6

Hydro-Electric Power Plant

6.1. Water Power

Water is the cheapest source of power. It served as the source of power to our civilization in its earlier days in the form of water wheels. Faraday's discovery of electricity has proved to be very useful to use water for producing electric power. A hydro-electric power plant is aimed at harnessing power from water flowing under pressure.

Hydro or water power is important only next to thermal power. Nearly 30% of the total power of the world is met by hydro-electric power. This was initiated in India in 1897 with a run of river scheme near Darjeeling. The first major hydro-electric development of 4.5 MW capacity named as Sivasamudram Scheme in Mysore was commissioned in 1902. In 1914 a hydro power plant named Khopol project of 50 MW capacity was commissioned in Maharashtra. Up to 1947 the hydro power capacity was about 500 MW.

Water power has some inherent advantages as follows :

(*i*) Running cost of hydro power plant is low as compared to steam power plant or nuclear power plant of same capacity.

(*ii*) The hydro plant system reliability is greater than that of other power plants.

(*iii*) The hydraulic turbines can be put off and on in matter of minutes. Nuclear power plants and steam power plants lack this facility.

(*iv*) Modern hydropower plant equipment has a greater life expectancy which is about 50 years or more whereas as nuclear power plant has an effective life about 30 years.

(*v*) Steam power plants have problem of ash disposal where as hydro power plants have no comparable problem.

(*vi*) Modern hydro generators give very high efficiency over a considerable range of load.

Although the capital investment of a hydro-electric power plant is more but the operating cost of this plant is minimum as compared to other power plants and power produced by this plant is cheaper than the power generated by other power plants using coal, oil etc. Besides power generation this plant is quite useful for irrigation and flood control. This plant can be used both as base load plant and peak load plant.

A schematic diagram of hydro-electric power plant is shown in Fig. 6.1. Water surface in the storage reservoir is known as head race level or simply headrace. Penstocks or canals are used to bring water from the dam of the turbines fitted in the power house which is built at some lower level. Penstocks are made up of steel, wood or reinforced concrete. Water centers the turbine through the inlet valve. Hydraulic turbines convert the potential energy of water into mechanical energy. The mechanical energy developed by the turbine is used in running the electric generator which is directly coupled to shaft of the turbine.

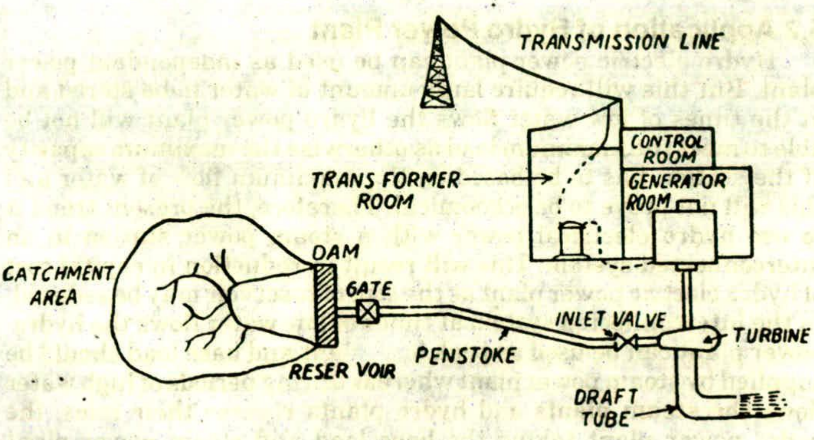


Fig. 6.1

Water power can be divided into two types as follows :

(*i*) Primary or firm power

(*ii*) Secondary or surplus power.

Primary power is the power corresponding to minimum stream flow with due consideration to the effects of pondage and load factor. It is the power always available to supply the load. The secondary power is available only when quantity of water and storage are sufficient.

Hydro power is a conventional renewable source of energy which is clean, free from pollution and generally having good environmental effect. The pace of utilization of hydro potential during the last decades has been slow compared to total energy development. Large investments, long gestation period and increased cost of power transmission are major obstacles in the utilisation of hydro power resources.

Hydro power is important next to thermal power. About 30% of total power of the world is met by hydro electric power plants. The total hydro potential of the world is about 5000 GW. There are some countries in the world where almost entire power generation is hydrobased. For example in Norway the hydropower forms 99% of total installed capacity.

Power output from a hydro power plant depends on the following three factors :

(*i*) Head
(*ii*) Efficiency
(*iii*) Discharge.

Power generation mainly depends upon the quantity of water available.

6.2 Application of Hydro Power Plant

Hydro electric power plant can be used as independent power plant. But this will require large amount of water to be stored and at the times of low water flows the hydro power plant will not be able to meet the maximum load as otherwise the maximum capacity of the station has to be based on the maximum flow of water and this will not prove to be economical. Therefore, the present trend it to use hydro electrical power with a steam power station in an interconnected system. This will result in reduction in capital cost of hydro electric power plant as the size of reservoir may be reduced. In the interconnected system at times of low water flows the hydropower plant can be used as peak load plant and base load should be supplied by steam power plant whereas during periods of high water flows the steam plants and hydro plants reverse their roles, the hydro power plant taking the base load and steam power plant supplying the peak load.

6.3 Essential Feature or Elements of Hydro-electric Power Plant

The essential elements of hydro-electric power plant are as follows :

(*i*) Reservoir
(*ii*) Dam
(*iii*) Forebay
(*iv*) Trash rack
(*v*) Water way
(*vi*) Draft tube
(*vii*) Surge tank
(*viii*) Spill way
(*ix*) Power house and equipment.

1. **Water Reservoir.** It is the basic requirement of a hydro-electric power plant. Water reservoir is used to store water which may be utilized to run the turbines to produce electric power. Reservoir may be natural such as lake or artificial reservoir can be built by erecting a dam across the river. Water held in upstream reservoir is called storage whereas water behind the dam at the plant is called pondage.

2. **Dam.** A dam is structure of masonry or some other material built at a suitable location across a river. The primary function of the dam is to provide a head of water. It also creates pondage or storage. Economy and safety are the basic requirement of a dam. Dam should be capable of resisting pressure of water and should be stable under all conditions.

Dams are classified based on the following factors :

(*i*) Function (*ii*) Shape

(*iii*) Construction materials (*iv*) Design.

Based on functions the dams may be called as storage dams, diversion dams or detention dams. Storage dams are mainly for storing water whereas diversion dams are constructed to raise the water level and to divert the river flow in another direction. Detention dams are primarily used to store flood waters.

Based on shape the dams may be of trapezoidal section, and arch type. The commonly used materials for constructing dams are earth, rock pieces, stone masonry, concrete and R.C.C. concrete dams may be plain as well as steel reinforced, earthen and rockfill dams are the three most popular categories of dams based on the material classification.

According to structural design the dams may be classified as :

(*a*) Gravity dam (*b*) Arch dam

(*c*) Buttress dam (*d*) Earthen dams

(*e*) Rock fill dam.

A gravity dam is one in which the retained water thrust is resisted by gravity action whereas in arch dam the thrust is resisted by the arch action. A buttress dam resists the water thrust with the help of buttresses which support the water through an inclined structural member such as a buttress. Based on hydraulic design dams may be classified as :

(*i*) Non over-flow dams (*ii*) Over-flow da

In non over-flow type dam water is not allowed in flow over top of dam whereas in overflow type water is allowed to flow over top of dam.

The various structural material used for dams may be concrete or stone masonry, earth, rock fill or timber. The type selected depends upon the topography of the site, foundation condition and economics. The foundation should be sufficiently impervious to prevent seepage of water under the dam. Timber dams are rarely used and need constant inspection to keep them in good condition. Masonry dams are quite popular and are of three major types :

(*i*) The solid gravity dam (*ii*) The buttress dam
(*iii*) The arched dam.

6.3.1 Types of Dam. The different types of dams are as follows.

(*i*) **Masonry Dam.** Masonry dams may be sub-classified as follows :

(*a*) *Gravity dam.* This type of dam resists the pressure of water by its weight. The construction material used for this dam, is solid masonry or concrete. Fig. 6.2 shows a gravity dam.

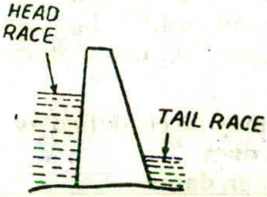


Fig. 6.2

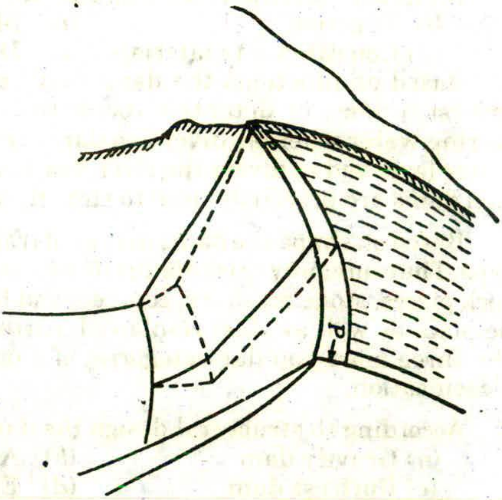


Fig. 6.3

A gravity dam is subjected to the following forces :

(*i*) Water pressure (*ii*) Weight of dam
(*iii*) Uplift pressure (*iv*) Earth pressure
(*v*) Reaction of the foundation
(*vi*) Earth-quake pressure (*vii*) Wind pressure.

These forces should be taken into account while analysing the structural stability of dam.

(*b*) *Arch dam.* It resists the pressures of water partly due to its weight and partly due to arch action. This type of dam is located in relatively narrow valley with steep slopes suitable for arch abutment (Fig. 6.3). The main advantage using an arch dam is that the amount of masonry or concrete required is much less than a gravity dam of compared height, consequently the material cost is much less. This type of dam cannot use the over fall type spillway as in gravity dam. The spillway has to be separately provided which increases the cost of outlet works and overall cost of the project.

(*c*) *Buttress Dam.* A buttress dam consists of buttresses supporting a flat slab or reinforced concrete. This type of dam is selected when the cost of reinforced concrete is high (Fig. 6.4).

Masonry dams have the advantages of maximum height, longest life most economical in water conservation and lowest maintenance cost as compared to earth dam.

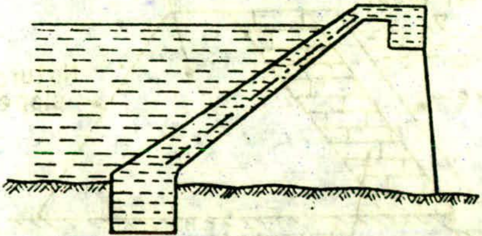


Fig. 6.4

(*ii*) **Earth Dams.** Earth dams are used for smaller power plants. They can be built safety and economically on all types of foundations of earth and rock. They can be further sub-classified as follows :

(*a*) Earth Dam (*b*) Rock Fill Dam.

Earthed dams are used when effective height of dam is not large, river banks are not steep and the site is unable to take the weight of gravity dam. Fig. 6.5 shows earth dam.

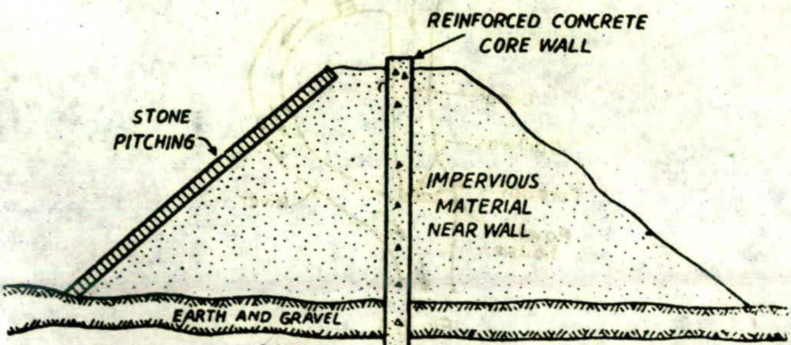


Fig. 6.5

(*iii*) **Rock-fill dam.** This time of dam is preferred where adequate quantity of good rock is available near the dam site. It is used extensively in remote locations. Various parts of dam are as follows :

(*a*) Loose rock fill.

(*b*) An up stream dry rubble cushion of laid up stone bonding into the dumped rock.

(*c*) An up stream impervious membrane resting on the dry rubble cushion.

Fig. 6.5 (*a*) shows cross section of a rockfill dam.

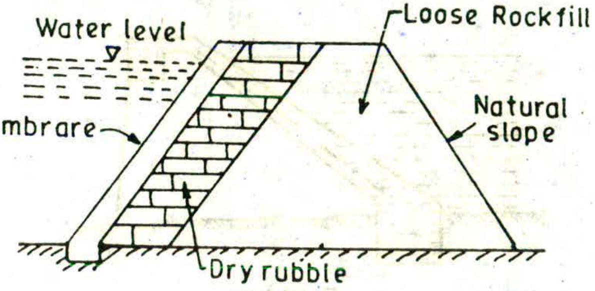


Fig. 6.5 (*a*)

Various advantages of rock fill dam are as follows :

(*i*) High resistance to earth quake.

(*ii*) Foundation rock need not be as strong as for gravity dams.

