless) injection

(*i*) **Air Injection.** In this system a multistage compressor delivers the air at a pressure of 70 kg/cm^2 into the fuel nozzle. The fuel supplied by the fuel pump into the fuel nozzle is thus discharged into the engine cylinder.

(*ii*) **Solid Injection.** In this system the fuel is sprayed into the engine cylinder at a pressure of about 100 to 140 kg/cm^2. Solid injection systems are available in three types :

(*i*) Unit injector.

(*ii*) Pump injection.

(*iii*) Distributor injection.

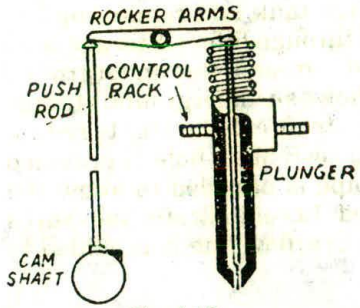


Fig. 4.18

(*i*) **Unit Injector.** In this system a pump plunger is actuated by a cam through a push rod and rocker arm mechanism. The plunger moving in a barrel raises the p sure of fuel oil meters the q of fuel and controls the inj timing. There is a spring lo delivery value in the nozzle. Th valve is actuated by the change in fuel oil pressure (Fig. 4.18).

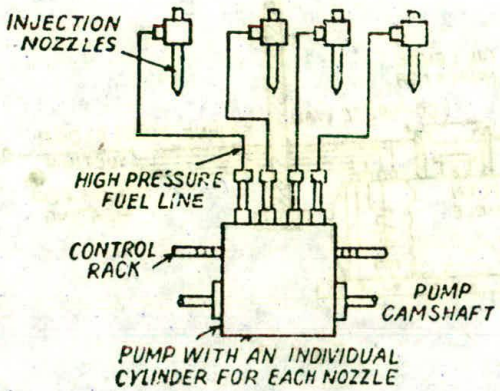


Fig. 4.19

(*ii*) **Pump Injection.** In this system individual pump is provided for each nozzle. The pump measures the fuel charge and controls the injection timing (Fig. 4.19).

(*iii*) **Distributor Injection.** In this system (Fig. 4.20) a pump measures and pressurises the fuel and supplies to it the various nozzles through a distributor block.

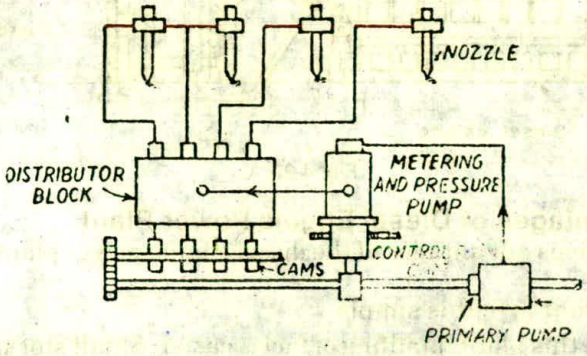


Fig. 4.20

4.17 Fuel Injection Nozzle

Fuel injection takes place through very fine holes in the nozzle body. There are several types of fuel injection nozzles. Two common types are multihole nozzle [Fig. 4.21 (*a*)] and pintle nozzle [Fig. 4.21 (*b*)]. In multihole nozzle each spray orifice produce a dense and compact spray. In pintle nozzle, fuel comes out in the form of conical spray.

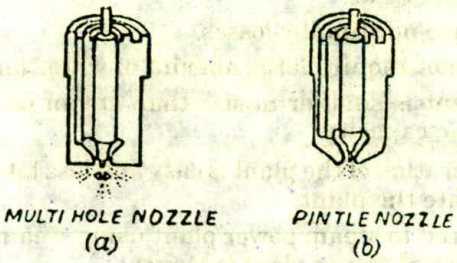


Fig. 4.21

4.18 Filter and Silencer Installation

Fig. 4.22 shows a typical filter and silencer installation for diesel engine. The air system begins with an intake located outside the building provided with a filter which may be oil impingement, oil path of dry type filter. The function of the filter is to catch dirt by

causing it to cling to the surface of filter material. A silencer is provided between the engine and the intake.

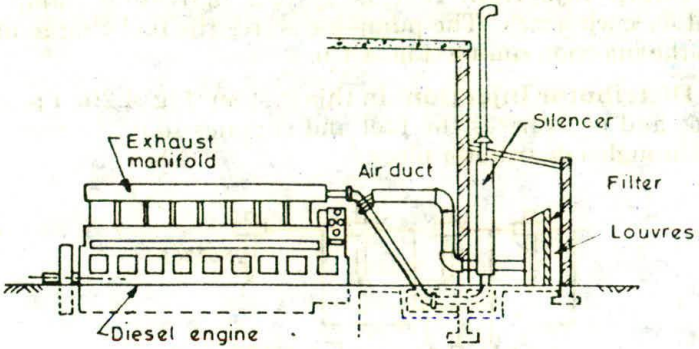


Fig. 4.22

4.19 Advantages of Diesel Engine Power Plant

The various advantages of the diesel engine power plants are as follows :

1. Plant layout is simple.
2. In this plant handling of fuel is easier. Small storage space for fuel is required, there is no refuse to be disposed off and oil needed can be easily transported.
3. It can be located near load centre.
4. A diesel engine extracts more useful work from each heat unit than other types or I.C. engines. Therefore, it becomes an attractive prime mover wherever first cost is written off and operating cost is important.
5. The plant can be quickly started and can pick up load in very short time.
6. There are no standby losses.
7. It does not require large amount of water for cooling.
8. The plant is smaller in size than steam power plant for the same capacity.
9. The operation of the plant is easy and less labour is needed to operate the plant.
10. Compared to steam power plant using steam turbine, the life of diesel power plant is longer.
11. Diesel engines operate at higher thermal efficiency as compared to steam power plants.

Disadvantages

1. Diesel oil is costly

2. The plant does not work satisfactorily under overload conditions for longer times.
3. Lubrication cost is high.
4. The capacity of plant is limited.

4.20 Site Selection

While selection the site for diesel engine power plant the following factors should be considered :

1. *Distance from load centre.* The plant should be located near the load centre. This will minimize the cost of transmission lines, the maintenance and power losses through them.

2. *Availability of water.* Water should be avaiiable in sufficient quantity at the site selected.

3. *Foundation condition.* Sub-soil conditions should be such that a foundation at a reasonable depth should be capable of providing a strong support to the engine.

4. *Fuel transportation.* The site selected should be near to the source of fuel supply so that transportation charges are low.

5. *Access to site.* The site selected should have road and rail transportation facilities.

The site selected should be away from the town so that the smoke and other gases coming out of the chimneys do not effect the inhabitants.

4.21 Layout

Layout of diesel engine power plant is shown in Fig. 4.23. Generally the various units are installed with parallel centre lines.

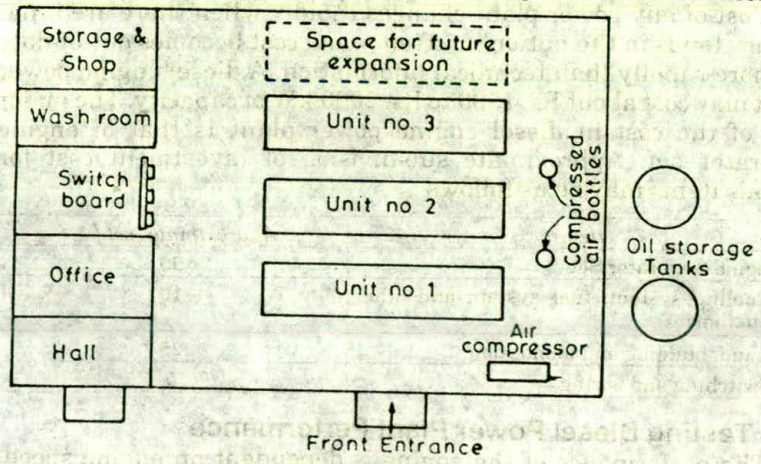


Fig. 4.23

Some space is left for future expansion. Sufficient space should be provided around the various units for dismantling and repairing the engine. The engine room should be provided with adequate ventilation. Fuel oil storage tanks may be located outside the main buildings.

4.22 Applications of Diesel Engine Plants

1. They are quite suitable for mobile power generation and are widely used in transportation systems consisting of rail roads, ships, automobiles and aeroplanes.
2. They can be used for electrical power generation in capacities from 100 to 5000 H.P.
3. They can be used as standby power plants.
4. They can be used as peak load plants for some other types of power plants.
5. Industrial concerns where power requirement are small say of the order of 500 kW, diesel power plants become more economical due to their higher overall efficiency.

Diesel power plant is quite suitable at places where

(*i*) Fuel prices or reliability of fuel supply favour oil over coal.

(*ii*) Water supply is limited.

(*iii*) Loads are relatively small.

(*iv*) Power from other power plants such as steam, hydro power plants etc. is not available or is available at too high rates.

4.23 Cost of Diesel Power Plant

Cost of any power plant changes rapidly when there are inflationary tends in the nation's currency and cost becomes out-of-date far more rapidly than technical information. A diesel engine power plant may cost about Rs. 1500 to Rs. 2000/kW of capacity. The major part of the cost in diesel engine power plant is that of engine generator set. Approximate sub-division of investment cost for various items may be as follows :

Item	*Approximate cost (%)*
(*i*) Engine Generator Set	90
(*ii*) Cooling system, fuel system and other auxiliaries	10
(*iii*) Land, building and foundation	25
(*iv*) Switching and wiring	5

4.24 Testing Diesel Power Plant Performance

The performance of the engine is dependent on engine speed, compression ratio, weight of inducted air and friction losses. The newly purchased equipment is tested for various standards set up

by the Indian Standards Institution and other such institutions. Tests such as checking of preliminary caliberations, accuracy of tolerances methods, specific thermal performance, accuracy of speed control, governor characteristics and cyclic irregularity are conducted to know whether the equipment supplied is up to the standards specified. Careful supervision of the equipment used for recording temperature, pressure and electrical data are essential. The temperature inside the engine should not be allowed to exceed safe limits as diesel engine is an all metal machine and there is no refractory protection. Incorrect working of pressure gauges, thermometers and automatic warning signals is very harmful. For testing the cycle of the engine mechanical indicators are used for low speed and for higher speed electronic indicators are used. Electronic indicators given pressure time data which can be converted into pressure volume (*p.v.*) data by graphical devices and then mean effective pressure, power, valve action etc., can be determined.

The important items can be measured for predicting the performance and making energy balance. They are as follows :

(*i*) Rate of fuel consumption
(*ii*) I.H.P. (*iii*) B.H.P.
(*iv*) Quantity of cooling water and its rise in temperature
(*v*) Quantity of air (*vi*) Atmospheric temperature
(*vii*) Temperature of exhaust gas
(*viii*) Orsat analysis.

To calculate air consumed by the engine the volumetric efficiency is calculated. To watch the performance of the plant heat balance sheet is drawn and for this flow of fuel, coolant, exhaust gases, temperature of these flows, quantity of fuel and air recorded. B.H.P. of the engine connected to the generator is calculated by finding the output of the generator (measurable by electrical instruments) and efficiency of the generator. The heat lost due to friction, radiation etc. can be found from the heat balance sheet.

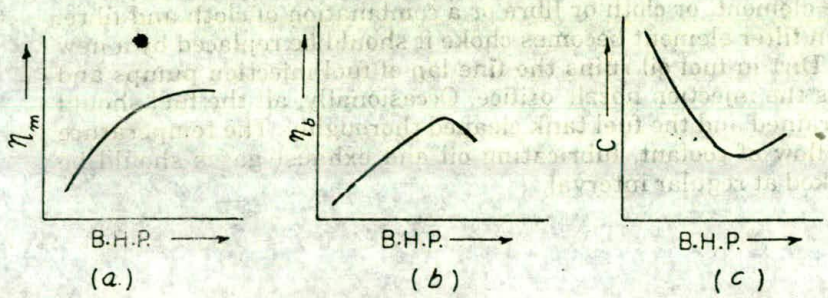


Fig. 4.24

The typical performance of a diesel engine is shown in Fig. 4.24. The variation of mechanical efficiency (η_m), brake thermal efficiency (η_b) and specific fuel consumption (S) with B.H.P. is indicated in the figure.

4.25 Log Sheet

It is the official record of instrument reading and operating details entered up by the plant operator.

4.26 Advantages of I.C. Engine over Steam Engine

Both I.C. engine and steam engine are basically heat engines but in I.C. engine the combustion of fuel takes place inside the engine cylinder whereas the combustion of fuel in steam engine takes place outside the cylinder. In I.C. engine the pressure and temperature inside the cylinder is very high and therefore, construction material with better resistance are required. The various advantages of I.C. engine over steam engine are as follows :

1. I.C. engine has higher efficiency ranging from 35 to 40% whereas the efficiency of steam engine lies between 15 to 20%.
2. I.C. engines has low weight to power ratio due to its compact design.
3. I.C. engines are usually single acting and hence there is no necessity of stuffing box glands for piston rod.
4. To start a steam engine firstly the boiler is to be fired and steam to be raised whereas I.C. engine can be quickly started.

4.27 Plant Maintenance

Diesel engine power plant maintenance depends on various factors. Careful supervision of the equipment used for recording temperature pressure and electrical data are essential. The temperature inside the engine should not be allowed to exceed the safe limits as diesel engine is an all metal machine and there is no refractory protection. The temperature, flow and quality of fuel oil should be checked from time to time. The fuel oil must be cleaned from dirt and other impurities by means of filters. Filters may have fibre element, or cloth or fibre or a combination of cloth and fibre. When filter element becomes choke it should be replaced by a new one. Dirt in fuel oil ruins the fine lap of fuel injection pumps and plugs the injection nozzle orifice. Occasionally, all the fuel should be drained and the fuel tank cleaned thoroughly. The temperature and flow of coolant, lubricating oil and exhaust gases should be checked at regular interval.