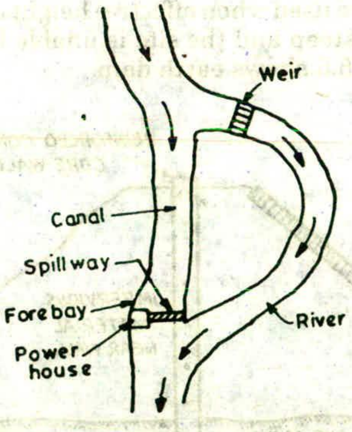


Fig. 6.6

3. **Forebay.** It acts as a sort of regulating reservoir temporarily. Water is temporarily stored in the forebay in the event of a rejection of load by the turbine and there is withdrawal of water from it when

load is increased. In diversion canal plants water of the river is diverted away from the main channel through a diversion canal. The end of canal is enlarged in the form of forebay as shown in Fig. 6.6. The forebay is provided with some type of outlet structure to direct water to pen stock.

Following are the parts of a typical forebay : (*i*) Entrance bay or basin ; (*ii*) Spillway ; (*iii*) Flushing sluice ; (*iv*) Screens ; (*v*) Valve chamber or gate chamber ; (*vi*) Penstock inlet.

4. **Trash rack.** It is provided for preventing the debris from getting entry into the intakes from dam or from the forebay. Manual cleaning or mechanical cleaning is used to remove the debris from trash rack.

Trash rack is made up of steel bars and it is placed across the intake to prevent the debris from going into the intake.

The spacing of bars depends upon the following factors :

(*i*) Type of turbine ; (*ii*) Size of floating material.

If floating material is large and height of trash rack structure is more, mechanical cleaning is economical.

(*iii*) Velocity of flow through trash rack.

The velocity of flow (V) through trash rack should be kept with-in limits so that it does not cause great loss of head. It is given by

$$V = 0.12\sqrt{2gh}$$

where h = difference in head.

Velocity greater than 90 cm/sec. may cause the trash rack structure to vibrate if bars are not rigidly stiffened and supported.

5. **Waterway.** A waterway is used to carry water from the dam to the power house. It includes canal, penstock (closed pipe) or tunnel. Tunnel is made by cutting the mountains where topography prevents the use of a canal or pipe line. Tunnel is made to save the distance. Various appliances used to control the flow of water are called head works or control works. Head works include gates, valves, and trash rack etc. Gates in the dam are very useful in discharging the excess water during flood period. The various types of gates used are sluice gates, tainter gates and rolling gates.

Penstocks are made up of steel, reinforced concrete and wood. For smaller developments cast iron pipes may be used. The intake of penstock at the dam or forebay of canal should be at a level low enough to provide an adequate water seal under all conditions particularly at low water. It is desirable that the penstock should be sloping towards the power house and its grade may be varied as desired to suit the topography. Sharp bends in the penstock should be avoided because they cause loss of head and require special anchorages. Generally penstocks are not covered because exposed pipes are cheaper and easily accessible for repairs and maintenance. Covered penstocks should be used where topography is such that there is danger from slides of snow, rock, earth etc. The velocity of water in penstock is about 2 m/sec in low head power plants and about 4 m/sec for medium head power plants and 7 m/sec for high head power plants. The diameter and cross-section area of a penstock pipe would be smaller if it were possible for the velocity of water to be high.

Penstocks may be of two types

(*i*) Exposed pen stocks (*ii*) Buried pen stocks

Advantages of exposed penstocks are as follows :

(*i*) It is less expensive to install
(*ii*) Maintenance is easier
(*iii*) Inspection is easier
(*iv*) Life is more.

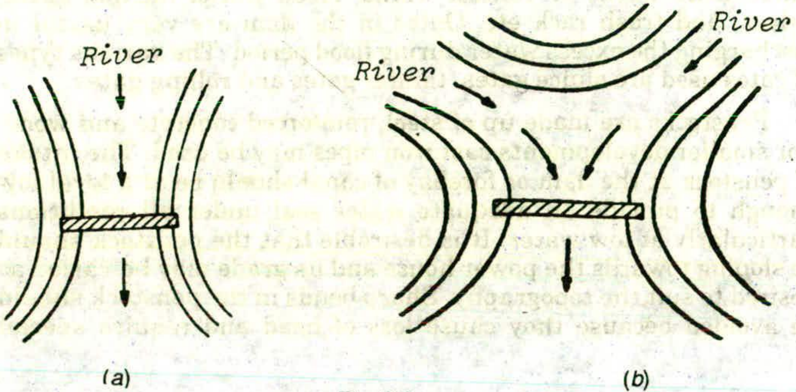
In case of buried pen stock are preferred where land slide, snow slide or falling rocks may take place. In very cold climates where freezing is expected buried pen stocks are used. However corrosion is more and life is less in case of buried penstocks.

6.4 Selection of Site for a Dam

The selection of site for a dam depends upon the following factors :

(*i*) Function of dam. (*ii*) Type of dam.

(*iii*) *Cost of dam* : The cost of construction and cost of tenance of dam should be low. To reduce the cost of dam the le of the dam should be small. This requires that the site should be o where river valley has a neck formation as shown in Fig. 6.6 (*a*) or the dam should be located after the confluence of two rivers as shown in Fig. 6.6 (*b*) taking the advantage of both the valleys to provide larger storage capacity.



(*a*) (*b*)

Fig. 6.6

(*iv*) *Geological features* : Sub soil investigations should be carried out to check that soil or rock strata would provide entirely satisfactory foundation.

(*v*) Accessibility from the view point of transportation of materials.

(*vi*) The area which would get submerged after the construction of dam.

(*vii*) *Safety* : The dam should be safe against floods and catastrophes like earth-quakes.

6.5 To Calculate Penstock Thickness

The thickness of steel penstock depends on water head and hoop stress allowed in the material. It is calculated using the following relation :

$$t = \frac{p.d}{2.f.\eta}$$

where t = Penstock thickness

d = Diameter of penstock

f = Permissible stress

P = Pressure due to water including water hammer

$= wH$

w being the specific weight of water and H head of water.

η = Joint efficiency.

The joint efficiency is about 80% for riveted joints and 90% for welded joints.

6.5.1 Number of penstocks

A hydro power plant uses a number of water turbines which are to be supplied water through penstocks. Following alternative choices may be considered :

(*i*) To use a single penstock for the whole of plant. Such a penstock will have a manifold at its end with as many branches as the number of turbines.

(*ii*) To use one penstock for each turbine separately. In this case each turbine draws water independently directly from the reservoir.

(*iii*) To provide multiple penstocks but each penstock supplying water to atleast two turbines.

Following factors should be considered while selecting the number of penstocks to be used to supply water to the turbines :

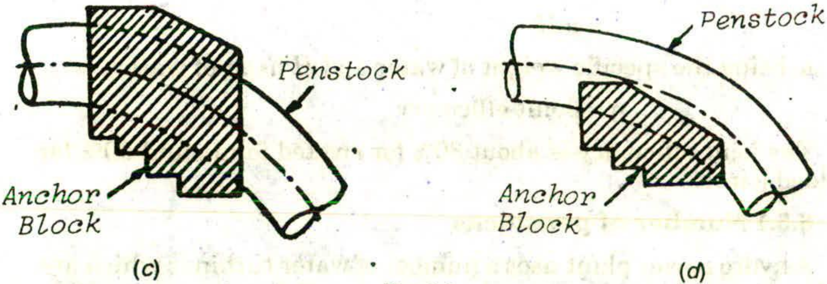
(*i*) *Economy.* From economic point of view if length of penstock is short one penstock should be provided for each turbine. For longer penstocks a single penstock or as few penstocks as possible may be used.

(*ii*) *Operational safety.* Use of a single penstock is not desirable because any damage to the penstock would necessitate a complete shut down at all the turbines.

(*iii*) *Transportation facilities.* The size of penstock selected should be such that transportation of penstock should be easier.

6.5.2 Anchor blocks for penstocks

Anchor blocks act as supports for penstocks. They are massive concrete blocks encasing the penstocks at intervals to anchor down the pipe to the ground securely. The blocks are provided at all horizontal and vertical bends of the penstock pipe. The anchor blocks may completely encase the penstocks as shown in Fig. 6.6 (*c*) or the anchor block may be constructed up to centre of penstock as shown in Fig. 6.6 (*d*) anchor blocks provide necessary reaction to the dynamic forces at the bends. In general the anchor blocks by transmitting loads to the ground provide the necessary degree of stability to the penstock.



(*c*) (*d*)

Fig. 6.6

6.5.3 Penstock Joints

The penstocks may be joined together by

(*a*) riveting (*b*) welding

Welding has the following advantages

(*i*) It is quick

(*ii*) Joint is strong

(*iii*) Joint is hydraulically more efficient.

The welded penstocks are subjected to the following tests.

(*i*) Ultrasonic testing

(*ii*) Radiographic testing
(*iii*) Testing using Dye-penetrants.

Example 6.1. *Determine the thickness of a steel penstock 2.5 metre in diameter if the water head is 200 metres. The allowable stress in steel is 1100 kg/cm² and the efficiency of the joint is 80%.*

Solution. d = Diameter of penstock = 2.5 metres

$$p = wH = 1000 \times 200 = 2 \times 10^5 \text{ kg/m}^2$$

$$f = \text{Allowable stress} = 1100 \text{ kg/cm}^2$$

$$= 1100 \times 10^4 \text{ kg/m}^2 = 11 \times 10^6 \text{ kg/m}^2$$

(η) Efficiency = 0.8

$$t = \frac{p.d.}{2.f\eta}$$

$$= \frac{2 \times 10^5 \times 2.5}{2 \times 11 \times 10^6 \times 0.8} = \frac{1}{35.2} \text{ metre}$$

$$= \frac{1}{35.2} \times 100 = 2.8 \text{ cm.} \quad \textbf{Ans.}$$

6. **The Power House and Equipment.** Power house consists of the main building of hydro electric development where the conversion of energy of water to electrical energy takes place. Some important items of equipment provided in the power house are as follows :

(*i*) Turbines
(*ii*) Generators
(*iii*) Governors
(*iv*) Relief valve for penstock fittings
(*v*) Gate valves
(*vi*) Flow measurement equipment
(*vii*) Air duct
(*viii*) Water circulating pumps
(*ix*) Transformers
(*x*) Switch board equipment and instruments
(*xi*) Reactors
(*xii*) Low tension and high tension bus bar
(*xiii*) Oil circuit breakers
(*xiv*) Storage batteries
(*xv*) Outgoing connections
(*xvi*) Cranes
(*xvii*) Shops and offices.

Power house should be structurally stable. The layout of the power house should be such that sufficient space is provided around the equipment like turbines generators, governors, valves, pumps etc. in order to facilitate the dismantling and repairing.

A power house has three distinct sub divisions in most cases.
(*i*) The sub-structure
(*ii*) Intermediate structure
(*iii*) The super structure.

The sub structure of a power house is that part which extends from top of generator to the soil or rock. It houses the most of the generating equipments. The sub-structure has to accommodate the draft tube in addition to other equipments in case of Francis and Kaplan turbines.

The intermediate structure of a power house is that part of the power house which extends from the top of the draft tube to top of generator foundation.

The super structure is that part which is above the generator level housing mostly the cranes for handling the heavy equipments in the sub-structures.

Depending upon subgrade a power house may be classified as follows :

(*i*) Resting on rock. (*ii*) Resting on soil.

The sub grade design will be based on the soil or rock condition below the foundation.

Depending on the type of super structure and covering provided and housing of generating units a power house may be classified as follows :

(*i*) Out-door type (*ii*) Semi out-door type
(*iii*) In-door type.

In out door type power houses the generators etc. are provided with local steel casing for weather protection but are fully exposed.

In semi out door type a low roof or deck is provided immediately over the generators, the other area being open. The indoor type power station has the conventional structure and all generating system are covered under a roof. This is the most commonly used type of power house.

7. **The Tail Race.** Tail-race is a waterway to lead the water discharged from the turbine to the river. The water after doing work on turbine runner passes through the draft tube to tail race. The water held in the tail race is called as tail-race water level.

6.6. Layout of Hydro Power Plant

The layout of a hydro power plant depends on the following factors :

(*i*) The services to be performed by the power plant
(*ii*) Surrounding topography
(*iii*) Controlling economics.

These factors in turn govern the type and arrangement of dams, spillways and conduit systems.

The power plant building encloses generators, power house crane, control room, offices, ancillary rooms etc. The crane provided in the power house building should be high enough to clear the generator and should be able to pull up turbine runner out of spiral casing and place it on operation floor for maintenance. Transformers and switch gears are located outside the building.

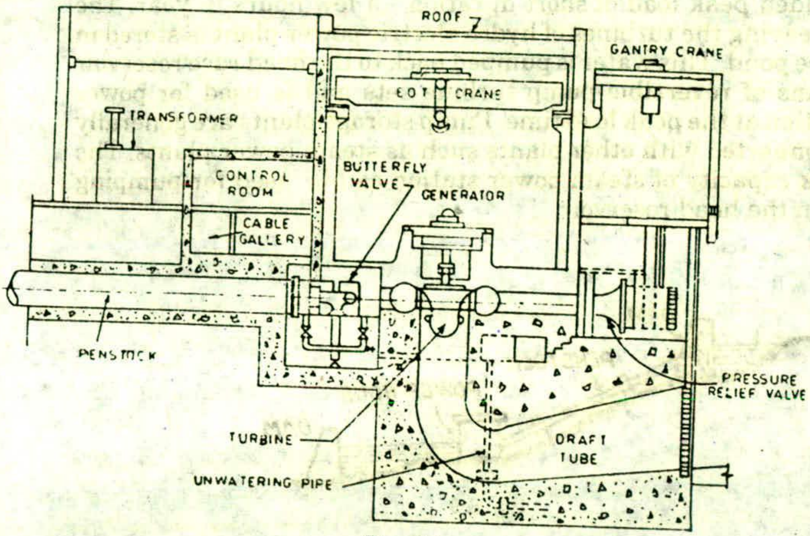


Fig. 6.7

Fig. 6.7 shows a typical layout of a hydro power plant using a Kaplan turbine. The height of building is decided by considering the equired clearance for the crane when handling largest part of the quipment. The spacing between generators units is determined fter finding the overall dimensions of the generators and the urbines.

.7 Classification of hydro-electric Power Plants

The classification of hydro electric power plants depends on the ollowing factors :

1. **Quantity of Water.** (*a*) *Run of River Plant.* This type of power lant has no control over the river flow and uses the water as it comes. During the rainy season high water flow is available and if the power plant is not able to use this large flow of water some quantity of water is allowed to flow over dam spillways as waste. Whereas during dry season, due to low rates of water, the power produced by such plants will be low. It is shown in Fig. 6.8.

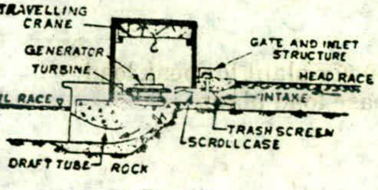


Fig. 6.8

(*b*) *Storage Plant.* This type of power plants has facilities for storing water. During rainy seasons the excess water is stored in the reservoir and it is released to supplement low rates of flow during run off (dry) periods. The advantage of this plant that the power generated by the plant during dry season will not be affected.

(*b*) *Pumped Storage Plant.* Pumped storage plant (Fig. 6.9) in combination with hydro electric power plant is used for supplying the sudden peak load of short duration - a few hours in year. The water leaving the turbines of hydro electric power plant is stored in tail-race pond. This water is pumped back to the head race reservoir by means of reversible pump turbine sets and is used for power generation at the peak load time. Pump storage plants are generally inter connected with other plants such as steam power plants. The off peak capacity of steam power station can be used for pumping water in the head reservoir. .

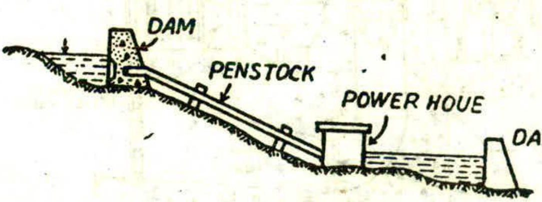


Fig. 6.9

A 400 MW pumped storage plant is at design stage at Kadamparai in Tamil Nadu. This will be built with the existing upper Aliyar Reservoir at the lower pool, the higher pool being constructed at Kadamparai river. There will be four 100 MW reversible units in an underground power house.

Advantages of pumped storage plants are as follows :

(*i*) The capital cost of pumped storage plant is low as compared to other peaking units.

(*ii*) There is a great deal of flexibility in the operational schedules of the system.

(*iii*) A pumped storage plant can pick up load rapidly and is dependable.

(*iv*) They operate at higher load factors and improve the overall efficiency of the system.

They are used as peak load plants.

Fig. 6.9 (*a*) shows the pumped storage power plant for peak load in conjunction with steam power plant as base load plant.

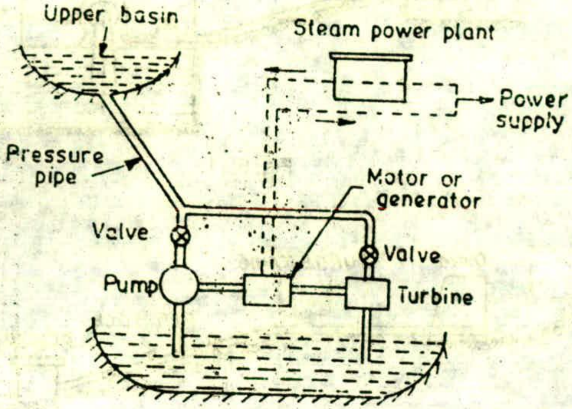


Fig. 6.9 (*a*)

2. **Availability of Head of Water.** According to head of water available the hydro-electric power plants can be classified as follows :

(*a*) *Low Head Plant.* When the operating head is less than 15 metres the plant is named as low head plant. This type of plant uses vertical shaft Francis turbine or Kaplan turbine. A small dam is built to provide the necessary head. A low head plant (canal water power plant) is shown in Fig. 6.10.

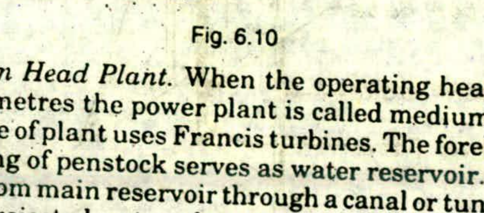


Fig. 6.10

(*b*) *Medium Head Plant.* When the operating head of water is from 15 to 50 metres the power plant is called medium head power plant. This type of plant uses Francis turbines. The forebay provided at the beginning of penstock serves as water reservoir. The forebay draws water from main reservoir through a canal or tunnel. Forebay also stores the rejected water when the load on the turbine decreases (Fig. 6.11).

(*c*) *High Head Power Plant.* When the head of water exceeds 50 metres the plant is known as high head power plant. A surge tank is attached to the penstock to reduce the water hammer effect on the penstock. Pelton turbines are used in such power plants. Fig. 6.12 shows a high head power plant.

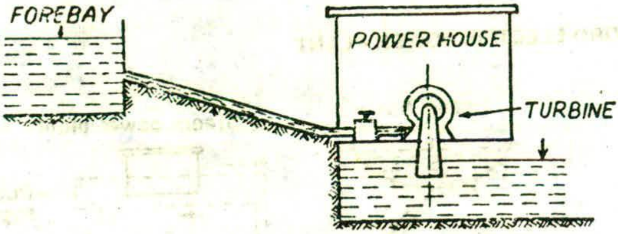


Fig. 6.11

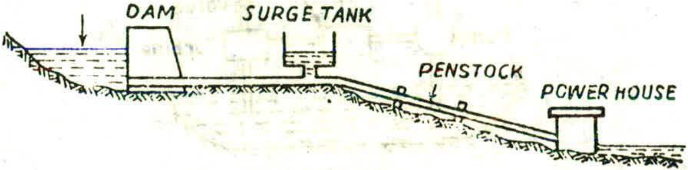


Fig. 6.12

Following are the main component parts of a high head hydroelectric power plant.

(*i*) Reservoir	(*ii*) Dam

(*iii*) Intake structure such as (*a*) Control gates (*b*) Screen

(*iv*) Penstock	(*v*) Surge tank
(*vi*) Power house	(*vii*) Tail race channel.

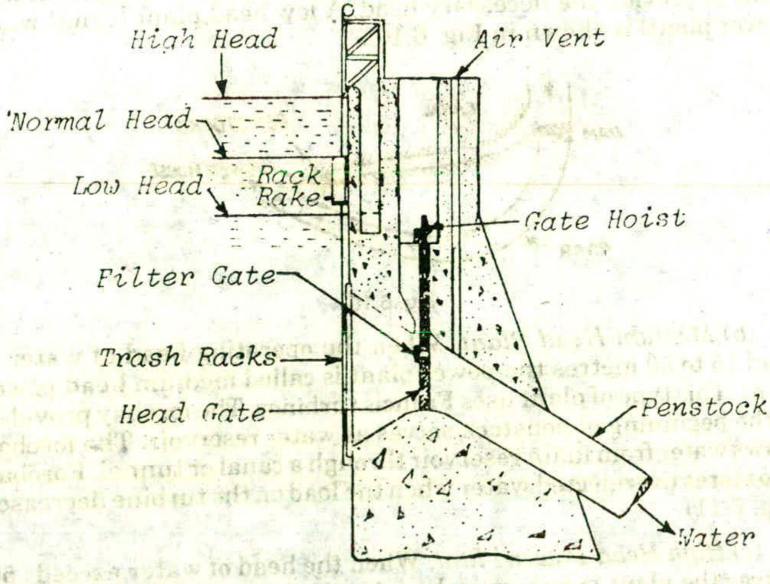


Fig. 6.13

Fig. 6.13 shows a typical high pressure intake head works. Trash racks remove floating or submerged debris directly at the intake entrance. Filter gate balances water pressure for opening the gate whereas air vent prevents penstock vacuum.

3. Classification according to topography
(*i*) Low land (*ii*) Hilly area
(*iii*) Mountaineous region.

4. Classification according to load supplied.
(*a*) Base load plant
(*b*) Peak load plant.

5. Classification according to capacity of plant
(*i*) Micro hydel plants — upto 5 MW
(*ii*) Medium capacity plants — 5 to 100 MW
(*iii*) High capacity plants — 101 to 1000 MW
(*iv*) Super plants — above 1000 MW.

6. Classification according to turbine characteristic, *i.e.* specific speed.
(*i*) High specific speed
(*ii*) Medium specific speed.

6.8 Advantages of Hydro-electric Power Plant

The major factor which go in favour of hydro-electric power plant are as follows :

1. Water is the cheapest and reliable source of generation of electric power because it exists as a free gift of nature.
2. There are no ash disposal problems. Also the atmosphere is not polluted because no smoke is produced in this plant.
3. No fuel transportation problem.
4. It can take up the loads quickly and it is capable of meeting the variable loads without any loss in efficiency.
5. Its maintenance cost is low.
6. It requires less supervising staff.
7. Auxiliaries needed in the plant are less as compared to steam plant of equal size.
8. Running cost of the plant is low.
9. In addition to the power generation such plants are used for irrigation and flood control purposes also.
10. Hydro electric power plants have become economics competitors with steam power plants and will acquire more economic advantage with the rise in price of coal and oil.
11. The life of the plant is more and the effect of age is comparatively small on the overall efficiency of the plant.

Disadvantages. The various disadvantages are as follows :

1. The power produced by the plant depends upon quantity of water which in turn is dependent upon the rainfall, so

if the rainfall is in time and proper and the required amount of water can be collected, the plant will function satisfactorily otherwise not.

2. Hydro-electric plants are generally situated away from the load centres. They require long transmission lines to deliver power. Therefore, the cost of transmission lines and losses in them will be more.
3. Initial cost of the plant is high.
4. It takes fairly long time for the erection of such plants.

6.9 Mini and Micro Hydro Power Plants

Micro hydro power plants (up to 100 kW capacity), mini hydro power plants (up to 1 MW) and small plants (up to 10 to 15 MW) can be successfully used for electrification of isolated pockets of villages where the transmission system cannot easily reach. This includes exploitation of mountain streams rivulets and canal drops. The power from mini-hydro power plants and micro-hydro power plants will be attractive as the energy generated can be consumed near the source itself without a big network of sub transmission systems.

Micro/mini hydro development is an extremely valuable, economic, renewable energy source in its endeavour to meet decentralised rural need of the country.

The potential in small hydro-electric projects in various countries ranges from 5 to 15% of the total hydro-potential of that country. In India the estimated hydro energy potential of micro/mini hydro power plants leads to an installed capacity of 10000 MW spread over 5000 to 6000 schemes. Small hydro power plants (SHP) which generate electricity in small scale are now being developed. These power plants are an attractive renewable source of energy in remote and hilly regions isolated from main grids.

Various advantages of small hydro-power plants (SHP) are as follows :

(*i*) Readily accessible source of renewable energy.
(*ii*) Can be installed making use of water head as low as 2 m and above.
(*iii*) Does not involve setting up of large dams.
(*iv*) Least polluting.
(*v*) Limited initial investments and short gestation periods.
(*vi*) Reduced transmission losses.

The Indian Renewable Energy Development Agency (IREDA) is encouraging both public and private organisations to set up small/mini/micro hydel power plants.

In our country nearly 120 micro/mini small hydel schemes (up to 3 MW capacity) with a total capacity of about 86 MW are in operation. Nearly 117 small power plants of total 125 MW capacity are under construction. Eighth five year plan proposals envisage a capacity addition through such schemes of about 600 MW.

The potential of small hydro power plants (up to 5 MW capacity) is estimated to be around 5000 MW. This remains largely untapped.

6.10 Draft Tube

It is an integral part of reaction turbine. Draft tube connects the runner exit to tail race. The area of the top of the draft tube is same as that of the runner to avoid shock and is of circular cross-section. The water after doing work on the turbine runner passes through the draft tube to the tail-race. Draft tube is a metallic pipe or concrete tunnel having gradually increasing cross-sectional area towards outlet to ensure that as little energy possibly is left in water as it discharges into the tail-race. Draft tube provides a negative section head at the runner outlet by which it becomes possible to install the turbine above the tail-race level without any loss of head. Secondly the velocity of water leaving the runner is quite high. Thus the kinetic energy of water due to this velocity will be lost if the water is allowed to be discharged freely. So by passing water through the draft tube, the outlet velocity of water is reduced considerably and gain in useful pressure head is achieved, that is the net working head on the turbine increases and thus output of the turbine also increases.

6.10.1 Types of Draft Tubes

1. *Straight Divergent Tube.* It is used by the low specific speed vertical shaft Francis turbine. This draft tube improves the speed regulation during falling load [Fig. 6.14 (*a*)]. Its maximum cone angle is 8 .