4.28 Specific Fuel Consumption

One of the most important parameters used for the comparison of engines and one which is based on power produced or delivered is the specific fuel consumption. It is defined as the ratio of amount of fuel (kg) used by the engine per hour to the horse power produced or delivered by the engine, when specific fuel consumption is based on I.H.P. produced it is called indicated specific fuel consumption and if specific fuel consumption is based in B.H.P. delivered it is called brake specific fuel consumption.

4.29 Comparison of a Diesel Engine and Petrol Engine

Diesel engines are quite efficient at part loads as compared to petrol engines and work efficiently in greater range.

A diesel engine is superior than a petrol engine because of the following factors :

(*i*) The compression ratio is higher than a petrol engine and this increases the efficiency of the engine. The variation of air standard efficiency (η) with ratio of compression(r) is shown in Fig. 4.25.

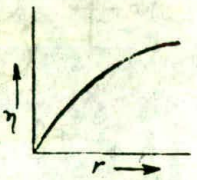


Fig. 4.25

(*ii*) In diesel engine, the combustion take place approximately at constant pressure rather than at constant volume as in a petrol engine.

(*iii*) No electric spark is required.

(*iv*) As diesel is cheaper than petrol, therefore, the power cost in diesel engine is low.

4.30 Supercharging

The I.H.P. produced by an I.C. engine is almost directly proportional to the air consumed by the engine. Increasing the air consumption permits the greater quantities of fuel to be added and results in greater power produced by the engine. It is, therefore, desirable that the engine should take in the greatest possible mass of air. The supply of air is pumped into the cylinder at a pressure greater than the atmospheric pressure and is called supercharging. When greater quantity of air is supplied to an internal combustion engine it would be able to develop more power for the same size and conversely a small size engine fed with extra air would produce the same power as a larger engine supplied with its normal air feed. Supercharging is used to increase rated power output capacity of a given engine or to make the rating equal at high altitudes corresponding to the unsupercharged sea level rating.

Supercharging is done by installing a super charger between engine intake and air inlet through air cleaner super charger 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. Power required to drive the super charger is taken from the engine and thereby removes from over all engine output some of the gain in power obtained through supercharging.

There are two types of compressors that may be used as super chargers. They are as follows :

(*i*) Positive displacement type super chargers.

(*ii*) Centrifugal type super chargers.

Positive displacement type super chargers are further of three types as follows :

(*a*) Rotary type. (*b*) Screw type

(*c*) Piston and cylinder type.

In rotary type super chargers the air is compressed by a meshing gear arrangement called Roots blower as shown in Fig. 4.26 or by a

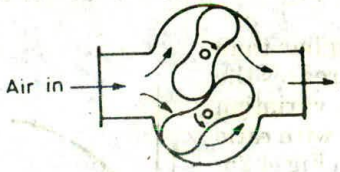


Fig. 4.26

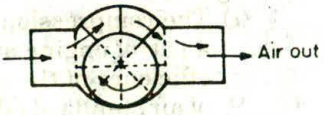


Fig. 4.27

rotating vane element as shown in Fig. 4.27. The air is taken from intake and discharged at outlet end. It screw type supercharger the air is trapped between inter meshing helical shaped gears and forced out axially. In piston and cylinder type super-charger the piston compresses the air in a cylinder whereas a centrifugal type super-charger has an impeller running in a housing at a high speed, centrifugal supercharger is commonly by used in reciprocating power plants for aircraft.

4.31 Advantages of Supercharging

Due to a number of advantages of supercharging the modern diesel engines used in diesel plants are generally supercharged. The various advantages of supercharging are as follows :

(*i*) For given output engine size is reduced.

(*ii*) Engine output can be increased by about 30 to 50%.

(*iii*) The specific fuel consumption of a super charged engine is less than natural aspirated engine. This is due to the fact that combustion is supercharged engine is better due to better mixing of fuel and air.

(*iv*) Supercharged engine has higher mechanical efficiency.

(*v*) Supercharging reduces the possibility of knocking in diesel engine.

4.32 Factors Affecting Engine Performance

Diesel engine can extract more work out of each heat with unit than other engines.

Various factors which affect performance of a diesel engine are as follows :

(*i*) Amount of fuel burnt per minute.

(*ii*) Brake mean effective pressure.

(*iii*) *Fuel injection system* : An efficient fuel injection system is needed. The required quantity of fuel should be measured out, injected, atomised and mixed with combustion-air.

(*iv*) Combustion process.

(*v*) Fuel-air ratio.

(*vi*) Type of engine such as two stroke or four stroke engine. Two stroke engines are generally used in diesel power plants.

(*vii*) Cooling method.

(*viii*) Size of cylinder.

4.33 Combustion Phenomenon in C.I. Engines

In C.I. engines the intake is air alone and the fuel is injected at high pressure in the form of fine droplets near the end of compression. The normal compression ratios are in the range of 14 to 17. The air fuel ratio used in C.I. engines lie between 18 and 25 as against 14 in S.I (spark ignition) engines. Therefore C.I. engines are bigger and heavier for the same power out put than S.I. engine.

In C.I. engine combustion occurs by the high temperature produced by the compression of air *i.e.* it is an auto ignition. 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 internal is inflamed at the surface of envelope.

4.34 Comparison of Gas Turbine with Reciprocating I.C. Engine

Gas turbines and reciprocating I.C. engines are used for former generation.

Advantages of gas turbines over I.C engines are as follows :

(*i*) Gas turbine has lesser number of parts.

(*ii*) Mechanical losses in gas turbines are less because in gas turbine the single rotating unit consists of a compressor and a turbine together with a few main bearings compared to complicated reciprocating mechanism with its valve gear arrangement which are the prime sources of losses due to firction. Further oil and fuel supply pumps are not used thus reducing mechanical losses.

(*iii*) The life of gas turbine is longer than I.C. engine.

(*iv*) It is easier to carry out heat transfer process.

(*v*) Gas turbine has large power to weight ratio.

This reduces cost of gas turbine. This makes it more suitable prime mover in mobile power units particularly in air crafts.

(*vi*) Gas turbine is simple in construction.

(*vii*) The gas turbine is reliable in operation because balancing of rotating masses both static and dynamic, can be very accurately done and unlike reciprocating engines the torsional vibration effects due to combustion load changes and inertia effects are absent due to the steady flow nature that renders continuous effect on the rotor blades of compressor and turbine.

Further the absence of valve and valve gears is another reason for quiet running of gas turbines.

(*viii*) In gas turbine the parts that are to be lubricated are few in numbers.

(*ix*) Maintenance is easier.

Example 4.6. *A diesel engine has a brake thermal efficiency of 30%. If the calorific value of fuel used in 10000 kcal/kg, calculate the brake specific fuel consumption.*

Solution. η_b = Brake thermal efficiency = 0.3

I.H.P. hr = 632.5 kcal

$$\eta_b = \frac{\text{H.P. hr equivalent}}{w \times \text{C.V.}}$$

where w = Specific fuel consumption per H.P. hr.

C.V. = Calorific value of fuel = 10,000 kcal/kg

$$0.3 = \frac{632.5}{w \times 10{,}000}$$

$$w = \frac{632.5}{0.3 \times 10{,}000} = 0.21 \text{ kg/H.P. hr.} \quad \textbf{Ans.}$$

Example 4.7. *A six cylinder two stroke cycle marine diesel engine with 100 mm bore and 120 mm stroke delivers 200 B.H.P. at*

2000 R.P.M. and uses 100 kg of fuel per hour. If I.H.P. is 240, determine the following :

(a) Torque, (b) Mechanical efficiency, (c) Indicated specific fuel consumption.

Solution. (a) $\text{B.H.P.} = \frac{2\pi NT}{4500}$

where T = Torque

N = R.P.M.

$$200 = \frac{2\pi \times 2000 \times T}{4500}$$

$$T = \frac{200 \times 4500}{2\pi \times 2000} = 71.7 \text{ kg.m}$$

(b) η_m = Mechanical efficiency

$$= \frac{\text{B.H.P.}}{\text{I.H.P.}} = \frac{200}{240} = 0.83.$$

(c) Indicated specific fuel consumption $= \frac{W}{\text{I.H.P.}}$

where W = Amount of fuel used per hour.

Indicated specific fuel consumption

$$= \frac{100}{240} = 2.41 \text{ kg/I.H.P. hour.}$$

Example 4.8. *A diesel engine develops 200 H.P. to over come friction and delivers 1000 BHP. Air consumption is 90 kg per minute. The air fuel ratio is 15 to 1. Find the following :*

(a) IHP, (b) Mechanical efficiency , (c) Specific fuel consumption.

Solution. (a) B.H.P. = 1000

F.H.P. = 200

IHP = BHP + FHP = 1000 + 200 = 1200

(b) η_m = Mechanical efficiency

$$= \frac{\text{BHP}}{\text{IHP}} = \frac{1000}{1200} = 0.83 = 83\%$$

(c) K = Air fuel ratio = 15

W = Air consumed per hour

= 90 × 60

= 5400 kg per hour

S = Amount of fuel consumed

$$= \frac{W}{K} = \frac{5400}{15}$$

$$= 360 \text{ kg per hour}$$

$$\text{Specific fuel consumption} = \frac{S}{IHP} = \frac{360}{1200}$$

$$= 0.3 \text{ kg/IHP hr.}$$

PROBLEMS

4.1. How will you classify I.C. engines ? Describe the working of two stroking of two stroke and four stroke cycle diesel engines. Discuss their relative merits and demerits.

4.2. What are the different methods of cooling diesel engine ? Compare air cooling and water cooling.

4.3. Describe the various methods used for starting diesel engine. Describe in correct sequence the steps for starting and stopped procedure.

4.4. Describe the auxiliary equipment of diesel engine power plant.

4.5. Give the layout of a diesel engine plant.

4.6. What are the various methods of fuel injection ? What precautions should be observed to ensure that fuel injection is satisfactory ?

4.7. What are the various factors to be considered while selecting the site for diesel engine power plant ? Discuss the advantages and disadvantages of the diesel power plant.

4.8. Compare I.C. engine with steam engine and state the advantage of I.C. engine over steam engine.

4.9. What is the importance of heat balance sheet ? What are the various items considered while drawing the heat balance sheet of I.C. engine ? Give a typical heat balance at full load for an I.C. engine.

4.10. Describe the procedure of testing diesel power plant performance. How is plant maintenance carried out ?

4.11. Write short notes on the following :
(*a*) Lubrication of diesel power plant.
(*b*) Indicated Thermal Efficiency, I.H.P. and B.H.P.
(*c*) Applications diesel power plant.
(*d*) Warming up of diesel engine.

4.12. Describe a typical filter and silencer installation for a diesel engine.

4.13. Define specific fuel consumption. Explain indicated specific fuel consumption and brake specific fuel consumption.

4.14. A four stroke diesel engine gave the following test results at a speed of 450 R.P.M.

Mean effective pressure	= 8.50 kg/cm^2
Cylinder bore	= 22 cm.
Stroke	= 26 cm.
Specific fuel consumption	= 0.32 kg/BHP/hr
Calorific value of fuel	= 11800 kcal per kg.

Mechanical Efficiency = 38%
Determine the following :
(*a*) B.H.P.
(*b*) I.H.P.
(*c*) Indicated thermal efficiency.
(*d*) Brake thermal efficiency.

4.15. Compare a diesel and petrol engine.

4.16. Write short notes on the following :
(*a*) I.C. engine fuels.
(*b*) Cost of diesel power plant.

4.17. (*a*) What is supercharging ? What methods are used for supercharging diesel engines ?
(*b*) Discuss the advantages of supercharging.

4.18. (*a*) Under what conditions diesel generating plants are preferred ?
(*b*) On what factors is the size of the generating plant selected ?
(*c*) Draw a net diagram of a cooling system used for diesel power plants 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 ?

4.19. Name the methods used to purify lubricating oil.

5

Nuclear Power Plant

5.1 Nuclear Energy

As large amounts of coal and petroleum are being used to produce energy, time may come when their reserves may not be able to meet the energy requirements. Thus there is tendency to seek alternative sources of energy. The discovery that energy can be liberated by the nuclear fission of materials like uranium (U), plutonium (Pu), has opened up a new sources of power of great importance. The heat produced due to fission of U and Pu is used to heat water to generate steam which is used for running turbo-generator.

It has been found that one kilogram of U can produce as much energy as can be produced by burning 4500 tonnes of high grade coal. This shows that nuclear energy can be successfully employed for producing low cost energy in abundance as required by the expanding and industrialising population of future.

Wisely used nuclear energy can be of great benefit for mankind. It can bridge the gap caused by inadequate coal and oil supplies. It should be used to as much extent as possible to solve power problem. Some of the factors which go in favour of nuclear energy are as follows :

1. Hydro-electric power is of storage type and is largely dependent on monsoons. The systems getting power from such plants have to shed load during the period of low rainfall.
2. Oil is mainly needed for transport, fertilizers and petrochemicals and thus cannot be used in large quantities for power generation.
3. Coal is available only in some parts of the country and transportation of coal requires big investments.
4. Nuclear power is partially independent of geographical factors, the only requirement being that there should be reasonably good supply of water. Fuel transportation net-

works and larger storage facilities are not needed and nuclear power plant is a clean source of power which does not pollute the air if radio active hazards are effectively prevented.

5. Large quantity of energy is released with consumption of only a small amount of fuel.

World's first nuclear power plant was commissioned in 1954 in U.S.S.R. Since then efforts are being made to make use of nuclear power.

In India, it was Dr. H.J. Bhabha who put India on the road to nuclear research, more than two decades ago. He had in his mind not the destructive power of atom but using this new source of immense energy for peaceful purposes like power production. India at present has four nuclear power plants. First nuclear power plant is at Tarapur. It has two boiling water reactors (B.W.R.) each of 200 MeW capacity and each uses enriched U as fuel. These two reactors have been built with the help of U.S.A. The other two nuclear power plants are at Rana Pratap Sagar in Rajasthan and at Kalpakkam in Tamil Nadu. The fourth nuclear power plant has been built at Narora in U.P.