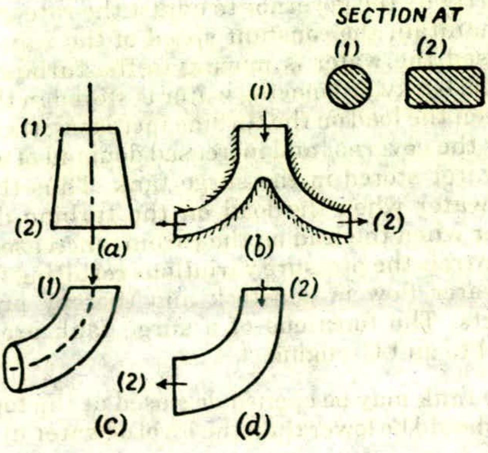


Fig. 6.14

2. *Moody Spreading Draft Tube*. This draft tube [Fig. 6.14 (*b*)] has an advantage that its conical portion at the centre reduces the whirl action of water moving with high velocity centre reduces.

3. Simple Elbow draft tube [Fig. 6.14 (*c*)] and draft tube with circular inlet and rectangular outlet [Fig. 6.14 (*d*)] require lesser excavation for their installation and thus cost of excavation is less for such draft tubes.

Efficiency of draft tube is given by the following formula

$$\eta = \text{Efficiency} = \frac{H}{H_1}$$

where H = Actual conversion of kinetic head into pressure head

$$= \frac{v_1^2}{2g} - \frac{v_2^2}{2g} - H_f$$

$$H_1 = \frac{v_1^2}{2g}$$

where V_1 = Velocity of water at inlet of draft tube

V_2 = Velocity of water at outlet of draft tube

H_f = Loss of head in draft tube.

6.11 Surge Tanks

Surge tank is a storage reservoir fitted to the penstock at a point near to the turbine. The functions of the storage tank can be summarized as follows :

When the load on the turbine decreases, the gates of the turbine are closed partly by the governor to adjust the rate of flow of water in order to maintain the constant speed of the runner. When the gates are closed the water is moving to the turbine has to move backward. This backward moving water is stored in the surge tank. Similarly, when the load on the turbine increases, the turbine gates are opened by the governor and increased demand of water is partly met by the water stored in the surge tank. Thus the surge tank controls the water when the load on the turbine decreases and supplies water when the load on the turbine increases. In this way surge tank controls the pressure variations resulting from the rapid changes in water flow in penstock and thereby prevents water hammer effects. The functions of a surge tank are similar to a flywheel fitted to an I.C. engine.

The surge tank may be opened or closed at the top. If it is open at the tope it should be lower than the level of water in the reservoir.

The various types of surge tanks are shown in Fig. 6.15. The surge tank shown in Fig. 6.15 (*a*) has a cylindrical storage reservoir connected by a vertical branch of pipe to the penstock. The surgetank in Fig. 6.15 (*b*) has a conical reservoir whereas surge tank in Fig. 6.15 (*c*) has a bell mouth spillway to discharge the excess water. Fig. 6.15 (*d*) shows a differential surge tank. It has a central riser with a small hole at its lower end. The water enters the surge tank through this hole and the function of the surge tank depends upon the area of hole. The surge tank shown in Fig. 6.15 (*e*) consists of separate galleries ; the upper one is used to store water when the load on the turbine decreases and the lower one to supply water when the load on the turbine increases.

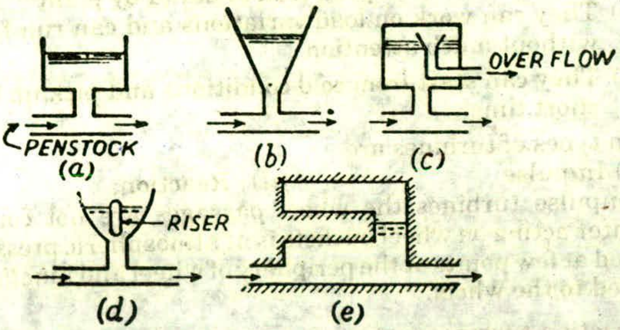


Fig. 6.15

6.12 Safety Measures in Hydro Power Station

Safety measures are provided for the safe operation. The various safety measures provided in a hydro power plant are as follows :

(*i*) Surge tanks	(*ii*) Pressure regulators
(*iii*) Screens	(*iv*) Fish passes
(*v*) Sand traps	(*vi*) Spillways.

Surge tanks are placed as near as possible to the water turbine. The surge tanks are provided to overcome the inertia forces in the supply pipe during fall of load and to act as reservoir of water during increase of load. A pressure regulator is provided near the turbine and its function is that when turbine gates are suddenly closed, pressure surges so produced are kept within the safe limits of the pipeline. Screens are used to prevent logs, fishes ice blocks and other obstructive elements from entering the pipelines and turbines whereas fish passes are provided along the dams so as to allow the fishes to pass to upstream without obstructions. Sand traps are provided to prevent the sand flowing with water in pipes.

A spillway is also considered as safety valve for dam. It discharges major flood water without damage to dam.

6.13 Hydraulic Turbines

In a hydro power station water turbine are designed to work well under the condition that the head does not fall below a certain minimum level. The minimum head on the turbines determines the dead storage behind the dam.

Hydraulic turbines have the following advantages.

(*i*) Simple in construction
(*ii*) Easily controllable
(*iii*) Efficient
(*iv*) Ability to work at peak load or stand by plant
(*v*) They can work on load variations and can run for weeks without much attention
(*vi*) They can start from cold conditions and pick up load in a short time.

Main types of turbines are

(*i*) Impulse (*ii*) Reaction.

In impulse turbines the wheel passages are not completely filled, water acting on wheel buckets is at atmospheric pressure and is supplied at few points at the periphery of wheel and kinetic energy is supplied to the wheel.

In reaction turbines water passages are completely filled with water, water acting on wheel vanes is under pressure greater than atmospheric, water enters all round the periphery of wheel, and energy in the form of both pressure and kinetic energy is utilised by the wheel.

The essential parts of a reaction turbine are as follows :

(*i*) Runner (*ii*) Guides and gates
(*iii*) Speed ring (*iv*) Casing or approach flume
(*v*) Draft tube.

Hydraulic turbine consists of the following parts :

1. *Runner*. Runner or wheel is fitted with vanes on its periphery. It rotates due to action of water gliding on the vanes.

2. *Guiding mechanism*. It guides the water coming from the pipe line (penstock) to the runner.

3. *Tail race*. The water after passing over the moving vanes of the runner flows to the tail-race.

6.13.1 Classification

Depending upon the various factors the water turbines are of two types :

6.13.1 (*a*) Based on action of water on moving blades

(*a*) Impulse turbines (*b*) Reaction turbines

1. *Impulse turbines*. In impulse turbines water coming out of the nozzle at the end of penstock is made to strike a series of buckets fitted on the periphery of a wheel or runner. Pressure energy of water is converted entirely into kinetic energy. The pressure at the inlet to the runner and discharge is same and is atmospheric throughout. The majority of impulse turbines are horizontal shaft turbines. Impulse turbines are suitable for water moving with high velocity and for high heads. The efficiency of the impulse turbine is not dependent upon the volume of water flow which may be supplied to the entire wheel. Pelton turbine (Fig. 6.16) is an impulse turbine.

The component parts of a Pelton wheel are as follows :

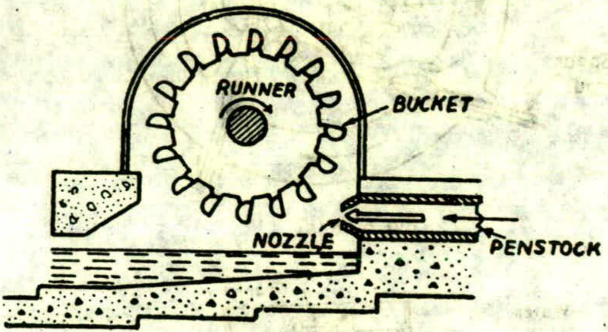


Fig. 6.16

(*a*) Buckets
(*b*) Nozzle and needle valve
(*c*) Shaft
(*d*) Penstock
(*e*) Tail race channel.

Buckets are the hemispherical cups bolted to a shaft. They are the main component parts which absorb and transmit the energy of water. Nozzle imparts a very high velocity to water. Needle valve is used to control the water discharge to the turbine. Penstock carries water from the reservoir to the turbine.

Water coming out of the turbine is discharged into the tail race.

Fig. 6.16 (*a*) shows multijet Pelton wheel arrangement.

Fig. 6.16 (*b*) shows super structure of pelton wheel power house. A power house is provided with a travelling crane which can span the width of power house and also travel its entire length. Crane should be able to lift generator rotor, shaft and runner. The roof and upper part of the super structure may be either steel truss or rigid frame.

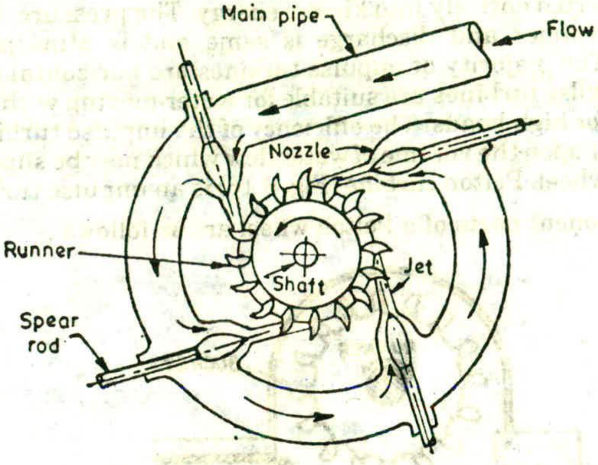


Fig. 6.16 (*a*)

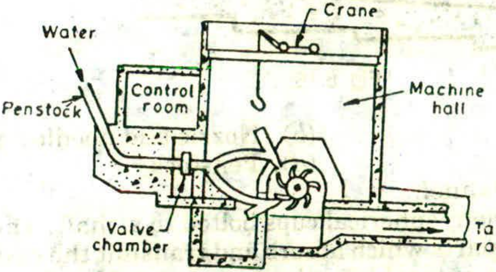


Fig. 6.16 (*b*)

Fig. 6.17 shows an impulse turbine installation. HRL, means headrace level, whereas TRL indicates tail race level.

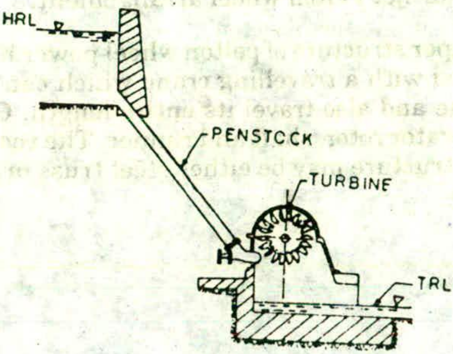


Fig. 6.17

2. *Reaction turbine.* In a reaction turbine water enters all round the periphery of runner and the runner remains full of water every time and water acting on wheel is under pressure which is greater than atmospheric. The turbine may be submerged below the tail race but the accessibility to the turbine becomes difficult. The turbine, therefore, is installed above the tail-race and water after doing work is discharged into the tail-race through a draft tube which remains submerged deep in the tail-race. Before entering the turbine water has both pressure energy and kinetic energy. The forces on the rotating parts are due to change of both potential and kinetic energy of water. The casing in a reaction turbine is essential as pressure at the inlet is more than at the outlet. This necessitates that the water should flow in a closed conduit to avoid splashing of water and, therefore, casing is necessary in this turbine.

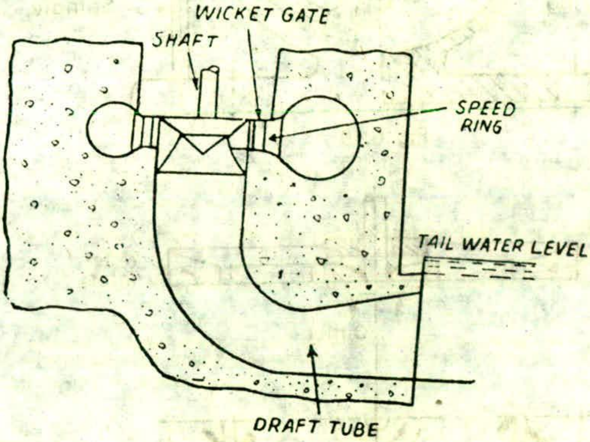


Fig. 6.18 (*a*)

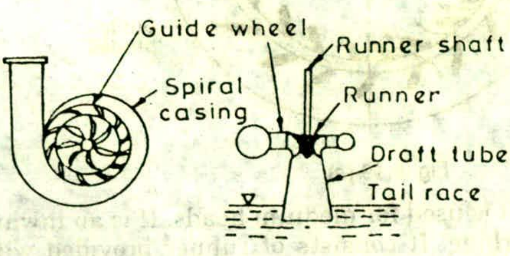


Fig. 6.18

Fig. 6.18 shows the position of various parts such as
(*i*) Spiral casing (*ii*) Guide wheel
(*iii*) Runner shaft (*iv*) Runner
(*v*) Draft tube.

Reaction turbines may be horizontal shaft type or vertical shaft type turbine but large reaction turbines are usually of the vertical types. These turbines are used for low and medium heads. Reaction turbines include Francis turbine (Fig. 6.18 (*a*)), Kaplan and Propeller turbines.

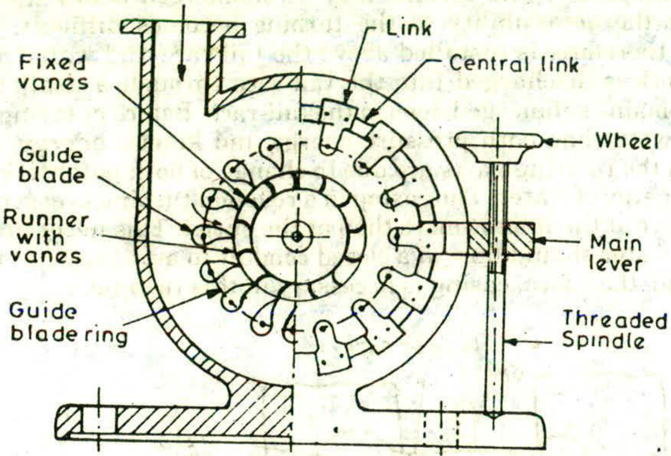


Fig. 6.19

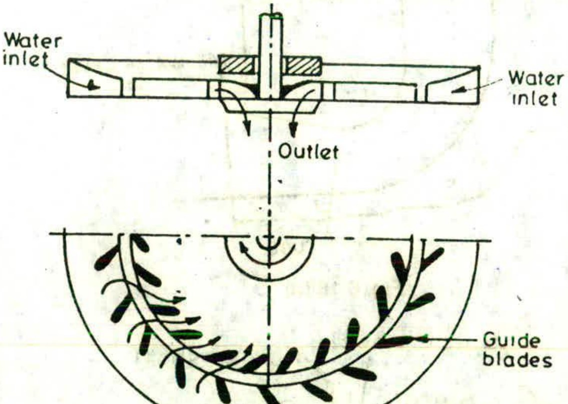


Fig. 6.19 (*a*)

Francis turbine. It is used for medium heads. It is an inward radial flow reaction turbine. It consists of runner provided with vanes, wicket gates (guide vanes), guide mechanism, draft tube and spiral casing. The runner is made up of C.I. for small output whereas for large output the runner is made up of cast steel. Guide vanes regulate the supply of water according to the load and also direct water to enter into the runner vanes at a suitable angle. The spiral casing surrounds the guide wheel. In this turbine the water enters the turbine through penstock connected to spiral casing. The water is then direct to enter the guide vanes and from guide vanes it enters the runner vanes. Finally the water is discharged through the draft tube. The overall efficiency of this turbine lies between 85 to 90%. Fig. 6.19 shows a Francis turbine.

As shown in Fig. 6.19 (*a*) the water flows radially inward and leaves at the centre axially. The pressure at outlet is quite low and therefore a draft tube is used for discharge at outlet.

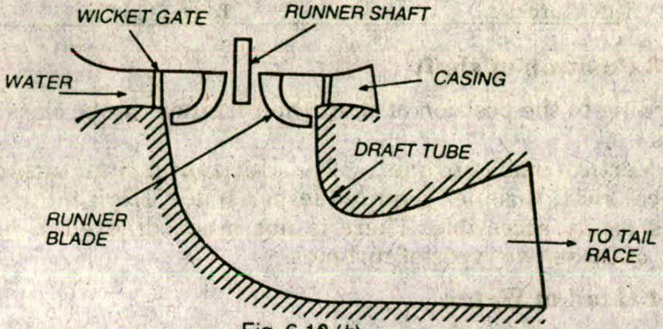


Fig. 6.19 (*b*)

Fig. 6.19 (*b*) shows sectional view of turbine. The blades are attached to the hub of runner. The runner is horizontal and it rotates about a vertical shaft. Water enters the turbine in a radial (inward) direction through an arrangement of movable wicket gates that control the water supply and act as stationary nozzles. The water is discharged in downward axial direction.

6.13.2 Direction of flow of water

According to the direction of flow of water the turbines may be classified as follows :

(*i*) Tangential flow turbine.

(*ii*) Radial flow turbine

(*a*) Radial Outward (*b*) Radial Inward

(*iii*) Axial Flow Turbine

(*iv*) Mixed Flow Turbine (Radial and Axial)

In tangential flow turbines as in case of Pelton turbines the water strikes the runner in a direction which is tangential to the path of rotation.

In a radial flow turbine the water moves in a plane perpendicular to the axis of the rotation. In inward flow turbine the water enters at the outer periphery and discharges at the inner periphery. In axial flow turbine the path of water during its flow is parallel to the axis of turbine shaft whereas in case of mixed flow turbine the water enters radially inward and discharge axially.

Table 6.1 summarises the flow directions of commonly used turbines.

Table 6.1

Type of turbine	*Flow Direction*
Propeller and Kaplan turbines	Axial flow
Francis turbine	Radial inward or mixed flow
Pelton turbines	Tangential flow

6.13.3 Position of shaft

According to the position of shaft the turbines can be classifie as follows :

1. Vertical shaft turbine 2. Horizontal shaft turbines.

Vertical shaft turbines required lesser space. Horizontal shaf turbine is easily accessible. There is not much difference in th efficiency of these two types of turbines.

6.13.4 Head of Water

According to the head of water the hydraulic turbines are classified as follows :

(*a*) High head turbines (*b*) Medium head turbines
(*c*) Low head turbines.

Impulse turbines are essential high head turbines whereas the reaction turbines are used for low and medium heads. The Pelto turbine is an impulse turbine and is used for high heads and lo flows. Francis turbine is used for low to medium heads and flows For low heads and high flows : Kaplan turbine also called propelle turbine is used. Table 6.2 shows the water heads for different type of turbines.

Table 6.2

Turbine	*Head*
Pelton turbine	150 to 300 m
Francis turbine	60 to 150 m
Kaplan turbine	up to 60 m

6.13.5 Classification based on speed.

As the turbine and generator are directly coupled, the rated speed of the turbine is same as the synchronous speed of the generator given by

$$N = \frac{60f}{P}$$

where N = Speed in R.P.M.

f = Frequency of generation

= 50 hertz (50 c.p.s) usually

p = No. of pairs of poles of the generator.

Therefore, the turbine speed is determined by the generator speed.

6.13.5 (*a*) Head on turbine

The total head or gross head is the difference between head race level and tail race level. Net head or effective head is the head available at the inlet of the turbine. As shown in Fig. 6.19 (*c*).

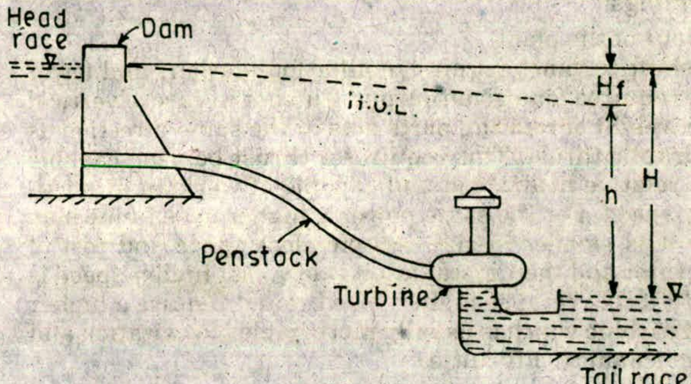


Fig. 6.19 (*c*)

H = Gross head

$= h + Hf$

where h = Net head

H_f = Frictional head

H.G.L. indicates hydraulic gradient line.

6.13.6 Classification based on specific speed

Turbines are never classified by their actual speed but always on the basis of the specific speed.

The specific speed (N_s) for a turbine is given by the formula

$$N_s = \frac{N\sqrt{p}}{H^{4/5}}$$

Table 6.3 indicates the specific speeds of different turbines.

6.14 Choice of turbines

The various factors to be considered while selecting a turbine are as follows :

1. Working Head
2. Nature of Load
3. Output
4. Specific Speed

For low heads propeller of Kaplan turbine are used. Kaplan turbine may be used under variable head and load conditions, whereas propeller turbines work satisfactorily when the head remains constant. For medium head Francis turbine is used and for high heads Pelton turbine is suitable. Pelton turbine has the advantages that it works quite satisfactorily even under variable load conditions. For low heads of 60 m or less Kaplan turbines are used for heads of 150 to 350 m Francis turbines are used and for very high heads 350 m or above Pelton turbines are used. Pelton turbines are simple and robust, their control is easy and their maintenance charges are lcw. The various factors influencing the choice between horizontal and vertical type of turbines are as follows :

1. Relative cost of the plant.
2. Site conditions, *i.e.* space available for foundations and buildings.
3. Layout of the plant.

Vertical shaft turbines require smaller foundations and fewer machines are required for a given output. Further in case of vertical shaft turbine weight of rotating parts acts in the same direction as the axial hydraulic thrust. This requires a thrust bearing capable of carrying a relative heavy load and capable of working at maximum runway speed. For the same power a higher speed unit may be chosen as it is smaller in size occupies less space and cost of turbine, generator and their installation is low. But higher speed is not always profitable because higher speed would require a higher specific speed turbine which is usually more liable to cavitation and create other mechanical difficulties.

6.15 Comparison of Pelton Wheel and Francis Turbine

(*i*) It is easier to regulate Pelton wheel than Francis turbine.

(*ii*) The operating efficiencies specially between half and full load are better in Francis turbine.

(*iii*) The parts of a Pelton wheel are more easily accessible and, therefore, it is easier to repair them.

(*iv*) For the same head the running speed of Francis turbine is more than Pelton wheel. This reduces cost of generators and dimensions of units.

(*v*) The dimensions of a Francis turbine are much less than those of Pelton wheel under similar operating head. Therefore, the power house of smaller size is required to accommodate the same number of Francis turbines.

(*vi*) Francis turbine utilises full available head by using a draft tube whereas the Pelton wheel has to be installed above the maximum tail race which causes loss of head.

6.16 Turbine Governing

Governing of turbine means speed regulation. In the normal condition the turbine should be run at constant speed irrespective of changes in load. This is achieved by means of a governor called oil pressure governor.

The various components of the oil pressure governor are as follows :

1. *Servomotor or Relay Cylinder.* In the servomotor a piston moves due to oil pressure and the movement of piston rod is transmitted to the controlling device of turbine such as spear rod in case of impulse turbine and guide vanes in case of reaction turbine.

2. *Pendulum and Actuator.* It is a flyball mechanism and it is operated by power taken from turbine main shaft.

3. *Distribution valve or control valve.* It controls the supply of oil to cylinders.

4. *Oil Pump and Gear Pump.* Oil pump pressurises the oil from the sump and sends it to the cylinder of distributing valve.

5. Pipes connecting oil pump with control valve and control valve with relay cylinder.

When the turbine is running at its normal speed, the position of lever arms the piston in relay cylinder and distributing valve will be in their normal place (Fig. 6.20). The ports *P* and *Q* remain closed.

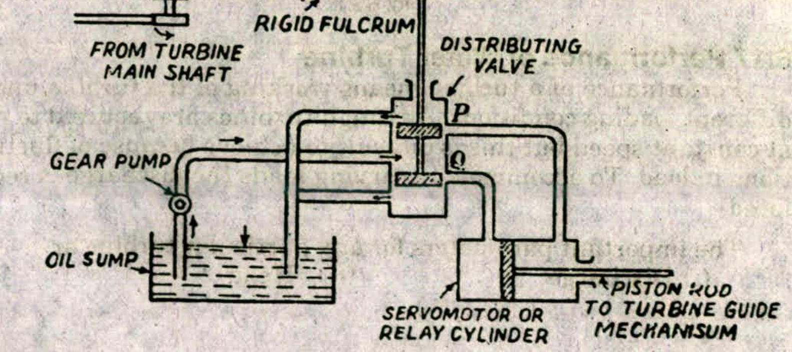


Fig. 6.20

When the load on the turbine increases, the speed of turbine falls and due to this the central spindle of the actuator will rotate at less speed bringing the fly balls down.

Since these balls are connected with the sleeve, the sleeve will also come down. This causes the main lever to rise pulling upward the pistons of distributing valve. The slight upward movement will open the port *P* and the oil under pressure will rush from distributing valve to the relay cylinder and to the right side of the piston. This causes the piston to move to the left. This movement is transmitted to the controlling device or guide mechanism of turbine casusing more water to enter the turbine which, therefore, will run faster and the speed will begin to increase. As the speed becomes normal again, the main lever, the pistons of distributing valve and relay cylinder will occupy this normal positions.

Similarly when the load on the turbine decreases, the speed will increase. To bring the speed back to normal the oil pressure governor acts quickly and operates the guide mechanism. Fig. 6.21 shows the guide mechanism for an impulse turbine. The governor closes the nozzle opening partially by pushing the needle in the nozzle thus allowing less water to enter the turbine which, therefore, will run slow.

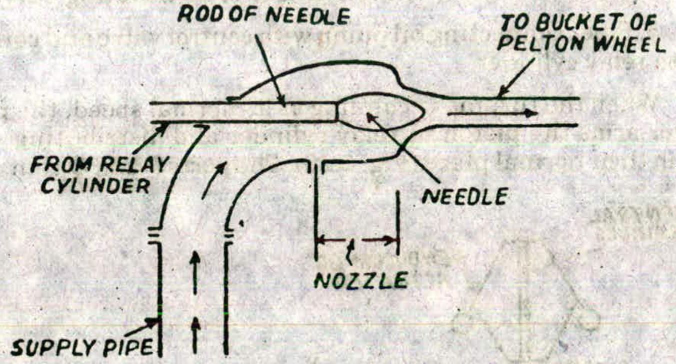


Fig. 6.21

6.17 Performance of Water Turbine

Performance of a turbine means working of the turbine under different loading conditions. Although turbines are required to run at constant speed but this is difficult to achieve because of fluctuations in load. To accommodate varying loads the discharge is regulated.