Nuclear energy is the most useful power available to mankind today. In large parts of the world it is becoming a predominant source of electrical power and a versatile tool for use in many areas of human endeavour. In India too atomic energy is being used to generate electricity and to bring about improvement in industry, agriculture, medicine and in other fields through its varied applications.

The major centre for research and development work in atomic energy in our country is the Bhabha Atomic Research Centre (BARC) at Trombay. The centre is the largest single scientific establishment in India. Besides BARC three other national institutions associated with some important aspects of atomic energy programme are as follows :

(*i*) Tata Institute of Fundamental Research, Bombay.
(*ii*) Tata Memorial Centre Bombay.
(*iii*) Saha Institute of Nuclear Physics, Calcutta.

Nuclear power plants resemble, convential thermal power plants insofar as they produce steam to drive a turbine whose rotational energy is converted into electricity by means of a generator. In contrast to power plants fired by coal, oil, or gas, nuclear power plant use the energy released from splitting atoms to convert water into steam. The "fuel" that leads itself to this splitting procedure is the uranium atoms, and its splitting, or fission, is engineered within a reactor.

India went nuclear in 1956 when its first research reactor went critical at Trombay. Six units are now under various phases of operation construction or design two each at Kota, Kalpakkam and Narora. They are all of the CANDU (Canadian-Deuterium-Uranium) type, most suited to Indian conditions. India has limited deposits of uranium and would not be dependent on foreign enrichment facilities or a foreign supply to enriched fuel, (used in the Tarapur power plant). CANDU reactors, which use fuel available within the country, do not require large capital and operating outlays for fuel enrichment. The nuclear power generation will be about 2270 MW by 1991-92 in our country.

5.2 Chain Reaction

Uranium exist as isotopes of U^{238}, U^{234} and U^{235}. Out of these isotopes U^{235} is most unstable. When a neutron is captured by a nucleus of an atom of U^{235}, it splits up roughly into two equal fragments and about 2.5 neutrons are released and a large amount of energy (nearly 200 million electron volts MeV) is produced. This is called fission process. The neutrons so produced are very fast moving neutrons and can be made to fission other nuclei of U^{235} thus enabling a chain reaction to take place. When a large number of fissions occurs, enormous amount of heat is produced.

The neutrons released have a very high velocity of the or 1.5×10^7 metres per second. The energy liberated in the reaction is according to Einstein law

$$E = mc^2$$

where E = Energy produced

m = mass in grams

c = speed of light in cm/sec equivalent to 3×10^{10} cm/sec.

Out of 2.5 neutrons released in fission of each nuclei of U^{235}, one neutron is used to sustain the chain reaction, about 0.9 neutron is captured by U^{238} which gets converted into fissionable material, Pu^{239} and about 0.6 neutrons is partly absorbed by control rod material, coolant moderator and partly escape from the reactor. Production of the fissionable material Pu^{239} during chain reaction compensates the burn up of primary fuel U^{235} U^{238} + neutron = Pu^{239}. If thorium is used in the reactor core it produces fissionable material U^{233}.

$$Th^{232} + \text{Neutron} \rightarrow U^{233}$$

Pu^{239} and U^{233} so produced are fissionable material and can be used as nuclear fuel and are known as secondary fuel. U^{235} is called primary fuel.

The chain reaction producing a constant rate of heat energy can continue only if the neutron liberated by fission, balance the disposal of neutrons by different ways listed below :

1. Escape of neutrons from the fissionable materials.
2. Fission capture by U^{235}, and Pu^{239} and U^{233}.
3. Non-fission capture by moderator, control rods, fission fragments and by impurities etc.

If the neutrons produced in the chain reaction are less than the neutrons disposed off in different ways, the chain reaction will stop. Fig. 5.1 shows the chain reaction.

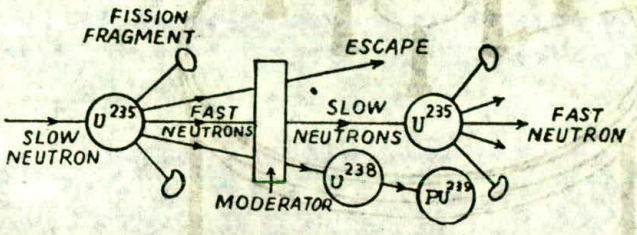


Fig. 5.1

5.3 Fertile Material

It is defined as the material which absorbs neutrons and undergoes spontaneous changes which lead to the formation of fissionable material. U^{238} and Th^{232} are fertile materials. They absorb neutrons and produce fissionable materials Pu^{239} and U^{233} respectively.

5.4 Unit of Radioactivity (Curie)

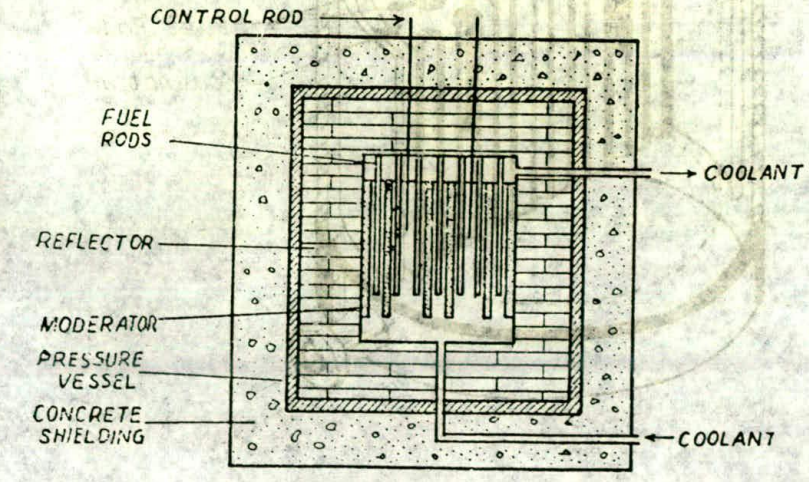


Fig. 5.2

The basic unit of radioactivity is named as *Curie.* It is the activity (Rate of decay) of one gram of radioactivity element radium. It has been estimated that rate of decay of one gram of radium is equal to 3.7×10^{10} disintegrations per second.

1 Curie $= 3.7 \times 10^{10}$ disintegrations per second. It describes the intensity of radioactivity in a sample of material.

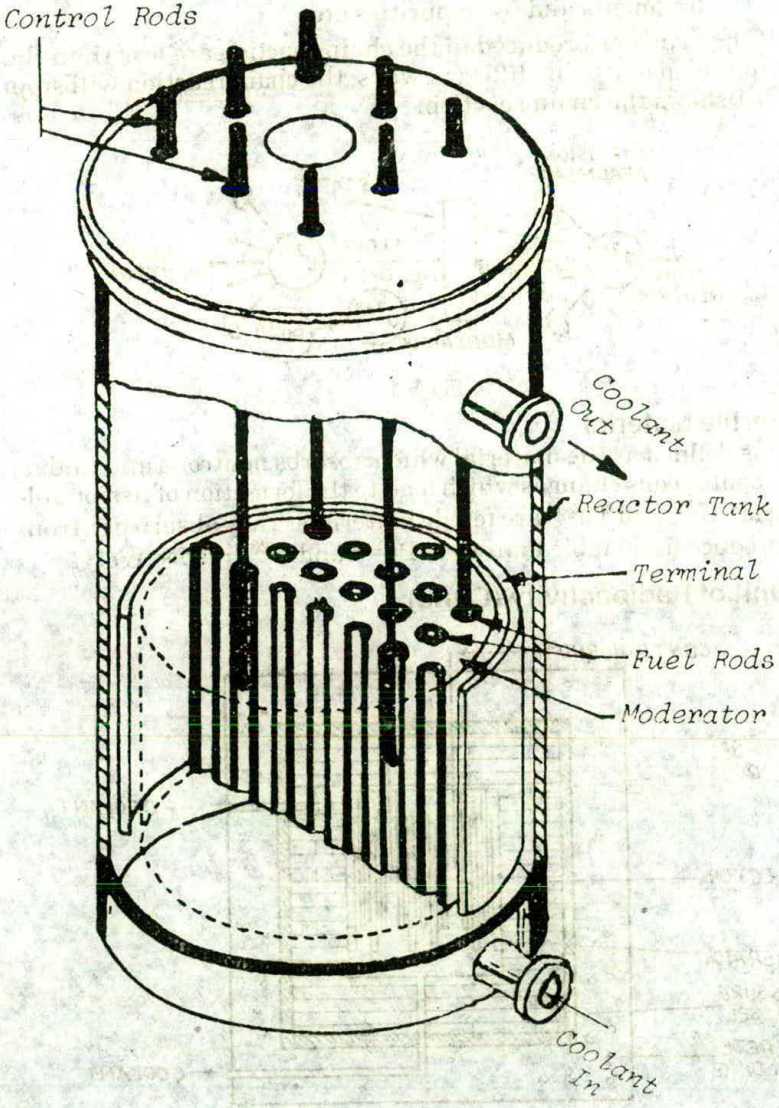


Fig. 5.3

5.5 Parts of a Nuclear Reactor

A nuclear reactor is an apparatus in which heat is produced due to nuclear fission chain reaction. Fig. 5.2 shows the various parts of reactor, which are as follows :

(*i*) Nuclear Fuel (*ii*) Moderator
(*iii*) Control Rods (*iv*) Reflector
(*v*) Reactors Vessel (*vi*) Biological Shielding
(*vii*) Coolant.

Fig. 5.3 shows a schematic diagram of nuclear reactor.

5.5.1 Nuclear Fuel

Fuel of a nuclear reactor should be fissionable material which can be defined as an element or isotope whose nuclei can be caused to undergo nuclear fission by nuclear bombardment and to produce a fission chain reaction. It can be one or all of the following U^{233} U^{235} and Pu^{239}.

Natural uranium found in earth crust contains three isotopes namely U^{234}, U^{235}, U^{238} and their average percentage is as follows :

$$U^{238} - 99.3\%;\ U^{235} - 0.7\%;\ U^{234} - \text{Trace}.$$

Out of these U^{235} is most unstable and is capable of sustaining chain reaction and has been given the name as primary fuel. U^{233} and Pu^{239} are artificially produced from Th^{232} and U^{238} respectively and are called secondary fuel.

Pu^{239} and U^{233} so produced can be fissioned by thermal neutrons. Nuclear fuel should not be expensive to fabricate. It should be able to operate at high temperatures and should be resistant to radiation damage.

Uranium deposits are found in various countries such as Congo, Canada, U.S.A., U.S.S.R., U.K., Australia, Czechoslovakia and Portugal etc.

The fuel should be protected from corrosion and erosion of the coolant and for this it is encased in metal cladding generally stainless steel or aluminium.

Adequate arrangements should be made for fuel supply, charging or discharging and storing of the fuel.

For economical operation of a nuclear power plant special attention should be paid to reprocess the spent up (burnt) fuel elements to recover the unconsumed fuel. The spent up fuel elements are intensively radioactive and emits some neutrons and gamma rays and should be handled carefully.

In order to prevent the contamination of the coolant by fission products, a protective coating or cladding must separate the fuel from the coolant stream. Fuel element cladding should possess the following properties :

(*i*) It should be able to withstand high temperature within the reactor.

(*ii*) It should have high corrosion resistance.

(*iii*) It should have high thermal conductivity.

(*iv*) It should not have a tendency to absorb neutrons.

(*v*) It should have sufficient strength to withstand the effect of radiations to which it is subjected.

Density of various nuclear fuels is indicated in Table 5.1.

Table 5.1

Fuel	*Density* (gm/cm^3)
U-233	18.68
U-235	18.68
U-238	18.68
U-239	19.6

Uranium oxide (UO_2) is another important fuel element. Uranium oxide has the following advantages over natural uranium:

(*i*) It is more stable than natural uranium.

(*ii*) There is no problem or phase change in case of uranium oxide and therefore it can be used for higher temperatures.

(*iii*) It does not corrode as easily as natural uranium.

(*iv*) It is more compatible with most of the coolants and is not attacked by H_2, N_2.

(*v*) There is greater dimensional stability during use.

Uranium oxide possesses following disadvantages :

(*i*) It has low thermal conductivity.

(*ii*) It is more brittle than natural uranium and therefore it can break due to thermal stresses.

(*iii*) Its enrichment is essential.

Uranium oxide is a brittle ceramic produced as a powder and then sintered to form fuel pellets.

Another fuel used in the nuclear reactor is uranium carbide (UC). It is a black ceramic used in the form of pellets.

Table 5.1 (a) indicates some of the physical properties of nuclear fuels.

Table 5.1 (*a*)

Fuel	*Thermal conductivity K-cal/m.hr°C*	*Specific heat kcal/kg°C*	*Density kg/m³*	*Melting point (°C)*
Natural uranium	26.3	0.037	19000	1130
Uranium oxide	1.8	0.078	11000	2750
Uranium carbide	20.6	–	13600	2350

5.5.2 Moderator

In the chain reaction the neutrons produced are fast moving neutrons. These fast moving neutrons are far less effective in causing the fission of U^{235} and try to escape from the reactor. To improve the utilization of these neutrons their speed is reduced. It is done by colliding them with the nuclei of other material which is lighter, does not capture the neutrons but scatters them. Each such collision causes loss of energy, and the speed of the fast moving neutrons is reduced. Such material is called Moderator. The slow neutrons (Thermal Neutrons) so produced are easily captured by the nuclear fuel and the chain reaction proceeds smoothly. Graphite, heavy water and beryllium are generally used as moderator.

Reactors using enriched uranium do not require moderator. But enriched uranium is costly due to processing needed.

A moderator should process the following properties :

(*i*) It should have high thermal conductivity.

(*ii*) It should be available in large quantities in pure form.