The important parameters for any particular turbine are :

(*i*) Discharge (*ii*) Head

(*iii*) Efficiency (*iv*) Speed
(*v*) Power.

It is desirable to study the behaviour of these quantities with respect to one another.

Such studies can be carried out under unit quantities like unit power, unit speed and unit discharge.

The turbine characteristic like unit power, unit speed and unit discharge help in studying the performance of turbines.

(*a*) *Unit Power* (P_u). It is defined as the power produced by the turbine when running under unit head (1 metre).

We know $$P = \frac{\omega H \times Q}{75}$$

where P = Power produced by a turbine
Q = Discharge in cumecs
H = Net Head is metres
ω = Unit weight of water.

Now $$Q = A \times V = k_1 \,.\, D^2 \,.\, V$$

where D = diameter of the runner
V = Velocity

$$V \propto \sqrt{2gH} = k_2 \sqrt{H}$$

$$\therefore \quad Q = k_1 \,.\, k_2 .\, D^2 \sqrt{H} = k . D^2 \sqrt{H}$$

$$P = \frac{\omega H}{75} \times Q$$

$$\therefore \quad = \frac{\omega k}{75} D^2 H \sqrt{H} = k_3 D^2 H^{3/2}.$$

For unit power (P_u).

$$H = 1$$

$$P_u = \frac{P}{H^{3/2}}$$

(*b*) *Unit speed* (N_u). It is the speed developed by a turbine when operating under a unit head (1 metre).

$$V = \frac{\pi D N}{60}$$

where N = speed of turbine in R.P.M.

Now $$V \propto \sqrt{2gH}$$

$$V = k_1 \sqrt{H}$$

$$\therefore \quad \frac{\pi DN}{60} = k_1 \sqrt{H}$$

$$\therefore \quad N = k_2 \frac{\sqrt{H}}{D}$$

For unit speed (N_u)

$$H = 1$$

$$\therefore \quad N_u = \frac{N}{\sqrt{H}}$$

(*c*) *Unit discharge* (φ_u). It is defined as the discharge of a turbine working under a unit head (1 metre).

$$\varphi = A.V. = k_1 D^2 V$$

$$= k_1 D^2 \sqrt{2gH} = k_2 D^2 \sqrt{H}$$

For unit discharge (φ_u).

$$H = 1$$

$$\therefore \quad Q_u = k_2 \times D^2$$

$$\therefore \quad \frac{\varphi_u}{\varphi} = \frac{1}{\sqrt{H}}$$

$$\varphi_u = \frac{\varphi}{\sqrt{H}}.$$

(*d*) *Specific Speed (Ns).* It is the speed of a geometrically similar turbine running under a unit head and producing unit power.

Specific speed is quite useful as follows :

(*i*) It helps in selecting type of turbine to be used for a particular power station.

(*ii*) It permits to visualise the performance of turbine.

(*iii*) Specific speed being known the normal running speed can be determined.

$$P = \frac{\omega\varphi H}{75} \propto \varphi H$$

As already proved $\varphi \propto D^2 \sqrt{H}$ ...(1)

$$\therefore \quad P \propto D^2 H^{3/2}$$

Also $V = \frac{\pi DN}{60}$ and $V \propto \sqrt{2gH}$

Therefore, $D \propto \frac{\sqrt{H}}{N}$

Substituting in equation (*i*),

$$P \propto \frac{H}{N^2} H^{3/2}$$

$$\propto \frac{H^{5/2}}{N^2}$$

$$N \propto \frac{\sqrt{H^{5/4}}}{\sqrt{P}} \propto \frac{H^{5/4}}{\sqrt{P}}$$

$$N = N_s \frac{H^{5/4}}{\sqrt{P}}$$

where N_s = specific speed

$$N_s = \frac{N\sqrt{P}}{H^{5/4}}$$

Table 6.3 shows the specific speeds for different turbines.

Table 6.3

Turbine	*Classification*	*Specific speed*
Pelton turbine	Impulse	10—45
Francis turbine	Reaction	45—450
Kaplan turbine	Reaction	450—1000

Example 6.2. *A turbine develops 18,000 H.P. working under a head of 520 m when running at 400 R.P.M. Calculate the specific speed of the turbine. Specify the type of turbine to be used.*

Solution. H = Head = 520 R.P.M.

N = R.P.M. = 400 R.P.M.

P = Horse Power = 18,000.

Specific speed $= N_s = \frac{N \, . \sqrt{P}}{N^{5/4}}$

$$N_s = \frac{400\sqrt{18,000}}{520^{5/4}} = 21.4$$

For this specific speed Pelton turbine is used.

Example 6.3. *Calculate the specific speed of a turbine and suggest the type of turbine required for a river having a discharge of 250 litre/sec with an available head of 50 metre. Assume efficiency of turbine as 80% and speed 450 R.P.M.*

Solution. Q = 420 litre/sec.

H = 50 metre

η = efficiency = 80%

N = 450 R.P.M.

P = Horse power developed

$$= \frac{\eta \omega \phi H}{75} = \frac{0.8 \times 1 \times 250 \times 50}{75} = 133.3$$

(Taking ω = 1 kg/litre)

Now, N_s = specific speed

$$= \frac{N\sqrt{P}}{H^{5/4}} = \frac{450\sqrt{133.3}}{50^{5/4}} = 39.9$$

For this specific speed Pelton turbine is suitable.

Example 6.4. *It is desired to build a hydro-electric power station across a river having a discharge of 30,000 litre / second at a head of 10 m. Assuming turbine efficiency 80% and speed ratio (K_u) as 0.83, determine the following :*

- (*a*) *Is it possible to use two turbines with a speed not less than 120 R.P.M. and specific speed not more than 350 R.P.M. ?*
- (*b*) *Specify the type of runner that can be used. Also calculate the diameter of runner.*

Solution. $P = \frac{\eta \omega \phi H}{75}$

where ρ = Total power available

ω = Specific weight of water

ϕ = Discharge

H = Head (metre)

$$\rho = \frac{0.8 \times 1 \times 30{,}000 \times 10}{75} = 3200$$

Using two turbine each of capacity 1600 H.P. the specific speed (N_s) of the turbine is calculated as follows :

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{120\sqrt{1600}}{10^{5/4}}$$

$$= 267 \text{ R.P.M.}$$

For this speed Francis turbine is suitable.

U = Tangential velocity of the runner

$$= K_u\sqrt{2gH} = \frac{\pi D N}{60}$$

where K_u = speed ratio and D = diameter of runner

$$D = \frac{60 \times K_u \sqrt{2gH}}{\pi \times N} = \frac{60 \times 0.83 \sqrt{2 \times 9.81 \times 8}}{\pi \times 120}$$

$= 1.85$ metres.

6.18 Efficiency

Different types of efficiencies used in connection with hydraulic turbine are as follows :

(*i*) Volumetric efficiency (*ii*) Hydraulic efficiency

(*iii*) Mechanical efficiency.

6.18.1 Volumetric efficiency

Some of the water flowing in the turbine may leak through the joints or some water may not be effective in imparting its energy to the turbine. The leakage of water reduces the efficiency of the turbine.

$$\eta_v = \frac{\phi - \phi_L}{\phi}$$

where η_v = Volumetric efficiency

ϕ = Discharge doing useful work

ϕ_L = Leakage from the turbine.

6.18.2 Hydraulic efficiency

Hydraulic efficiency takes into account the loss of head that takes place in the turbine due to incomplete conversion of head over the blades into useful work. It is defined as follows :

$$\eta_H = \frac{H - h}{H}$$

where η_H = Hydraulic efficiency

H = Net head utilised

h = Head not effectively utilised.

6.18.3 Mechanical efficiency

Mechanical efficiency takes into account the power loss due to friction.

$$\eta_M = \frac{P_1 - P_2}{P}$$

where P = Power produced by the turbine

P_1 = Shaft power

P_2 = Power loss.

6.18.4 Overall efficiency (η)

Overall efficiency of the hydraulic turbine is about 90% and is given by

$$\eta = \eta_v \times \eta_H \times \eta_M$$

6.19 Coupling of Turbine and Generator

A hydraulic turbine is coupled with electrical A.C. generator in the following two ways :

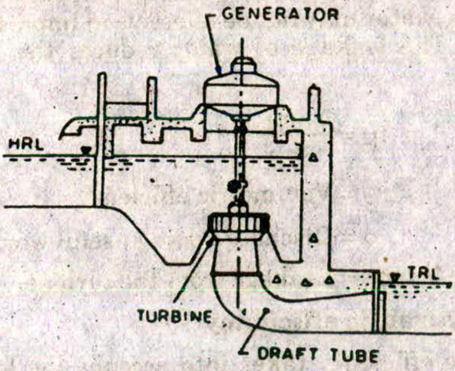


Fig. 6.22

(*i*) Direct Coupling (*ii*) Gear Drive.

Direct coupling system is used for low speed turbines. In this system both the turbine and generator shaft are directly coupled and run at same speed. Any fluctuation in turbine shaft speed is directly reflected in generator. In gear drive system spur gears or bevel gears are used to connect turbine shaft with generator shaft. This arrangement is quite commonly used.

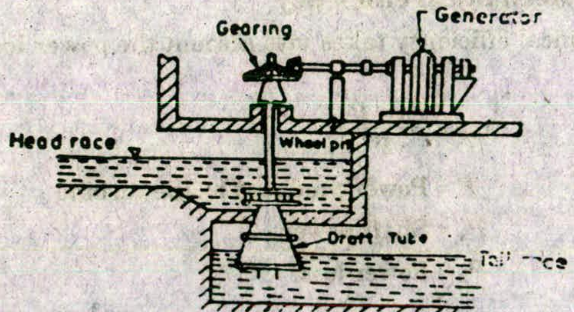


Fig. 6.22 (*a*)

Fig. 6.22 shows a low head turbine installation.

Fig. 6.22 (*a*) shows a turbine of smaller out put installed directly in the head race. The water enters the wheel to the runner and discharges into tail race (TRL) through a vertical draft tube. At the end of the turbine shaft a bevel gear is mounted which enables a generator to be connected for power generation.

6.19.1 Speed and pressure regulation

When the load on the generator coupled to the turbine changes, the governor comes into action to regulate the inflow of water into the turbine. With the sudden closing of gates there is a pressure rise in the pen stock. This pressure rise is counter balanced by

(*a*) installing surge tanks at the end of pen stock near the power station.

(*b*) providing pressure release openings or valves on the pipe line at suitable places.

The normal maximum pressure rise permissible is 10 to 20% for Pelton turbines and up to about 30% for Francis turbines.

6.19.2 Power generated

The generator coupled to the turbines produces electric power corresponding to the power developed by the turbines less losses in the set. The speed of the power generating set depends on :

(*i*) head
(*ii*) specific speed of the turbine
(*iii*) power of the unit.

Reaction turbines are vertical and at the power plant sufficient substructure and super structure is needed to accommodate the necessary arrangement of draft tube etc. The impulse turbines are either horizontal or vertical and do not require special substructure.

6.20 Synchronous Speed

It is defined as the speed of turbine which corresponds to the generator speed or some multiple of the speed of the generator. It depends on the way the turbine is coupled with the generator.

6.21 Cavitation

In water turbine the water is conveyed to it through penstocks. When the water pressure at any point in the penstock reaches the vapour pressure a large number of small bubbles of vapours are formed. These bubbles are carried by the stream to higher pressure zones where the vapours get condensed to liquid. Due to this a cavity is formed and the surrounding liquid rushed to fill it. Such an action causes a violent collapse of cavity and produces loud noise and very high pressure. The pressure produced may be so high that it may cause pitting or tearing off the surface of the material. This phenomenon which causes pitting of the metallic surface is called cavitation because of the formation of cavities. Pitting may also occur at following points in a turbine :

(*i*) On the upper part of the walls of the draft tube.
(*ii*) Near the tip of the valves in impulse turbine.
(*iii*) On the back of the bucket of the Pelton turbine where water leaves the runner.

Thoma has suggested a cavitation parameter for water turbines and pumps.

$$\sigma = \text{Cavitation factor}$$

$$= \frac{H_b - H_s}{H}$$

where H = Total effective head

H_b = Barometric head.

H_s = Suction head or height of pump about tail water level.

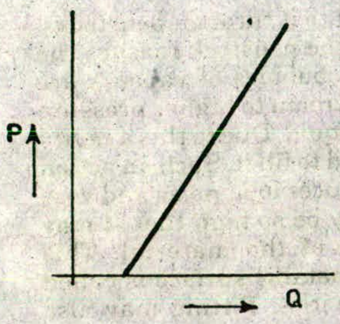
For cavitation free running σ has to be greater than critical value σ_{crit}.

$$(\sigma_{crit}) \leq \frac{H_b - H_s}{H}$$

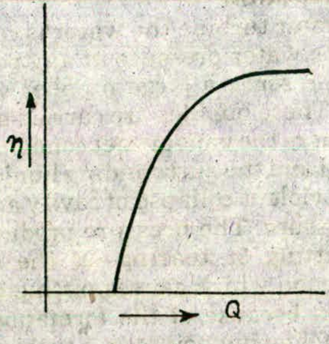
$$H_s \leq H_b - \sigma_{crit} H$$

σ_{crit} is a function of specific speed.