(*iii*) It should have high melting point in case of solid moderators and low melting point in case of liquid moderators. Solid moderators should also possess good strength and machinability.

(*iv*) It should provide good resistance to corrosion.

(*v*) It should be stable under heat and radiation.

(*vi*) It should be able to slow down neutrons.

5.5.3 Moderating Ratio

To characterise a moderator it is best to use so called moderating ratio which is the ratio of moderating power to the macroscopic neuron capture coefficient. A high value of moderating ratio indicates that the given substance is more suitable for slowing down the neutrons in a reactor. Table 5.2 indicates the moderating ratio for some of the material used as moderator.

Table 5.2

Material	*Moderating ratio*
Beryllium	160
Carbon	170
Heavy Water	12,000
Ordinary Water	72

This shows that heavy water, carbon and, beryllium are the best moderators.

Table 5.3 indicates density of various moderators.

Table 5.3

Moderator	*Density* (gm/cm^3)
H_2O	1
D_2O	1.1
C	1.65
Be	1.85

Table 5.4 shows some of the physical constants of heavy water (D_2O) and ordinary water (H_2O).

Table 5.4

Physical constant	*D_2O*	*H_2O*
Density at 293°K	1.1 gm/cm^3	0.9982 gm/cm^3
Freezing temperature	276.82	273
Boiling temperature	374.5	373°K
Dissociation Constant	0.3×10^{-14}	1×10^{-14}
Dielectric Constant at 293°K	80.5	82
Specific heat at 293°K	1.018	1

5.5.4 Control Rods

The control and operation of a nuclear reactor is quite different from a fossil and fuelled (coal or oil fired) furnace. The furnace is fed continuously and the heat energy in the furnace is controlled by regulating the fuel feed and the combustion air whereas a nuclear reactor contains as much fuel as is sufficient to operate a large power plant for some months. The consumption of this fuel and the power level of the reactor depends upon its neutron flux in the reactor core. The energy produced in the reactor due to fission of nuclear fuel during chain reaction is so much that if it is not controlled properly the entire core and surrounding structure may melt and radioactive fission products may come out of the reactor thus making it uninhabitable. This implies that we should have some means to control the power of the reactor. This is done by means of control rods.

Control rods in the cylindrical or sheet form are made of boron or cadmium. These rods can be moved in and out of the holes in the reactor core assembly. Their insertion absorbs more neutrons and damps down the reacation and their withdrawal absorbs less neutrons. Thus power of reaction is controlled by shifting control rods which may be done manually or automatically.

Control rods should possess the following properties :

(*i*) They should have adequate heat transfer properties.

(*ii*) They should be stable under heat and radiation.

(*iii*) They should be corrosion resistant.

(*iv*) They should be sufficient strong and should be able to shut down the reactor almost instantly under all conditions.

(*v*) They should have sufficient cross-sectional area for the absorption.

5.5.5 Reflector

The neutrons produced during the fission process will be partly absorbed by the fuel rods, moderator, coolant or structural material etc. Neutrons left unabsorbed will try to leave the reactor core never to return to it and will be lost. Such losses should be minimised. It is done by surrounding the reactor core by a material called reflector which will send the neutrons back into the core. The returned neutrons can then cause more fission and improve the neutrons economy of the reactor. Generally the reflector is made up of graphite and beryllium.

5.5.6 Reactor Vessel

It is a strong walled container housing the core of the power reactor. It contains moderator, reflector, thermal shielding and control rods.

5.5.7 Biological Shielding

Shielding the radioactive zones in the reactor from possible radiation hazard is essential to protect, the operating men from the harmful effects. During fission of nuclear fuel, alpha particles, beta particles, deadly gamma rays and neutrons are produced. Out of these neutrons and gamma rays are of main significance. A protection must be provided against them. Thick layers of lead or concrete are provided all round the reactor for stopping the gamma rays. Thick layers of metals or plastics are sufficient to stop the alpha and beta particles.

5.5.7 (*a*) Coolant

Coolant flows through and around the reactor core. It is used to transfer the large amount of heat produced in the reactor due to fission of the nuclear fuel during chain reaction. The coolant either transfers its heat to another medium or if the coolant used is water

it takes up the heat and gets converted into steam in the reactor which is directly sent to the turbine.

Coolant used should be stable under thermal condition. It should have a low melting point and high boiling point. It should not corrode the material with which it comes in contact. The coolant should have high heat transfer coefficient. The radioactivity induced in coolant by the neutrons bombardment should be nil. The various fluids used as coolant are water (light water or heavy water), gas (Air, CO_2, hydrogen, Helium) and liquid metals such as sodium or mixture of sodium and potassium and inorganic and organic fluids.

Power required to pump the coolant should be minimum. A coolant of greater density and higher specific heat demands less pumping power and water satisfies this condition to a great extent. Water is a good coolant as it is available in large qualities can be easily handled, provides some lubrication also and offers no unusual corrosion problems. But due to its low boiling point (212F at atmospheric pressure) it is to be kept under high pressure to keep it in the liquid state to achieve a high that transfer efficiency. Water when used as coolant should be free from impurities otherwise the impurities may become radioactive and handling of water will be difficult.

5.5.8 Coolant Cycles

The coolant while circulating through the reactor passages take up heat produced due to chain reaction and transfer this heat to the feed water in three ways as follows :

(*a*) *Direct Cycle.* In this system [Fig. 5.4 (*a*)] coolant which is water leaves the reactor in the form of steam. Boiling water reactor uses this system.

(*b*) *Single Circuit System.* In this system [Fig. 5.4 (*b*)] the coolant transfers the heat to the feed water in the steam generator. This system is used in pressurised reactor.

(*c*) *Double Circuit System.* In this system [Fig. 5.4 (*c*)] two coolant are used. Primary coolant after circulating through the reactor flows through the intermediate heat exchanger (IHX) and passes on its heat to the secondary coolant which transfers its heat in the feed water in the steam generator. This system is used in sodium graphite reactor and fast breeder reactor.

5.5.9. Reactor Core

Reactor core consists of fuel rods, moderator and space through which the coolant flows.

5.6 Conservation Ratio

It is defined as the ratio of number of secondary fuel atoms to the number of consumed primary fuel atoms. A reactor with a conversion ratio above unity is known as a breeder reactor. Breeder reactor produces more fissionable material than it consumes. If the fissionable material produced is equal to or less than the consumed, the reactor is called converter reactor.

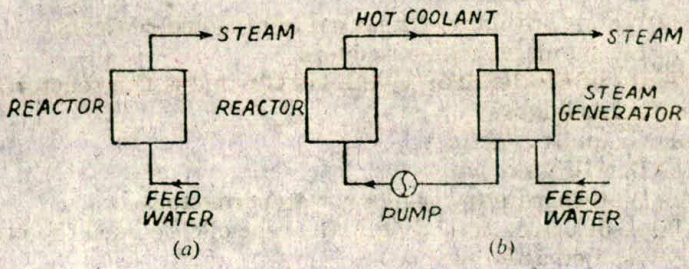


Fig. 5.4

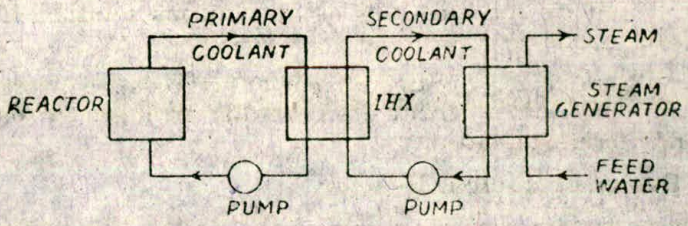


Fig. 5.4 (c)

5.7 Neutron Flux

It is a measure of the intensity of neutron radiation and it is the number of neutrons passing through 1 cm^2 of a given target in one second. It is expressed as uv, where u is number of neutrons per cubic centimetre and v is velocity of neutrons in cm/sec.

5.8 Classification of Reactors

The nuclear reactors can be classified as follows :

1. **Neutron Energy.** Depending upon the energy of the neutrons at the time they are captured by the fuel to induce fissions, the reactors can be named as follows :

(*a*) *Fast Reactors.* In such reactors fission is brought about by fast (non moderated) neutrons.

(*b*) *Thermal Reactors or Slow Reactors.* In these reactors the fast moving neutrons are slowed down by passing them through the moderator. These slow moving neutrons are then captured by the fuel material to bring about the fission.

(*c*) *Intermediate Reactors.* In such reactors most of the fission events are caused by neutrons in the course of slowing down.

2. **Type of Fuel Used.** Nuclear reactor may use U^{235}, U^{238} and Th^{232} as their fuels Th^{232} and U^{238} get converted in fissionable materials like U^{233} and Pu^{239} respectively.

3. **Type of Coolant Used.** On the basis of coolant used the reactors may be classified as follows :

(*a*) Gas cooled reactor.
(*b*) Water (ordinary or heavy water) cooled reactors.
(*c*) Liquid metal cooled reactors.

4. **Type of Moderator Used.** On this basis the reactors may be classified as follows :

(*a*) Graphite reactors.
(*b*) Beryllium reactors.
(*c*) Water (ordinary or heavy water) reactors.

5. **Type of Core.** According to the type of core used the reactor may be classified as follows :

(*a*) *Homogeneous reactor.* In this reactor fuel and moderator represent a uniform mixture such as an aqueous solution of a uranium salt.

(*b*) *Heterogeneous reactor.* In such reactor fuel rods are inserted in moderator. The fuel elements are generally arranged in some regular order forming a lattice.

5.8.1 Design of Nuclear Reactor

The basic factors considered during the design of a nuclear power reactor are as follows :

(*i*) Type of reactor.
(*ii*) Type of fuel to be used.
(*iii*) Power rating of reactor in MW.
(*iv*) Coolant system.
(*v*) Control system.
(*vi*) Rates of neutron production and absorption.
(*vii*) Safety of reactor.

5.9 Main Component of a Nuclear Power Plant

The main components of a nuclear power plant are shown in Fig. 5.5. These include nuclear reactor, heat exchanger (steam generator), turbine, electric generator and condenser. Reactor of a nuclear power plant is similar to the furnace of steam power plant. The heat liberation in the reactor due to the nuclear fission of the fuel is taken up by the coolant circulating through the reactor core. Hot coolant leaves the reactor at top and then flows through the tubes of steam generator (boiler) and passes on its heat to the feed water. The steam produced is passed through the turbine and after work has been

done by the expansion of steam in the turbine steam leaves the turbine and flows to the condenser. Pumps are provided to maintain the flow of coolant, condensate and feed water.

5.10 Boiling Water Reactor (B.W.R.)

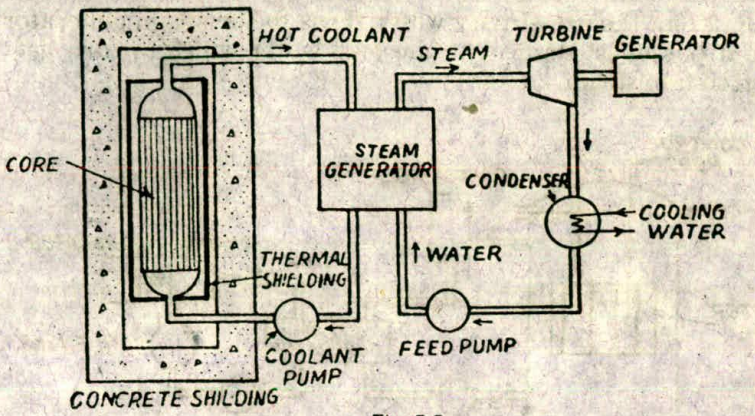


Fig. 5.5

Fig. 5.6 shows nuclear power plant using B.W.R. In this reactor enriched uranium (enriched uranium contains more fissionable isotope U^{235} then the naturally occurring percentage 0.7%) is used as nuclear fuel and water is used as coolant. Water enters the reactor at the bottom. It takes up the heat generated due to the fission of fuel and gets converted into steam. Steam leaves the reactor at the top and flows into the turbine. Water also serves as moderator. India's first nuclear power plant at Tarapur has two reactors (each of 200 MW capacity) of boiling water reactor type.

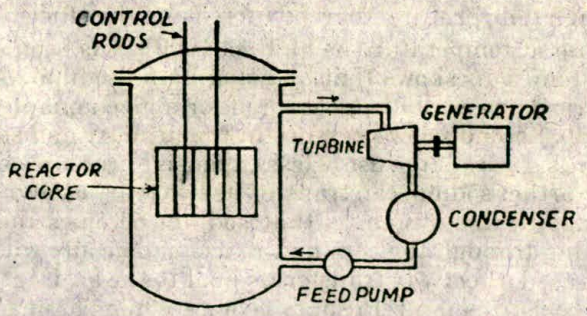


Fig. 5.6

5.11 Pressurised Water Reactor (P.W.R.)

A P.W.R. nuclear plant is shown in Fig. 5.7. It uses enriched U as fuel. Water is used as coolant and moderator. Water passes

through the reactor core and takes up the heat liberated due to nuclear fission of the fuel. In order that water may not boil (due to its low boiling point 212 F at atmospheric conditions) and remain in liquid state it is kept under a pressure of about 1200 p.s.i.g. by the pressuriser. This enables water to take up more heat from the reactor. From the pressuriser water flows to the steam generator where it passes on its heat to the feed water which in turn gets converted into steam.

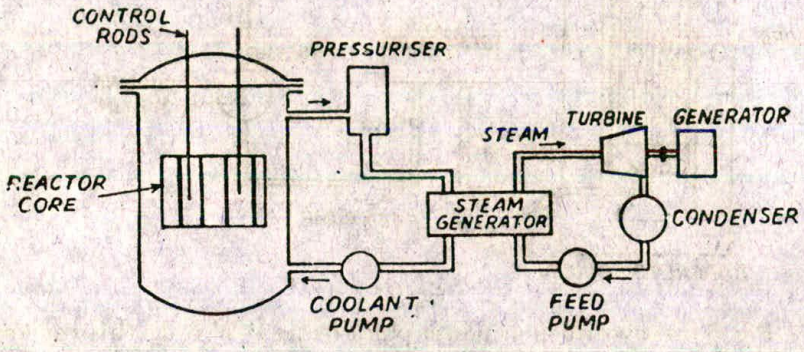


Fig. 5.7

5.12 Sodium Graphite Reactor (SGR)

The reactor shown in Fig. 5.8 uses two liquid metal coolants. Liquid sodium (Na) serves as the primary coolant and an alloy of sodium potassium (NaK) as the secondary coolant.

Sodium melts at 208°C and boils at 1625°F. This enable to achieve high outlet coolant temperature in the reactor at moderate pressure nearly atmospheric which can be utilized in producing steam of high temperature, thereby increasing the efficiency of the plant. Steam at temperature as high as 1000°F has been obtained by this system. This shows that by using liquid sodium as coolant more electrical power can be generated for a given quantity of the fuel burn up. Secondly low pressure in the primary and secondary coolant circuits, permit the use of less expensive pressure vessel and pipes etc. Further sodium can transfer its heat very easily. The only disadvantage in this system is that sodium becomes radioactive while passing through the core and reacts chemically with water. So it is not used directly to transfer its heat to the feed water, but a secondary coolant is used. Primary coolant while passing through the tubes of intermediate heat exchanges (I.H.X.) transfers its heat to the secondary coolant. The secondary coolant then flows through the tubes of steam generator and passes on its heat to the feed water. Graphite is used as moderator in this reactor. For heat exchanger refer Fig. 5.10 (*b*). Liquid metals used as heat transfer media have

certain advantages over other common liquids used for heat transfer purposes. The various advantages of using liquid metals as heat transfer media are that they have relatively low melting points and combine high densities with low vapour pressure at high temperatures as well as with large thermal conductivities.

5.13 Fast Breeder Reactor (FBR)

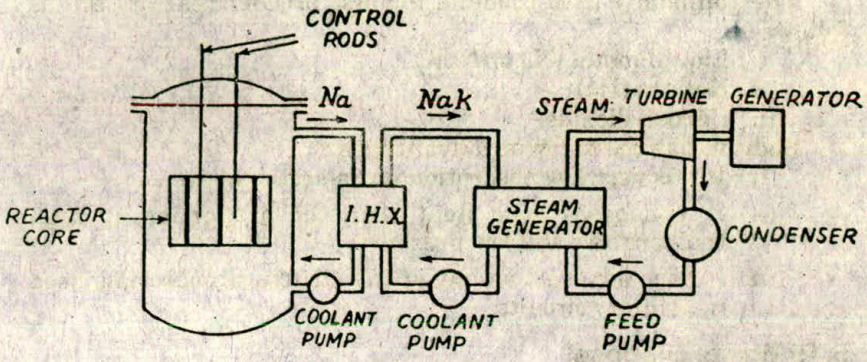


Fig. 5.8

Fig. 5.9 shows a fast breeder reactor system. In this reactor the core containing U^{235} is surrounded by a blanket (a layer of fertile material placed outside the core) or fertile material U^{238}. In this reactor no moderator is used. The fast moving neutrons liberated due to fission of U^{235} are absorbed by U^{238} which gets converted into fissionable material Pu^{239} which is capable of sustaining chain reaction. Thus this reactor is important because it breeds fissionable material from fertile material U^{238} available in large quantities. Like sodium graphite nuclear reactor this reactor also uses two liquid metal coolant circuits. Liquid sodium is used as primary coolant when circulated through the tubes of intermediate heat exchange transfers its heat to secondary coolant sodium potassium alloy. The secondary coolant while flowing through the tubes of steam generator transfer its heat to feed water.

Fast breeder reactors are better than conventional reactor both from the point of view of safety and thermal efficiency. For India which already is fast advancing towards self reliance in the field of nuclear power technology, the fast breeder reactor becomes inescapable in view

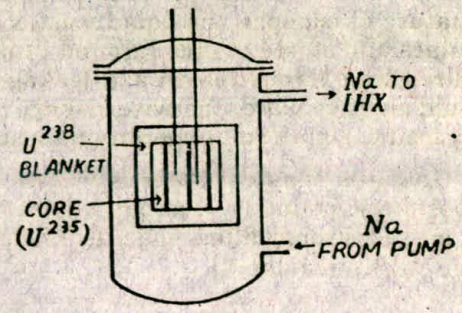


Fig. 5.9

of the massive reserves of thorium and the finite limits of its uranium resources. The research and development efforts in the fast breeder reactor technology will have to be stepped up considerably if nuclear power generation is to make any impact on the country's total energy needs in the not too distant future.

5.14 Coolants for Fast Breeder Reactors

The commonly used coolants for fast breeder reactors are as follows :

(*i*) Liquid metal (Na or NaK)
(*ii*) Helium (He)
(*iii*) Carbon dioxide.

Sodium has the following advantages :

(*i*) It has very low absorption cross-sectional area.

(*ii*) It possesses good heat transfer properties at high temperature and low pressure.

(*iii*) It does not react on any of the structural materials used in primary circuits.

5.15 Waste Disposal

Waste disposal problem is common in every industry. Wastes from atomic energy installations are radioactive, create radioactive hazard and require strong control to ensure that radioactivity is not released into the atmosphere to avoid atmospheric pollution.

The wastes produced in a nuclear power plant may be in the form of liquid, gas or solid and each is treated in a different manner:

Liquid Wastes. The disposal of liquid wastes is done in two ways :

(*i*) *Dilution.* The liquid wastes are diluted with large quantities of water and then released into the ground. This method suffers from the drawback that there is a chance of contamination of underground water if the dilution factor is not adequate.

(*ii*) *Concentration to small volumes and storage.* When the dilution of radioactive liquid wastes is not desirable due to amount or nature of isotopes, the liquid wastes are concentrated to small volumes and stored in underground tanks. The tanks should be of assured long term strength and leakage of liquid from the tanks should not take place otherwise leakage or contents, from the tanks may lead to significant underground water contamination.

Gaseous Wastes. Gaseous wastes can most easily result in atmospheric pollution. Gaseous wastes are generally diluted with air, passed through filters and then released to atmosphere through large stacks (chimneys).

Solid Wastes. Solid wastes consist of scrap material or discarded objects contaminated with radioactive matter. These wastes if combustible are burnt and the radioactive matter is mixed with concrete, drummed and shipped for burial. Non-combustible solid wastes, are always buried deep in the ground.

5.16 Homogeneous Reactor

Fig. 5.10 shows a Homogeneous Aqueous Reactor (H.A.R.). In this reactor heavy water is used as coolant and moderator. It makes use of both fertile and fissionable material which circulate with coolant. Fissionable U^{238} solution is contained in one zone and slurry of Thorium oxide and Deuterium oxide is contained in the other zone. Main advantage of this reactor is that problems associated with solid fuels elements are avoided. As heavy water is used as moderator coolant there is good neutron economy. The disadvantages or this system are :

(*i*) Large amount of fuel is required.

(*ii*) Circulative fuel system causes the external components to become radioactive.

(*iii*) High vapour pressure of water.

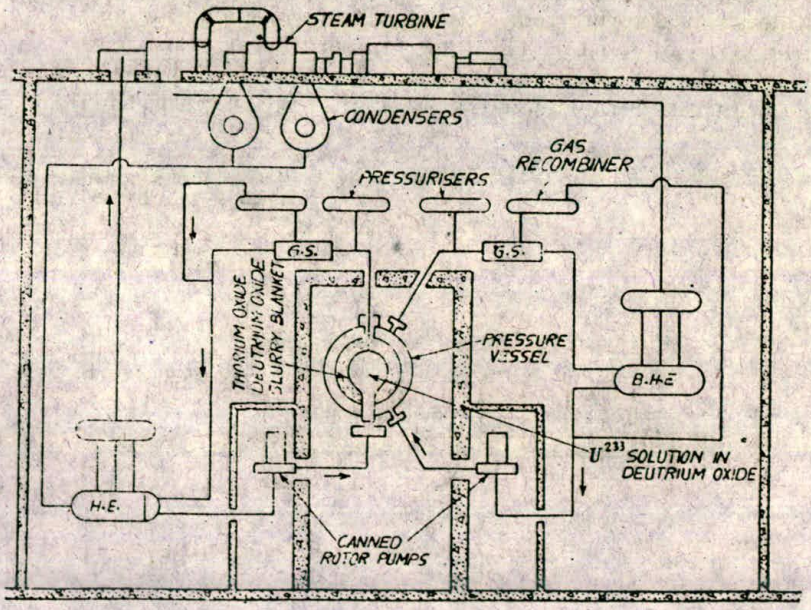


Fig. 5.10

In the figure, H.E. represents Heat Exchanger, B.H.E. represents Blanket Heat Exchanger, G.S. represents Gas Separator.

5.17 Heat Exchanger

The heat exchanger used in sodium graphite reactor is shown in Fig. 5.11. The two coolants separated by a thin wall move in the opposite directions. The narrow space between the partition walls is filled with mercury to ensure a high efficiency of heat transfer. The mercury circulates in a small separate circuit. If some radioactivity is observed in mercury this indicates leakage in the primary circuit and serves as a warning.

5.17.1 Candu Reactor

Candu (Canadian–Deuterium uranium) reactor shown in Fig. 5.10 (*a*) uses heavy water (99.8 per cent Deuterium oxide D_2O) as moderator and coolant. Natural uranium containing 0.7% U^{235} is used as fuel. The reactor vessel is a steel cylinder containing number of tubes which are subjected to high internal pressure. The tubes also called channels contain fuel elements and the pressurised coolant flows along the channels and around the fuel elements to remove the heat generated by fission. The coolant flow is in opposite directions in adjacent channels.

In this reactor refuelling (removal of spent fuel and replacement by fresh fuel) is carried out while the reactor is operating. Number of neutron absorber rods of cadmium are provided for control protection of reactor. The high temperature coolant leaving reactor flows to steam generator to heat the feed water so that it gets converted into steam. The coolant then returns to the reactor.

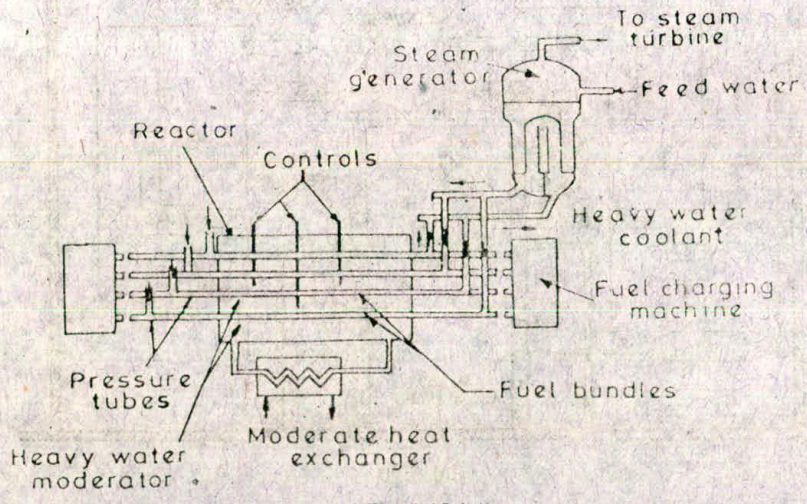


Fig. 5.10 (*a*)

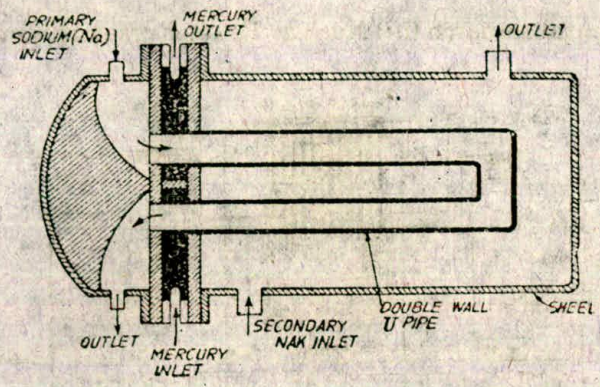


Fig. 5.11

5.18 Gas Cooled Reactor

In this reactor (Fig. 5.12) carbon dioxide gas is used to carry away the heat produced in the reactor. The gas is circulated at a pressure of about 7 kg/m^2. The gas flowing up through each of the channels round the elements leaves the reactor at the top and flows to heat exchanger where it transfer its heat to water which gets converted into steam. The gas is recirculated with the help of gas blowers. The steam drives the turbines which in turn drives alternator to generate electricity.

5.18.1 Objectives of R and D in Nuclear Energy

The Research and Development (R&D) activities in the field of nuclear energy in our country are directed towards the following :

(*i*) Development of nuclear fuels

(*ii*) Development of reactor technologies for example fast breeder reactor (FBR) system

(*iii*) Development of heavy water production technology

(*iv*) Development of nuclear safety devices

(*v*) Nuclear waste disposal

(*vi*) Nuclear fuel reprocessing

(*vii*) Safe operation of nuclear power plants.

In our country the Atomic Energy Commission (AEC) is responsible for formulation of policies and programmes in the field of nuclear energy. The Bhabha Atomic Research Centre (BARC) at Trombay is the national research centre for research and development work in nuclear energy and related disciplines.

Other institutes which provide research support in nuclear energy are : (*i*) Saha Institute of nuclear physics (*ii*) Tata Institute

of fundamental research (*iii*) Nuclear Reactor research centre Kalpakkam.