When H is large H_s comes out to be negative and there becomes essential to provide the pump with negative suction h i.e. the power house location has to be so fixed that pump operate under submerged conditions.



(*a*)



(*b*)

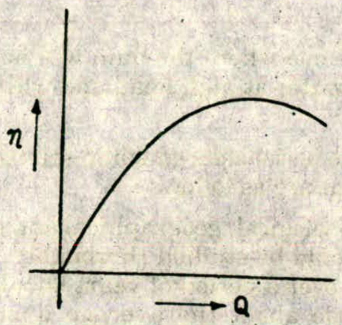


Fig. 6.23 Constant speed curves.

6.22 Operating Characteristics

Operating characteristics or constant speed curves of turbine exhibit the behaviour of water turbine when the turbine is working for the generation of power under constant speed. Such curves show the relationship between Power (*P*) and discharge (*Q*), efficiency (η) and discharge (*Q*) and efficiency and power (*P*). These curves are shown in Fig. 6.23.

6.23 Efficiency Load Curves

The efficiency load curves of various types of water turbines are shown in Fig. 6.24. The efficiency load curve of a Pelton turbine (impulse turbine) is shown in Fig. 6.25. The efficiency curve of a Pelton turbine remains slightly lower than that of a Francis turbine but is less affected by variations of load.

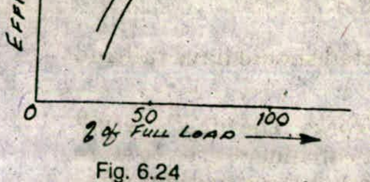


Fig. 6.24

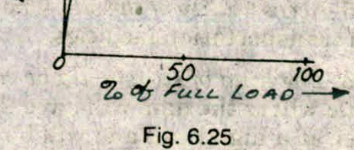


Fig. 6.25

Francis turbines are suitable for operation of the plant from 75% load to full load. Propellor turbines with fixed blade construction are used at fairly constant load between 75% and 100% of their capacity.

Kaplan turbine is suitable for frequent part-load operation. The efficiency of a Pelton wheel unit is about 88%.

6.24 Site Selection

The ideal site will be one where the dam will have the largest catchment area to store water at high head and will be economical in construction.

The various factors to be considered while selecting the site for hydro-electric power plant are as follows :

1. *Water available.* Geological, geographical and meteorological conditions of the site should be studied thoroughly. Daily, weekly and monthly flow water over a period of years should be recorded. Estimate should be made about the average quantity of water available throughout the year and also about maximum and minimum quantity of water available during the year. These factors are necessary to decide the capacity of the hydro-electric plant, setting up of peak load plant such as steam, diesel or gas turbine plant and to provide adequate spillways or gate-relief during the flood period.

2. *Storage of water.* Water used in the hydro electric power plant is mainly dependent on the rain and since the rainfall is not regular throughout the year, therefore, it is essential to store water to afford a uniform output. Thus a storage reservoir is constructed at the site. During rainy season the excess water is stored in the reservoir and it is released to supplement low rates of flow during run-off periods to maintain the output. The reservoir should have large catchment area so that water in it should never fall below the minimum level.

3. *Head of water.* Water is large quantities and at a sufficient head should be available. For a given power output an increase in effective head reduces the quantity of water required to be passed through the turbines.

4. *Distance from Load Centre.* It is desirable that the power plant should be set up near the load centres, so that costs of erection of the transmission lines and their maintenance are low. However, in hydro-electric power plants it may not be possible because this plant will be located where sufficient quantity and head of water is available.

5. *Accessibility of the site.* The site selected should have rail and road transportation facilities.

6. *The land of site should be cheap and rocky.* The ideal site will be one where the dam will have the largest catchment area to store water at a high head and will be economical in construction. After the location has been chosen the exact position of the various structures are fixed by considering the following factors :

(*a*) Details of foundation conditions

(*b*) Requirements of head, flow demands of storage capacity

(*c*) Arrangement and type of following :

(*i*) Dam. (*ii*) Intake system

(*iii*) Conduits (*iv*) Surge tanks

(*v*) Power house

(*d*) Cost of dam and project

(*e*) Transport facilities and accessibility of site.

6.25 Comparison of Hydro Electric Power Plant and Steam Power Plant

1. The initial (cost of land, dam, diversion works, water rights, rail, road and generating plant) of a hydro electric power plant is nearly twice (or more) as that of steam power plant of equal size ; but the labour, maintenance and repair costs of hydroplant are much less than the stream power plant. In hydro-plant the costs of dam and waterways constitute the major portion of plant costs. Depending upon the conditions the cost of a hydroplant vary from Rs. 700 to Rs. 1800 per kW.

2. For preliminary estimates the fixed charges for the hydro-power station usually vary from 9 to 12%.

Interest	6%
Depreciation	2%
Taxes and insurance	1%
Total	9%

The fixed charges for a steam power plant are higher and may be assumed from 12 to 14%. This is because of greater proportion of equipment and machinery costs and the depreciation charges are relatively high.

3. It is easy to locate steam power plant near the load centre and this eliminates the need for long transmission lines and thus transmission cost is less whereas power generated by a hydro plant is to be transmitted over longer distance and hence at greater cost.

4. The time to put the most steam power stations into operation is nearly 30 minutes whereas a hydro electric power plant can be put into operation in very short time ranging from few seconds to 3 or 5 minutes. Thus where power is to be supplied both by hydroelectric power plant and steam power plant, the steam power plant should be used as base load plant and hydro-power plant should be used as peak load plant.

5. The efficiency of steam power plant drops as it gets older.

6. Steam power station can be operated as desired to suit the demand of the load system whereas power to be generated from

hydro-plant is dependent on the quantity of water available in the storage.

7. The cost of transportation of fuel is quite high in case of steam power plant.

8. As compared to steam power plant the hydro-electric generation is the cleanest and most simple way.

6.25.1 Cost of Hydro Power

The power produced by a hydro electric power plant is the cheapest but the initial cost of any hydro electric project is very high.

The cost of a hydro electric development includes the following costs :

(*i*) Cost of land and water rights.
(*ii*) Cost of railways and high way required for the construction work.
(*iii*) Cost of constructions and engineering supervision of project.
(*iv*) Cost of equipment and building etc.
(*v*) Cost of power transmission equipment.

Example 6.4. *The various costs for a hydro power project are as follows :*

Dam : 50 crores
Power house building and others = 10 crores
Turbines and generators = 4 crores
Transmission line = 6 crores
Penstock = 5 crores.
Load acquisition = 0.7 crore
Taxes and insurance = 1%
Interest rate = 5%
Maintenance cost per year = 1.2 crores.

Power is generated from 5 units each of 30 MW capacity. The firm power is 60 MW and is sold at 12 paise per kWh and secondary power is supplied for 240 days at 60% load factor.

The secondary power is 80 MW and is sold at 6 paise per kWh.

Assuming useful life for dam, generator etc. Find whether the project is under loss or profit.

Solution.

(i) To calculate total depreciation cost

Item	*Cost (crores)*	*Useful life (years)*
Concrete dam	50	50
Building	10	50
Generator and turbine	4	20
Transmission line	6	25
Penstock	5	25

r = Rate of interest = 0.05

C_1 = Depreciation cost for dam and building

$$= \frac{(50 + 10) \times r}{(1 + r)^n - 1} = \frac{60 \times 0.05}{(1 + 0.5)^{50} - 1}$$

$$= \frac{60 \times 0.05}{11.46 - 1} = 0.287 \text{ crore}$$

where n = Life in years = 50

Cost of dam and building

$= 50 + 10 = 60$ crores

C_2 = Depreciation cost for generat

$$= \frac{4 \times 0.05}{(1 + 0.05)^{20} - 1} = \frac{3 \times 0.05}{0.65 - 1}$$

$= 0.12$ crore

C_3 = Depreciation cost for transmission line and penstock

$$= \frac{11 \times 0.05}{(1 + 0.25)^{25} - 1} = \frac{11 \times 0.05}{3.39 - 1}$$

$= 0.23$ crore

C = Total annual depreciation cost

$= C_1 + C_2 + C_3$

$= 0.287 + 0.12 + 0.23 = 0.637$ crore

(ii) To Calculate Interest

S_1 = Interest on capital cost

Capital cost $= 50 + 10 + 4 + 6 + 5 = 75$ crores

$$S_1 = \frac{5}{100} \times 75 = 3.75 \text{ crores}$$

(iii) S_2 = Maintenance cost per year = 1.2 crores

S_3 = Taxes and insurance cost

$= \frac{1}{100} \times 75 = 0.75$ crore

S = Total cost per year = $C + S_1 + S_2 + S_3$

$= 0.637 + 3.75 + 1.2 + 0.75 = 6.337$ crores.

(*iv*) **To find Income**

Firm power $= 60 \times 10^3$ kW

$= 60 \times 10^3 \times 365 \times 24$ kWh

$= 52.56 \times 10^7$ kWh

R_1 = cost of firm power

$= 52.5 \times 10^7 \times \frac{12}{100}$

= Rs. $630.72 \times 10^5 = 6.31$ crores.

Secondary power $= 80 \times 10^3$ kW at 60% load factor is supplied for 200 days.

$= 80 \times 10^3 \times 0.6 \times 200 \times 24 = 23 \times 10^4$ kWh

R_2 = Cost of secondary power

$= 23 \times 10^4 \times \frac{6}{100} = 138 \times 10^5$

$= 1.38$ crores.

R = Total income = $R_1 + R_2$

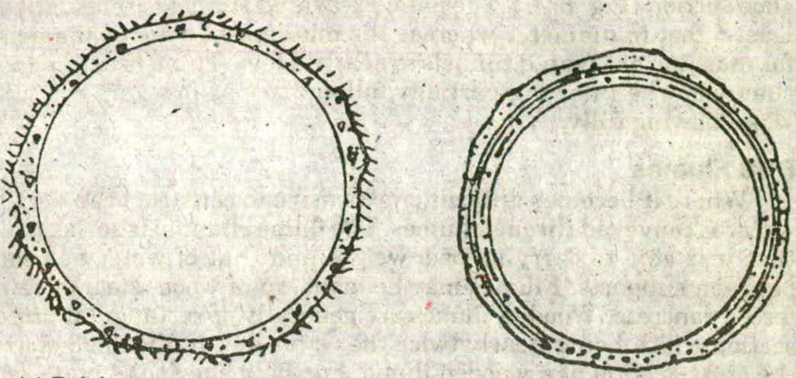
$= 5.31 + 1.38 = 7.69$ crores.

Net profit $= R - S = 7.69 - 6.337 = 1.353$ crores.

6.26 Hydro-steam Inter-connected System

A hydro power plant may be used as a base load plant or as peak load plant but the trend is towards use of hydro power plant with steam power plant in an inter-connected system. Power from hydro electric plants usually costs less and, therefore, when flow of water is adequate hydro power plant should be used as base load plant and steam power plant should be used as peak load plant whereas during low water in reservoir the functions of two plants should be reversed.

By interconnecting hydro power plant with steam power plant a great deal of saving in cost is achieved and standby requirements are reduced in an interconnected system. The interconnected system should have a suitable load allocation plant set prehand for each day. Hydro turbines can be started from cold in a few minutes while steam units need about 5 to 8 hours.



(a) Reinforced concrete tunnel.

(b) Pressure tunnel unreinforced.

Fig. 6.26

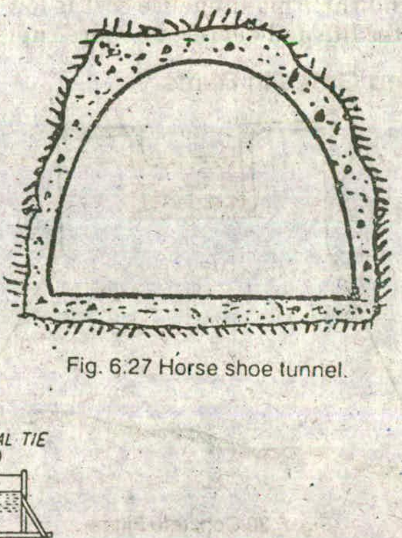


Fig. 6.27 Horse shoe tunnel.

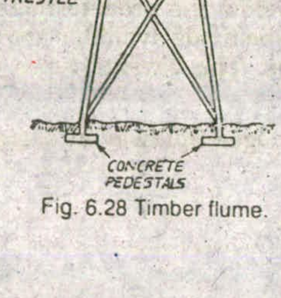


Fig. 6.28 Timber flume.

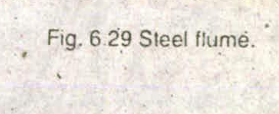


Fig. 6.29 Steel flume.

6.27 Tunnels

The tunnels are generally of circular section (Fig. 6.26) or horse shoe section (Fig. 6.27). The hand excavated tunnels are usually at least 6 feet in diameter whereas the minimum economic diameter for machine excavated tunnels is nearly 8 feet. Tunnels act as open channels when flowing partially full and act as pressure conduits when flowing fully.