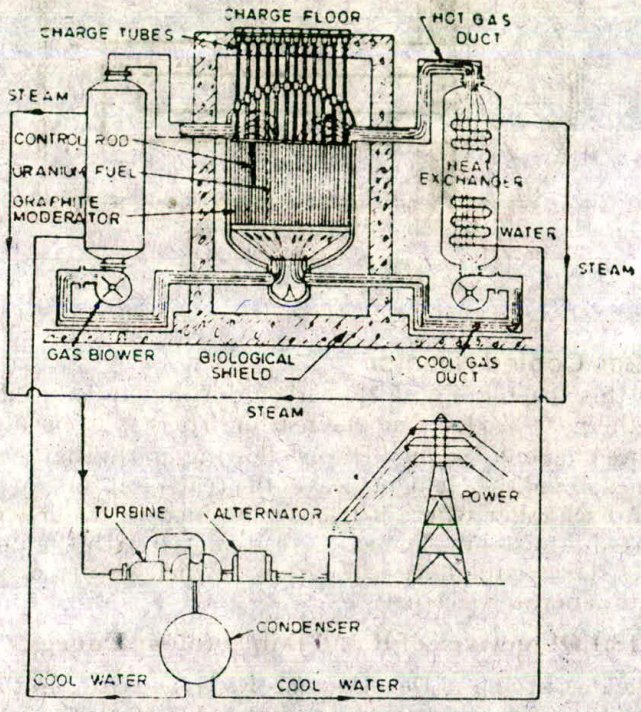


Fig. 5.12

5.19 Breeding

It is the process of producing fissionable material (fissionable material) from a fertile material such as uranium 238 (U^{238}) and thorium 232 (Th^{232}) by neutron absorption.

$$(U^{238}) + \text{neutron} \rightarrow Pu^{239}$$

$$Th^{232} + \text{neutron} \rightarrow U^{233}$$

Pu^{239} and U^{233} are fissionable materials and can be used in chain reaction.

5.19.1 Electron Volt (eV)

The electron volt is the amount of energy required to raise the potential of an electron by one volt.

One electron volt (eV) = 1.60203×10^{-12} erg.

$= 1.60203 \times 10^{-19}$ Joules.

5.20 Thermal Neutrons

Such neutrons are in thermal equilibrium with the material in which they are moving ; for example in the moderator. They possess a mean energy of about 0.025 eV, at normal temperature (15°C)

5.21 Fast Neutrons

Fast neutrons are those neutrons which have lost relatively little energy since being produced in the fission process. The lower limit of their energy is taken as 1.0 MeV (million electron volts.)

The general neutrons energies are as follows :

(*a*) Thermal neutrons – 0.025 eV
(*b*) Intermediate neutrons – 1.0 to 0.1 MeV
(*c*) Fast neutrons – 0.1 MeV or more.

Thermal neutrons are the most effective in causing fission and, therefore it is desirable to slow down or moderate the fast neutrons which normally have an energy of about 1 MeV.

5.22 Burn Up

It is the amount of fissible material in a reactor that gets destroyed due to fission or neutron capture expressed as a percentage of the original quantity of fissionable materials.

5.23 Cost of Nuclear Power Plant

Nuclear power plant is economical if used as base load power plant and run at higher load factors. The cost of nuclear power plant is more at low load factors. The overall running cost of a nuclear power plant of large capacity may be about 5 paisa per kWh but it may be as high 15 paisa per kWh if the plant is of smaller capacity. The capital cost of a nuclear power plant of larger capacity (say 250 MW) is nearly Rs. 2500 per kW installed. A typical sub-division of cost is as follows :

Item	*Approximate Cost %*
(*a*) Capital cost of land, building and equipment etc.	62%
(*b*) Fuel cost	22%
(*c*) Maintenance cost	6%
(*d*) Interest on capital cost	10%

The capital investment items include the following :

(*i*) Reactor plant : (*a*) Reactor vessel, (*b*) Fuel and fuel handling system, (*c*) Shielding. (*ii*) Coolant system. (*iii*) Steam turbines, generators and the associated equipment. (*iv*) Cost of land and construction costs.

The initial investment and capital cost of a nuclear power plant is higher as compared to a thermal power plant. But the cost of transport and handling of coal for a thermal power plant is much

higher than the cost of nuclear fuel. Keeping into view the depletion of fuel (coal, oil, gas) reserves and transportation of such fuels over long distances, nuclear power plants can take an important place in the development of power potentials.

5.24 Nuclear Power Station in India

The various nuclear power stations in India are as follows :

(*i*) **Tarapur Nuclear Power Station.** It is India's first nuclear power plant. It has been built at Tarapur 60 miles north of Bombay with American collaboration. It has two boiling water reactors each of 200 MW capacity and uses enriched uranium as its fuel. It supplies power to Gujarat and Maharashtra.

Tarapur power plant is moving towards the stage of using mixed oxide fuels as an alternative to uranium. This process involves recycling of the plutonium contained in the spent fuel. In the last couple of years it has become necessary to limit the output of reactors to save the fuel cycle in view of the uncertainty of enriched uranium supplies from the United States.

(*ii*) **Rana Pratap Sagar (Rajasthan) Nuclear Station.** It has been built at 42 miles south west of Kota in Rajasthan with Canadian collaboration. It has two reactors each of 200 MW capacity and uses natural uranium in the form of oxide as fuel and heavy water as moderator.

(*iii*) **Kalpakkam Nuclear Power Station.** It is the third nuclear power station in India and is being built at about 40 miles from Madras City. It will be wholly designed and constructed by Indian scientists and engineers. It has two fast reactors each of 235 MW capacity and will use natural uranium as its fuel.

The first unit of 235 MW capacity has started generating power from 1983 and the second 235 MW unit is commissioned in 1985. The pressurised heavy water reactors will use natural uranium available in plenty in India. The two turbines and steam generators at the Kalpakkam atomic power project are the largest capacity generating sets installed in our country. In this power station about 88% local machinery and equipment have been used.

(*iv*) **Narora Nuclear Power Station.** It is India's fourth nuclear power station and is being built at Narora in Bullandshahar District of Uttar Pradesh. This plant will initially have two units of 235 MW each and provision has been made to expand its capacity of 500 MW. It is expected to be completed by 1991.

This plant will have two reactors of the CANDU—PHW (Canadian Deutrium—Uranium—Pressurised Heavy Water) system and will use natural uranium as its fuel. This plant will be wholly designed and constructed by the Indian scientists and en-

gineers. The two units are expected to be completed by 1989 and 1990 respectively.

This plant will use heavy water as moderator and coolant. This plant will provide electricity at 90 paise per unit. Compared to the previous designs of Rajasthan and Madras nuclear power plants the design of this plant incorporates several improvements. This is said to be a major effort towards evolving a standardised design of 235 MW reactors and a stepping stone towards the design of 500 MW reactors. When fully commissioned plant's both units will provide 50 MW to Delhi, 30 MW to Haryana, 15 MW to Himachal Pradesh, 35 MW to Jammu and Kashmir, 55 MW to Punjab, 45 MW to Rajasthan, 165 MW to Uttar Pradesh and 5 MW to Chandigarh. The distribution of remaining power will depend on the consumer's demands. In this plant one exclusion zone of 1.6 km radius has been provided where no public habitation is permitted. Moderate seismicity alluvial soil conditions in the region of Narora have been fully taken into account in the design of the structure systems and equipment in Narora power plant.

Narora stands as an example of a well coordinated work with important contributions from Bhabha Atomic Research Centre, Heavy Water Board, Nuclear Fuel Complex, Electronics Corporation of India Limited (ECIL) and other units of Department of Atomic Energy and several private and public sector industries Instrumentation and control systems are supplied by ECIL. Bharat Heavy Electricals Limited (BHEL) is actively associated with Nuclear Power Corporation of India. It has supplied steam generators, reactor headers and heat exchangers for Narora Atomic Power Plant (NAPP) 1 and 2 (2×235 MW).

NAPP is the fore-runner of a whole new generation of nuclear power plants that will come into operation in the next decade. The design of this reactor incorporates several new safety features ushering in the state of the art in reactor technology. The design also incorporates two fast acting and independent reactor shut down systems conceptually different from those of RAPP and MAPP.

Some of the new systems introduced are as follows :

(*i*) Emergency Core Cooling System (ECCS).
(*ii*) Double Containment System.
(*iii*) Primary Shut off rod System (PSS).
(*iv*) Secondary Shut off rod System (SSS).
(*v*) Automatic Liquid Poison Addition System (ALPAS).
(*vi*) Post accident clean up system.

According to Department of Atomic Energy (DAE) the Narora Atomic Power Plant (NAPP) has the following features.

(*i*) It does not pose safety and environmental problems for the people living in its vicinity.

The safety measures are constantly reviewed to ensure that at all times radiation exposure is well within limits not only to the plant personnel but also to the public at large.

(*ii*) NAPP design meets all the requirement laid down in the revised safety standards. The design of power plant in corporates two independent fast acting shut down systems high pressure, intermediate pressure and low pressure emergency core cooling systems to meet short and long term requirements and double containment of the reactor building.

Narora Atomic Power Plant (NAPP) is pressurised heavy water reactor (PHWR) that has been provided with double containment. The inner containment is of pre-stressed concrete designed to withstand the full pressure of 1.25 kg/cm^2 that is likely to be experienced in the event of an accident. The outer containment is of reinforced cement concrete capable of withstanding the pressure of 0.07 kg/cm^2. The angular space between the two containments is normally maintained at a pressure below atmosphere to ensure that any activity that might leak past primary containment is vented out through the stock and not allowed to come out to the environment in the immediate vicinity of the reactor building. The primary and the secondary containments are provided with highly efficient filteration systems which filter out the active fission products before any venting is done.

The moment containment gets pressurised it gets totally sealed from the environment. Subsequently the pressure in the primary containment is brought down with the help of the following provisions.

(*i*) Pressure suppression pool at the basement of the reactor building.

(*ii*) Special cooling fan units which are operated on electrical power obtainable from emergency diesel generators.

The containment provisions are proof tested to establish that they are capable of withstanding the pressures that are expected in the case of an accident. Fig. 5.12 (*a*) shows primary and secondary containment arrangement.

(*iii*) The cooling water to all the heavy water heat exchangers is maintained in a closed loop so that failure in these do not lead to escape of radioactivity very little water from River Ganga would be drawn for cooling purposes and most of water would be re-cycled.

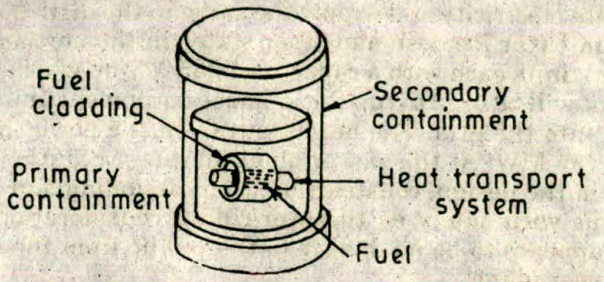


Fig. 5.12 (*a*)

(*iv*) The power plant has a waste management plant and waste burial facility within the plant area.

(*v*) NAPP is the first pressurised heavy water reactor (PHWR) in the world to have been provided with double containment.

(*vi*) No radioactive effluent, treated or otherwise will be discharged into Ganga River. Therefore there will be no danger of pollution of the Ganga water.

(*vii*) An exclusion zone of 1.6 km radius around the plant has been provided where no habitation is permitted.

(*viii*) A comprehensive fire fighting system on par with any modern power station has been provided at NAPP.

(*ix*) NAPP has safe foundations. It is located on the banks of river Ganges on alluvial soil. The foundations of the plant reach upto a depth where high relative densities and bearing capacities are met. The foundations design can cater to all requirements envisaged during life of plant.

(*x*) It is safe against earthquakes.

(*xi*) In the event of danger over heated core of the reactor would be diffused with in a few seconds by two features namely shut down through control rods followed by injection of boron rich water which will absorb the neutrons and stop their reaction in the core. This is in addition to other feature like double containment system provided in the reactor.

Above features assure total radiation safety of the plant personnel, general public and the environment during the operation of power plant. With the completion of NAPP it would make a useful contribution to the Northern grid thereby accelerating the pace of development in this region.

Narora Atomic Power Plant is the fourth atomic power project to be commissioned in India, the others in commercial operation

being TAPS 1 and 2 (Tarapur, Maharashtra 1969), RAPS 1 and 2 (Kota, Rajasthan 1973 and 1981) and MAPS 1 and 2 (Kalpakkam Madras, Tamil Nadu 1983 and 1986). This power plant is meant to generate electricity and supply the same to the distribution system (grid) in Uttar Pradesh and other states in the northern region. It has two units each with a capacity of 235 MW of which about seven per cent will be used to run the in house equipment and the rest will be fed into the grid. The net output from the power plant will be about 435 MW. At this power plant all due precautions have been taken in the design, construction, commissioning and operation of the unit with safety as the over-riding consideration. Therefore there appears to be no danger to the public from the operation of this power plant.

(*v*) **Kakarpar Nuclear Power Plant.** This fifth nuclear power plant of India is to be located at Kakarpar near Surat in Gujarat. This power station will have four reactors each of 235 MW capacity. The reactors proposed to be constructed at Kakarpar would be of the Candu type natural uranium fuelled and heavy water moderated reactors-incorporating the standardised basic design features of the Narora reactors suitably adapted to local conditions. The fuel for the power plant will be fabricated at the Nuclear Fuel complex, Hyderabad. The power plant is expected to be completed by 1991.

The Kakarpur unit has two fast shut down systems. The primary one works by cadmium shut off rods at 14 locations which drop down in case of heat build up and render the reactor sub-critical in two seconds. There are 12 liquid shut off rods as a back up, further backed by slow acting automatic liquid poison addition system which absorbs neutrons completely and stop the fissile reaction.

In case of sudden loss of coolant, heavy water inside the reactor, there is an emergency core-cooling system which also stops the fissile reaction. Lastly, the pressure suppression system in which cool water under the reactor rises automatically to reduce pressure in case it increases and a double containment wall ensures that no radioactivity would be released at ground level even in case of an unlikely accident.

The Department of Atomic Energy (DAE) has also evolved emergency preparedness plans for meeting any accident even after all these safety measures. It ensures a high level of preparedness to face an accident including protecting the plant personnel and surrounding population. There is no human settlement for five km belt around a nuclear power installation as a mandatory provision.

(*vi*) **Kaiga Atomic Power Plant.** The sixth atomic power plant will be located at Kaiga in Karnatka. Kaiga is located away from human habitation and is a well suited site for an atomic power plant.

It will have two units of 235 MW each. It is expected to be commissioned by 1995.

This nuclear power plant will have CANDU type reactors. These reactors have modern systems to prevent accidents. The plant would have two solid containment walls—inner and outer—to guard against any leakage. The inner containment wall could withstand a pressure of 1.7 kg/cm^2 and could prevent the plant from bursting. The outer containment walls of the reinforced cement concrete has been design to withstand pressure of 0.07 kg/cm^2. The annular space between the two containment walls would be maintained at a lower pressure below that of the atmosphere to ensure that no radioactivity leaked past the primary containments.

5.25 Light Water Reactors (LWR) and Heavy Water Reactors (HWR)

Light water reactors use ordinary water (technically known as light water) as coolant and moderator. They are simpler and cheaper. But they require enriched uranium as their fuel. Natural uranium contains 0.6% of fissionable isotope U^{235} and 99.3% of fertile U^{238} and to use natural uranium in such reactors it is to be enriched to about 3% U^{235} and for this uranium enrichment plant is needed which requires huge investment and high operational expenditure. Heavy water reactors use heavy water as their coolant and moderator. They have the advantage of using natural uranium as their fuel. Such reactors have some operation problem too. Heavy water preparation plants require sufficient investment and leakage of heavy water must be avoided as heavy water is very costly. Heavy water required in primary circuits must be 99% pure and this requires purification plants heavy water should not absorb moisture as by absorbing moisture it gets degraded. In order to have sufficient quantity of heavy water required for nuclear power plants, the work is fast progressing in our country on four heavy water plant. These plants are situated at Kotah (100 tonnes per year), Baroda (67.2 tonnes), Tuticorin (71.3 tonnes) and Talcher (67.2 tonnes per year). These plants will give our country an installed heavy water production capacity of about 300 tonnes per year.

5.26 Importance of Heavy Water

The nuclear power plants of Kota in Rajasthan, Kalpakkam in Tamil Nadu and Narora in U.P. use heavy water as coolant and moderator. All these projects have CANDU reactors using natural uranium as fuel and heavy water as moderator. After this enriched uranium natural water reactor at Tarapur, the CANDU reactors are the second generation of reactors in India's nuclear power programme. The CANDU reactor will produce plutonium which will

be the core fuel for fast breeder reactor. In fact in breeder reactor heavy water is used as moderator.

A CANDU reactor of 200 MW capacity requires about 220 tonnes of heavy water in the initial stages and about 18 to 24 tonnes each year subsequently. Therefore, about one thousand tonnes of heavy water will be required to start the different nuclear power stations using heavy water. The total capacity of different heavy water plants will be about 300 tonnes per year if all the heavy water plant under construction start production. It is expected that heavy water from domestic production will be available from Madras and Narora atomic power plants. The management of the heavy water system is a highly complicated affair and requires utmost caution. Heavy water is present in ordinary water in the ratio 1 : 6000. One of the methods of obtaining heavy water is electrolysis of ordinary water.

5.27 Advantages of Nuclear Power Plant

The various advantages of a nuclear power plant are as follows:

1. Space requirement of a nuclear power plant is less as compared to other conventional power plants are of equal size.
2. A nuclear power plant consumes very small quantity of fuel. Thus fuel transportation cost is less and large fuel storage facilities are not needed. Further the nuclear power plants will conserve the fossil fuels (coal, oil, gas etc.) for other energy need.
3. There is increased reliability of operation.
4. Nuclear power plants are not effected by adverse weather conditions.
5. Nuclear power plants are well suited to meet large power demands. They give better performance at higher load factors (80 to 90%).
6. Materials expenditure on metal structures, piping, storage mechanisms are much lower for a nuclear power plant than a coal burning power plant. For example for a 100 MW nuclear power plant the weight of machines and mechanisms, weight of metal structures, weight of pipes and fittings and weight of masonry and bricking up required are nearly 700 tonnes, 900 tonnes, 200 tonnes and 500 tonnes respectively whereas for a 100 MW coal burning power plant the corresponding value are 2700 tonnes, 1250 tonnes, 300 tonnes and 1500 tonnes respectively. Further area of construction site required for 100 MW nuclear power plant is 5 hectares whereas for a 100 MW

coal burning power plant the area of construction site is nearly 15 hectares.

7. It does not require large quantity of water.

Disadvantages

1. Initial cost of nuclear power plant is higher as compared to hydro or steam power plant.
2. Nuclear power plants are not well suited for varying load conditions.
3. Radioactive wastes if not disposed carefully may have bad effect on the health of workers and other population.

In a nuclear power plant the major problem faced is the disposal of highly radioactive waste in form of liquid, solid and gas without any injury to the atmosphere. The preservation of waste for a long time creates lot of difficulties and requires huge capital.

4. Maintenance cost of the plant is high.
5. It requires trained personnel to handle nuclear power plants.

5.28 Site Selection

The various factors to be considered while selecting the site for nuclear plant are as follows :

1. *Availability of water.* At the power plant site an ample quantity of water should be available for condenser cooling and made up water required for steam generation. Therefore the site should be nearer to a river, reservoir or sea.

2. *Distance from load centre.* The plant should be located near the load centre. This will minimise the power losses in transmission lines.

3. *Distance from populated area.* The power plant should be located far away from populated area to avoid the radioactive hazard.

4. *Accessibility to site.* The power plant should have rail and road transportation facilities.

5. *Waste disposal.* The wastes of a nuclear power plant are radioactive and there should be sufficient space near the plant site for the disposal of wastes.

6. *Safe guard against earthquakes.* The site is classified into its respective seismic zone 1, 2, 3, 4, or 5. The zone 5 being the most seismic and unsuitable for nuclear power plants. About 300 km of radius area around the proposed site is studied for its past history of tremors, and earth-quakes to assess the severest earth-quake that could occur for which the foundation building and equipment supports are designed accordingly. This ensures that the plant will

retain integrity of structure, piping and equipments should an earthquake occur. The site selected should also take into account the external natural events such as floods, including those by up-stream dam failures and tropical cyclones.

The most important consideration in selecting a site for a nuclear power plant is to ensure that the site-plant combination does not pose radio logical or any hazards to either the public, plant personnel on the environment during normal operation of plant or in the unlikely event of an accident.

The Atomic Energy Regulatory Board (AERB) has stipulated a code of practice on safety in Nuclear Power Plant site and several safety guide lines for implementation.

5.29 Comparison of Nuclear Power Plant and Steam Power Plant

The cost of electricity generation is nearly equal in both these power plants. The other advantages and disadvantages are as follows :

(*i*) The number of workman required for the operation of nuclear power plant is much less than a steam power plant. This reduces the cost of operation.

(*ii*) The capital cost of nuclear power plant falls sharply if the size of plant is increased. The capital cost as structural materials, piping, storage mechanism etc. is much less in nuclear power plant than similar expenditure of steam power plant. However, the expenditure of nuclear reactor and building complex is much higher.

(*iii*) The cost of power generation by nuclear power plant becomes competitive with cost of steam power plant above the unit size of about 500 MW.

5.30 Multiplication Factor

Multiplication factor is used to determine whether the chain reaction will continue at a steady rate, increase or decrease. It is given by the relation,

$$K = \frac{P}{A + E}$$

where K = Effective multiplication factor.

P = Rate of production of neutrons.

A = Combined rate of absorption of neutrons.

E = Rate of leakage of neutrons.

$K = 1$ indicates that the chain reaction will continue at steady rate (critical) $K > 1$ indicates that the chain reaction will be building up

(super critical) whereas $K < 1$ shows that reaction will be dying down (subcritical).

5.31 Uranium Enrichment

In some cases the reaction does not take place with natural uranium containing only 0.71% of U^{235}.

In such cases it becomes essential to use uranium containing higher content of U^{335}. This is called U^{235} concentration of uranium enrichment. The various methods of uranium enrichment are as follows :

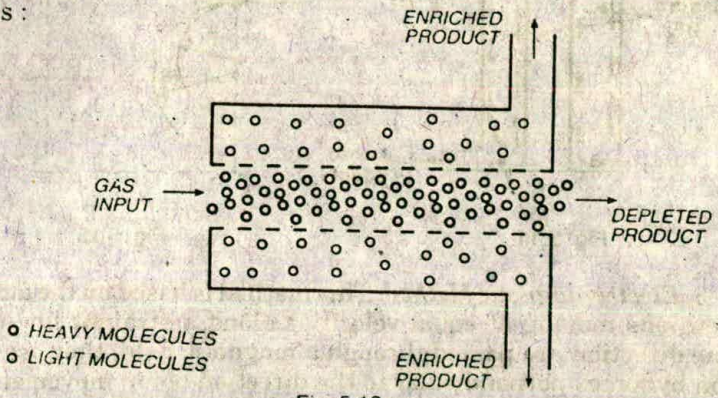


Fig. 5.13

1. *The gaseous diffusion method.* This method is based on the principle that the diffusion or penetration molecular of a gas with a given molecular weight through a porous barrier is quicker than the molecules of a heavier gas. Fig. 5.13 shows a separating stage for gaseous diffusion. Non-saturated uranium hexa-flouride (UF^6) is used for gaseous diffusion. The diffusing molecules have small difference in mass. The molecular weight of $U^{235}F_6 = 235 + 6 \times 19 = 349$ and that of $U^{238}F_6 = 352$. The initial mixture is fed into the gap between the porous barrier. That part of the material which passes through the barrier is enriched product, enriched in U^{235} F_6 molecules and the remainder is depleted product.

2. *Thermal diffusion method.* In this method (Fig. 5.14) a column consisting of two concentric pipes is used. Liquid UF_6 is filled in the space between the two pipes. Temperature of one of the pipes is kept high and that of other is kept low. Due to difference in temperature the circulation of the liquid starts, the liquid rising along the hot wall and falling along the cold wall. Thermal diffusion takes place in the column. The light U^{235} F_6 molecules are concentrated at the hot wall and high concentration of U^{236} F_6 is obtained in the upper part of the column.

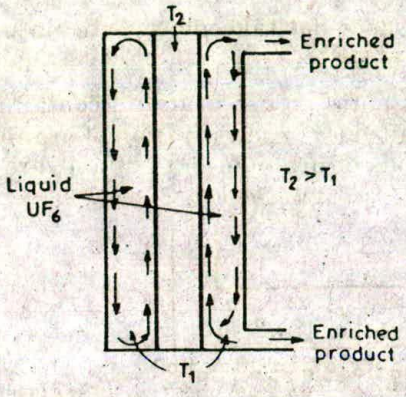


Fig. 5.14

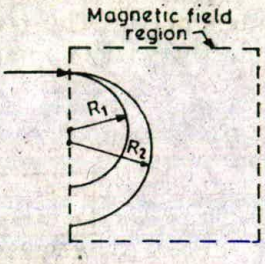


Fig. 5.15

3. *Electromagnetic Method.* This method is based on the fact that when ions moving at equal velocities along a straight line in the same direction are passed through a magnetic field, they are acted upon by forces perpendicular to the direction of ion movement and the field.

Let P = force acting on ion

e = charge on ion

v = velocity of ion

H = magnetic field strength

$m = I_{on}$ mass

R = radius of ion path

$P = evH$

As this force is centripetal

$$\therefore \quad P = \frac{mv^2}{R}$$

$$\therefore \quad \frac{mv^2}{R} = evH$$

$$\therefore \quad R = \frac{mv}{eH}$$

This shows that ions moving at equal velocities but different masses move alo ng circumferences of different radii (Fig. 5.15). Fig. 5.16 shows an electromagnetic separation unit for uranium isotopes. A gaseous uranium compound is fed into the ion source, where neutral atoms are ionised with the help of ion bombardment. The

ions produced come out in the form of narrow beam after passing through a number of silos. This beam enters the acceleration chamber. These ions then enter a separation chamber where a magnetic field is applied. Due to this magnetic field the ions of different masses move along different circumference.

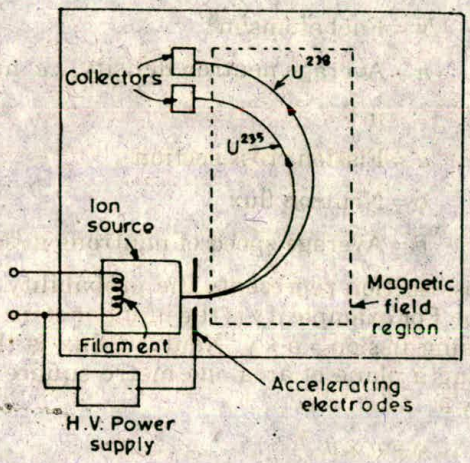


Fig. 5.16

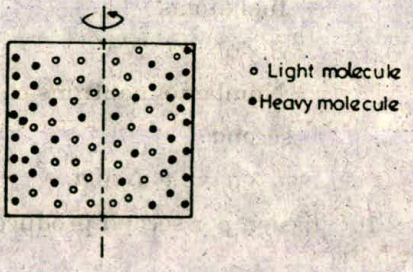


Fig. 5.17

4. *Centrifugation Method.* This method is based on the fact that when a mixture of two gases with different molecular weight is made to move at a high speed in a centrifuge, the heavier gas is obtained near the periphery (Fig. 5.17). UF_6 vapour may be filled in the centrifuge and rotated to separate uranium isotopes.

5.32 Power of a Nuclear Reactor

In a nuclear reactor a large number of neutrons are incident on nuclear fuel atoms, causing fission and producing energy. A control-

led chain reaction takes place so that the heat energy released can be controlled.

Let V = Volume of energy

N = Fuel atoms/m^3

n = Average neutron density, *i.e.* number per m^3

a = Fission cross section

ϕ = Neutron flux

v = Average speed of neutrons m/sec.

F ission cross-section represents the probability of fission per incident neutron. For example if y is the number of incident neutron then those causing fission = $a \times y$. Neutron flux is the number of neutrons crossing a plane of area one metre square held at right angle to velocity v.

$\phi = n \times v$

S = total fuel atoms in reactor = $N.V.$

h = number of incident neutrons per second on fuel atoms

$= S \times \phi = n.v.N.V.$

x = Number of neutrons causing fission per second

$= h \times a = n.v.N.V.a.$

Now 3.1×10^{10} fission per second produce a power of one watt (See example 5.3)

P = Power of nuclear reactor

$$= \frac{x}{3.1 \times 10^{10}} = \frac{n.v.N.V.a.}{3.1 \times 10^{10}} \text{ watts}$$

Let the fuel used in the reaction be U^{235}

Mass per atom of U^{235}

$$= \frac{\text{At. weight of } U^{235}}{\text{Avogadro Number}} = \frac{235}{6.02 \times 10^{26}} \text{ kg.}$$

Mass of NV atoms = $N.V.$ × Mass per atom

$$= NV \times \frac{235}{6.02 \times 10^{26}} = M \text{ kg (say)}$$

$$\therefore \quad NV = \frac{6.02 \times 10^{26} \times m}{235}$$

Now
$$P = \frac{n.v.N.V.a.}{3.1 \times 10^{10}} \text{ watts}$$

$$= \frac{\phi \times 6.02 \times 10^{26} M \times 582 \times 10^{-28}}{3.1 \times 10^{10} \times 235}$$

$$= 4.8 \times 10^{-12} M\phi \text{ watts.}$$

5.33 Reactor Power Control

The power released in a nuclear reactor is proportional to the number of mole fissioned per unit time this number being in turn proportional to density of the neutron flux in the reactor. The power of a nuclear reactor can be controlled by shifting control rods which may be either actuated manually or automatically.

Power control of a nuclear reactor is simpler than that of conventional thermal power plant because power of a nuclear reactor is a function of only one variable whereas power of a thermal power plant depends on number of factors such as amount of fuel, its moisture content, air supply etc. This shows that power control of thermal plant requires measuring and regulating several quantities which is of course considerably more complicated.

5.34 Nuclear Power Plant Economics

Major factors governing the role of nuclear power are its economic development and availability of sufficient amount of nuclear fuel.

It is important to extract as much energy from a given amount of fuel as possible. The electrical energy extracted per unit of amount of fuel or expensive moderator might be called the "material efficiency". In a chain reactor the high material efficiency as well as high thermal efficiency leads to low over all energy cost.

Since the most attractive aspect of nuclear energy is the possibility of achieving fuel costs considerably below that for coal, all nuclear power system being considered for large scale power production involve breeding or regenerative systems. This program includes the development of the technology of low neutron absorbing structural materials such as zirconium, the use of special moderating materials such a D_2O and the consideration of special problems associated with fast reactors. In so far as economic factors are concerned it is necessary to consider neutron economy in a general way such as that measured by the conversion ratio of the system. The conversion ratio is defined as the atoms of new fuel produced in fertile material per atom of fuel burnt. The conversion ratio varies

with the reactor design. Its values for different reactors are indicated in Table 5.5.

Table 5.5

Type of reactor	*Conversion ratio*
BWR, PWR and SGR	1
Aqueous thorium breeder	1.2
Fast breeder reactor	1.6

5.35 Safety Measures for Nuclear Power Plants

Nuclear power plants should be located far away from the populated area to avoid the radioactive hazard. A nuclear reactor produces α and β particles, neutrons and γ-quanta which can disturb the normal functioning of living organisms. Nuclear power plants involve radiation leaks, health hazard to workers and community, and negative effect on surrounding forests.

At nuclear power plants there are three main sources of radioactive contamination of air.

(*i*) Fission of nuclei of nuclear fuels.

(*ii*) The second source is due to the effect of neutron fluxes on the heat carrier in the primary cooling system and on the ambient air.

(*iii*) Third source of air contamination is damage of shells of fuel elements.

This calls for special safety measures for a nuclear power plant. Some of the safety measures are as follows.

(*i*) Nuclear power plant should be located away from human habitation.

(*ii*) Quality of construction should be of required standards.

(*iii*) Waste water from nuclear power plant should be purified.

The water purification plants must have a high efficiency of water purification and satisfy rigid requirements as regards the volume of radioactive wastes disposed to burial.

(*iv*) An atomic power plant should have an extensive ventilation system. The main purpose of this ventilation system is to maintain the concentration of all radioactive impurities in the air below the permissible concentrations.

(*v*) An exclusion zone of 1.6 km radius around the plant should be provided where no public habitation is permitted.

(*vi*) The safety system of the plant should be such as to enable safe shut down of the reactor whenever required. Engineered safety features are built into the station so that during normal operation as well as during a severe design

basis accident the radiation dose at the exclusion zone boundary will be within permissible limits as per internationally accepted values.

Adoption of a integral reactor vessel and end shield assemblies, two independent shut down systems, a high pressure emergency core cooling injection system and total double containment with suppression pool are some of the significant design improvements made in Narora Atomic Power Project (NAPP) design. With double containment NAPP will be able to withstand seismic shocks.

In our country right from the beginning of nuclear power programme envisaged by our great pioneer Homi Bhabha in peaceful uses of nuclear energy have adopted safety measures of using double containment and moderation by heavy water one of the safest moderators of the nuclear reactors.

(*vii*) Periodical checks be carried out to check that there is no increase in radioactivity than permissible in the environment.

(*viii*) Wastes from nuclear power plant should be carefully disposed off. There should be no danger of pollution of water of river or sea where the wastes are disposed.

In nuclear power plant design, construction, commissioning and operation are carried out as power international and national codes of protection with an over-riding place given to regulatory processes and safety of plant operating personnel, public and environment.

5.36 Site Selection and Commissioning Procedure

In order to study prospective sites for a nuclear power plant the Department of Atomic Energy (DAE) of our country appoints a site selection committee with experts from the following :

(*i*) Central Electricity Authority (CEA).

(*ii*) Atomic Minerals Division (AMD).

(*iii*) Health and safety group and the Reactor Safety Review group of the Bhabha Atomic Research Centre (BARC).

(*iv*) Nuclear Power Corporation (NPC).

The committee carries out the study of sites proposed. The sites are then visited, assessed and ranked. The recommendations of the committee are then forwarded to DAE and the Atomic Energy Commission (AEC) for final selection.

The trend is to locate a number of units in a cluster at a selected site. The highest rated units in India are presently of 500 MW. The radiation dose at any site should not exceed 100 milligram per member of the public at 1.6 km boundary.

The commissioning process involves testing and making operational individually as well as in an integrated manner the various systems such as electrical service water, heavy water, reactor

regulating and protection, steam turbine and generator. To meet the performance criteria including safe radiation levels in the plant area and radioactive effluents during operation the stage-wise clearance from Atomic Energy Regulatory Board (AERB) is mandatory before filling heavy water, loading fuel making the reactor critical, raising steam, synchronising and reaching levels of 25%, 50%, 75% and 100% of full power. The commissioning period lasts for about two years.

Example 5.1. *Calculate the number of fission in uranium per second required to produce 2 kW of power if energy released per fission is 200 meV.*

Solution. P = Power = 2 kW

E = Energy released per fission = 200 MeV

$= 200 \times 10^6$ eV $= 200 \times 10^6 \times 1.6 \times 10^{-12}$

$= 3.2 \times 10^{-4}$ ergs

$P = 2$ kW $= 2000$ Watts $= 2000$ joules/sec.

$= 2000 \times 10^7$ ergs/sec $= 2 \times 10^{10}$ ergs/sec

N = Number of fissions per sec.

$$= \frac{P}{E} = \frac{2 \times 10^{10}}{32 \times 10^{-4}} = 6.25 \times 10^{13}. \textbf{ Ans.}$$

Example 5.2. *A nuclear reactor uses U^{235} as fuel. If the mass of fuel is 1.2 kg and neutron flux is 10^{16} per sec. Calculate the power of reactor.*

Solution. M = Mass of fuel = 1.2 kg

ϕ = Neutron flux = 10^{16}/sec

P = Power of reactor

$= 4.8 \times 10^{-12}$ m ϕ watts

$= 4.8 \times 10^{-12} \times 1.2 \times 10^{16}$

$= 57.6 \times 10^3$ watts = 57.6 kW.

Example 5.3. *Calculate the fission rate of U^{235} for producing power of one watt if 200 MeV if energy is released per fission of U^{235}.*

Solution. P = Power = 1 watt

E = Energy released per fission of U^{235} nucleus

$$= 200 \text{ MeV} = 200 \times 1.6 \times 10^{-13} \text{ J}$$

$$= 3.2 \times 10^{-11} \text{ watt sec.}$$

as $1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J}$

Fission rate of producing one watt of power

$$= \frac{P}{E} = \frac{1}{3.2 \times 10^{-11}} = 3.1 \times 10^{10} \text{ fissions/sec.}$$

Example 5.4. *A railway engine is driven by atomic power at an efficiency of 40% and develops an average power of 1600 kW during 8 hour run from one station to another. Determine how much U^{235} would be consumed on the run if each atom on fission releases 20 0 MeV.*

Solution. Output = 1600 kW

Efficiency = 0.4

$$0.4 = \frac{\text{Output}}{\text{Input}}$$

$$\text{Input} = \frac{1600}{0.4} = 4000 \text{ kW} = 4 \times 10^6 \text{ watts.}$$

E = Energy released per fission = 200 MeV

$$= 200 \times 1.6 \times 10^{-12} \text{ J} = 3.2 \times 10^{-11} \text{ J}$$

t = Time = 8 hours = 8×3600 seconds.

Input nuclear energy required = Input $\times t$

$$= 4 \times 10^6 \times 8 \times 3600 \text{ J} = 115.2 \times 10^9 \text{ J}$$

Number of U^{235} atoms required for 8 hour run

$$= \frac{115.2 \times 10^9}{E} = \frac{115.2 \times 10^9}{3.2 \times 10^{-11}} = 36 \times 10^{20}$$

We know that 235 gm of U^{235} contains 6.02×10^{23} atoms (Avogadro's hypothesis).

Mass of U^{235} consumed

$$= \frac{36 \times 10^{20} \times 235}{6.02 \times 10^{28}} = 1.4 \text{ gm.}$$

Example 5.5. *Determine the energy released by the fission of 1.5 gm of U^{235} in kWh assuming that energy released per fission is 200 MeV.*

Avogadro number = 6.025×10^{23}

Mass of Uranium = 235 *a.m.u.*

Solution. n = Number of atoms in 1.5 gm of U^{235}

$$= \frac{1.5 \times 6.025 \times 10^{23}}{235}$$

E_1 = Energy released per fission = 200 MeV

$$= 200 \times 10^6 \times 1.6 \times 10^{-19} = 3.2 \times 10^{-11} \text{ Joules}$$

E = Energy released by 1.5 gm of U^{235}

$$= n \times E_1 \text{ Joules}$$

$$= \frac{1.5 \times 6.025 \times 10^{23}}{235} \times \frac{3.2 \times 10^{-11}}{60 \times 60 \times 10^3} \text{ kWh}$$

$$= 3.42 \times 10^4 \text{ kWh.} \quad \textbf{Ans.}$$

Example 5.6. *Determine the fission energy released when a U-235 nucleus is fissioned by a thermal neutron and two fission fragments and two neutrons are produced. The average binding energy per nucleon is 8 MeV in the fissioned U-235 nucleus and 8.8 MeV in the fission fragments.*

Solution. E = fission energy released

$$= 234 \times 8.8 - 236 \times 8$$

$$= 158.4 \text{ MeV.}$$

PROBLEMS

5.1. What is a chain reaction ? How it is controlled ?

5.2. What is a nuclear reactor ? Describe the various parts of a nuclear reactor.

5.3. What are different types of reactors commonly used in nuclear power stations ? Describe the fast breeder reactor ? What are its advantages over sodium graphite reactor ?

5.4. How waste is disposed off in a nuclear power station ? What are main difficulties in handling radioactive waste ?

5.5. Discuss the various factors to be considered while selecting the site for nuclear power station. Discuss its advantages and disadvantages.

5.6. Write short notes on the following :
(*a*) Boiling water reactor (B.W.R.)
(*b*) Pressurised water reactor (P.W.R.)
(*c*) Multiplication factor.
(*d*) Fertile and fissionable material.

5.7. What are the different components of a nuclear power plant ? Explain the working of a nuclear power plant. What are the different fuels used in such a power plant ?

5.8. What is a Homogeneous Reactor ? Describe a Homogeneous Aqueous Reactor (H.A.R.).

5.9. What is meant by Uranium enrichment ? Describe some methods of Uranium enrichment.

5.10. Compare the economic (cost) of nuclear power plant with steam power plant.

5.11. Explain the terms 'Breeding' and 'Burn up'.

5.12. Make a neat sketch and explain the working of a gas cooled reactor.

5.13. State the properties of control rods.

5.14. Explain the properties of moderator used in a nuclear reactor.

5.15. Explain the principle of operation of a sodium graphite reactor.

5.16. Discuss the factors which go in favour of nuclear power plant as compared to other types of power plants.

5.17. Write short notes on various nuclear power plants in India.

5.18. Write short notes on the following :
(*i*) Multiplication factor.
(*ii*) Moderating ratio.
(*iii*) Conversion ratio.

5.19. Compare the control of nuclear reactor and steam power plant.

5.20. Discuss the economics of a nuclear power plant.

5.21. Discuss the safety measures in nuclear power plant.

5.22. Describe various types of nuclear fuels.

5.23. Describe the objectives of R and D in nuclear energy in India.

5.24. Discuss the safety measures provided at Narora Atomic Power Plant (NAPP).

5.25. Describe the site selection and commissioning procedure of Nuclear Power plants in our country.