6.28 Flumes

Where it becomes difficult or expensive to construct canals, the water is conveyed through flumes. The flume channel is so designed that it is able to carry its own weight and that of water as beam between supports. Flumes may be made up of wood, steel or reinforced concrete. Wooden flumes are generally of rectangular cross-section width being nearly twice the water depth. Fig. 6.28 shows the cross-section of a wooden flume. Fig. 6.29 shows the cross-section of a semi-circular steel flume. Fig. 6.30 shows the cross-section of a concrete flume on concrete piers. Reinforced concrete flumes have longer life and their maintenance cost is low whereas wooden flume are of shorter life and depreciate more rapidly.

6.29 Spillway and Gates in Dams

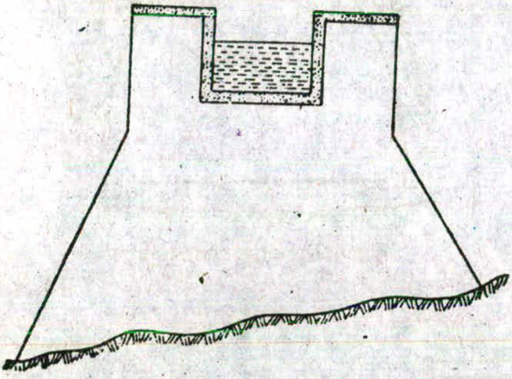


Fig. 6.30 Concrete Flume.

Spillway. A spillway acts as safety valve for a dam. Spillways and gates help in the passage of flood water without any damage to the dam. They keep the reservoir level below the predetermined maximum level. An additional storage can be made available above the spillway crest with the help of gates. The various types of spillways are as follows :

(*i*) *Ogee Spillway.* Fig. 6.31 shows an Ogee Spillway at design capacity.

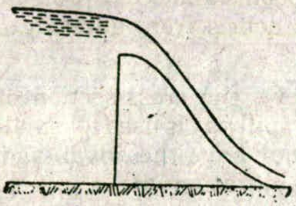


Fig. 6.31 Ogee spillway.

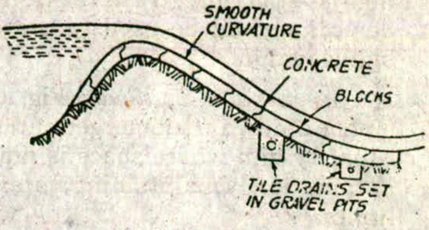


Fig. 6.32 Chute spillway.

(*ii*) *Chute Spillway.* In this spillway (Fig. 6.32) the discharging water flows into a steep sloped open channel called chute. The channel is made of reinforced concrete slabs. This type of spillway is suitable for earth dams.

(*iii*) *Shaft Spillway.* In this spillway (Fig. 6.33) water flowing through a vertical shaft enters a horizontal conduit from where it flows out of the dam.

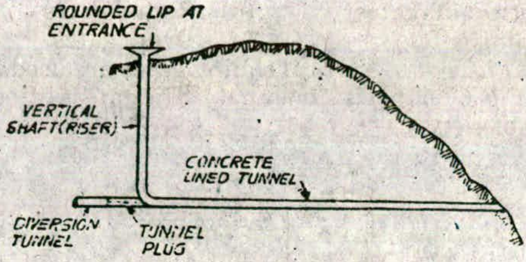


Fig. 6.33 Shaft spillway.

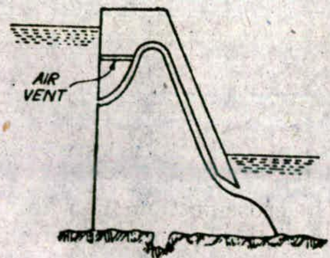


Fig. 6.34 Siphon spillway.

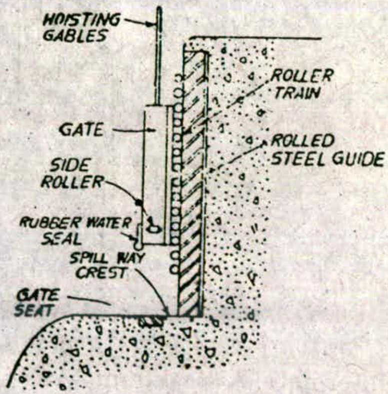


Fig. 6.35 Stoney Gate.

The drawback of this spillway is the hazard of clogging with debris. Therefore, trash racks, floating booms and other protection devices should be used to prevent the debris from entering the spillway inlet.

(*iv*) *Siphon Spillway.* Fig. 6.34 shows the cross-section of a siphon spillway (submerged outlet). This spillway is used for smaller capacity and where space is limited. They have the advantage of automatically maintaining water surface elevation within very close limits.

6.30 Gates

Water is allowed into the penstock, canal or direct to the turbine through the intake.

The following structures are provided with intake :

(*i*) Gate
(*ii*) Operating and hoisting mechanism
(*iii*) Trash screen
(*iv*) Cleaning mechanism for trash screen.

The various types of gates commonly used are as follows :

(*a*) Vertical lift gates (*b*) Radial gates
(*c*) Rolling gates (*d*) Drum gates.

(*i*) *Vertical lift gates.* Vertical sliding gates are used for smaller installation. Fig. 6.35 shows stoney gate. The gate is lifted by means of hoisting cables.

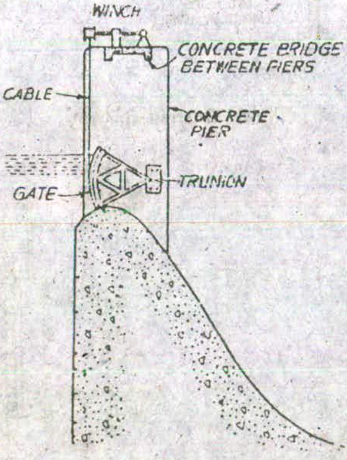


Fig. 6.36 Tainter gate.

(*ii*) *Radial gates.* Fig. 6.36 shows the cross-section of a radial or tainter gate. A steel framework supports the face to the gate, the face being a cylindrical segment. The steel framework is pivoted on trunions set in the downstream portion of the piers on the spillway crest. In such gates friction is concentrated at a pin and is much less than in sliding gates.

(*iii*) *Rolling gates.* Fig. 6.37 shows a rolling gate. It consists of cylindrical drum made of steel. The lower portion of the gate is a cylindrical segment and touches the spillway crest. The gate rolls on the rack when force is applied by means of hoisting cables.

(*iv*) *Drum gates.* This gate (Fig. 6.38) which is a segment of a cylinder can fit in the recess provided in the top of spillway. When water enters the recess the gate is raised by water pressure upto the closed position.

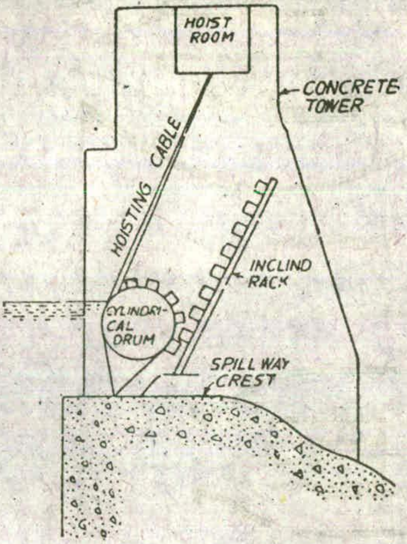


Fig. 6.37 Rolling gate.

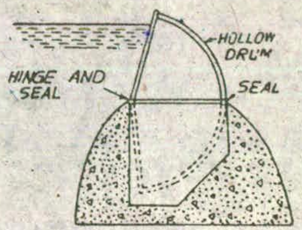


Fig. 6.38 Drum gate.

6.31 Types of Valves

Various types of valves used in hydro-power plants are as follows :

(*i*) Regulating valves (*a*) Needle valves ; (*b*) Tube valves ; (*c*) Hollow get valves.

(*ii*) Open-shut valves (*a*) Gate valves ; (*b*) Fish tail valves, (*c*) Butterfly valves ; (*d*) Rotary valves.

(*iii*) Energy dissipators

The gate valves are used to regulate the flow. For moderate heads butterfly valves are preferred. For high head installations needle valves and tube valves are used. These valves are generally placed at the down stream end of sluices, discharge taking place directly into the atmosphere. Fig. 6.39 shows a needle valve it consists of three water filled chambers *M*, *N* and *P* in which the hydraulic pressure can be varied. The valve is opened and closed by varying pressure in these chambers. The valve is opened by forcing the needle to the left and this is done by increasing pressure in chamber *P* and releasing in chambers *M* and *N* which are interconnected. To close the valve pressure is increased in chambers *M* and *N* while chamber *P* is exhausted to atmosphere.

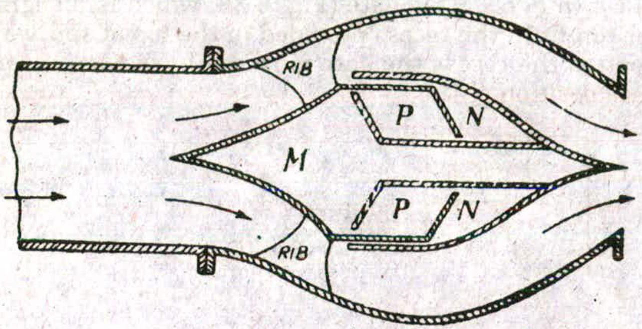


Fig. 6.39. Needle valve.

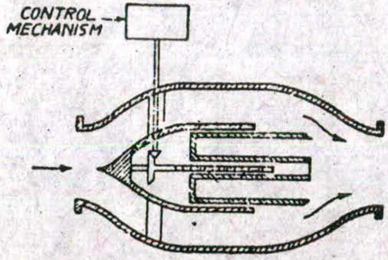


Fig. 6.40

Fig. 6.40 shows tube valve. This valve is open or closed by mechanical means. To open or close the valve cylinder (tube) is moved towards or away from the valve seat with the help of screw stem activated by a bevel gear. As compared to needle valve this valve is lighter in weight and is shorter in length.

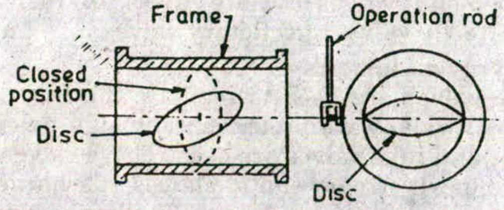


Fig. 6.40 (*a*)

Butterfly valve. This valve is used not only as intake gate for penstock but also is used before the turbine to facilitate the inspection without dewatering the whole of the penstock line. Fig. 6.40 (*a*) shows a butterfly valve. It consists of a lens shaped disc which can be moved in the frame of the valve.

6.32 Average Life of Various Components

The approximate average life of various components of a hydropower plant is indicated in Table 6.3.

Table 6.3

	Item	*Average Life (year)*
1.	Dams	
	(*a*) Earthen concrete or of masonry	150
	(*b*) Loose Rock	60
2.	Reservoirs	75
3.	Waterways	
	(*a*) Canals, tunnels	50—100
	(*b*) Penstocks	
	Steel	40—50
	Concrete	25—50
4.	Power house and equipment	
	(*a*) Building	30—50
	(*b*) Generators	25
	(*c*) Transformers	30
	(*d*) Turbines hydraulic	5
	(*e*) Pumps	18—25

6.33 Hydraulic Accumulator

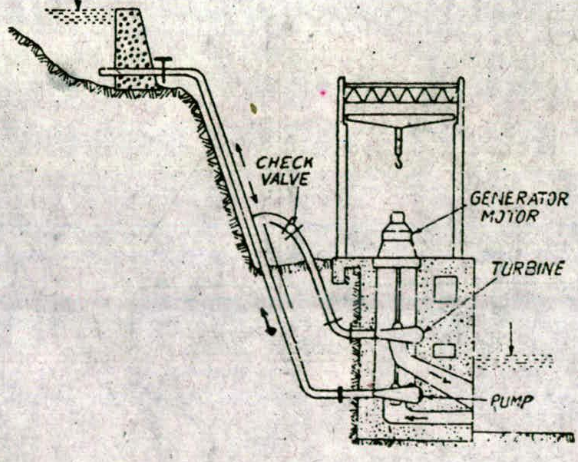


Fig. 6.41 Hydraulic Accumulator

Hydraulic accumulator system (Fig. 6.41) pumps water into reservoir with off-peak power. In this system the centrifugal pump Hydraulic turbine and motor generator are mounted on the same shaft.

6.34 Cost of Hydroelectric Power Plant

Hydroelectric power plants cost nearly Rs. 700 to 1800 per kW of capacity. The cost of dam, intake tail-race and reservoir is more as compared to other items of the power plant. A typical sub-division of investment cost is as follows :

(*i*) Dam, tail-race, reservoir, intake –36%
(*ii*) Turbine and generators –20%
(*iii*) Land, building and foundations –29%
(*iv*) Switching and wiring –6%
(*v*) Switchyard –4%
(*vi*) Miscellaneous –5%

6.35 Hydrology

Hydrology is the natural science that deals with the distribution of water on land beneath the surface of earth. It deals with the solid, liquid and vapour forms of water. The various conditions which bring about the transformation of one form into another are dealt under this science.

6.36 Hydrologic Cycle

The various processes involved in the transfer of moisture from the sea to the land and back to the sea again constitute which is called hydrologic cycle (Fig. 6.42). Hydrologic equation is expressed as follows :

$$P = R + E$$

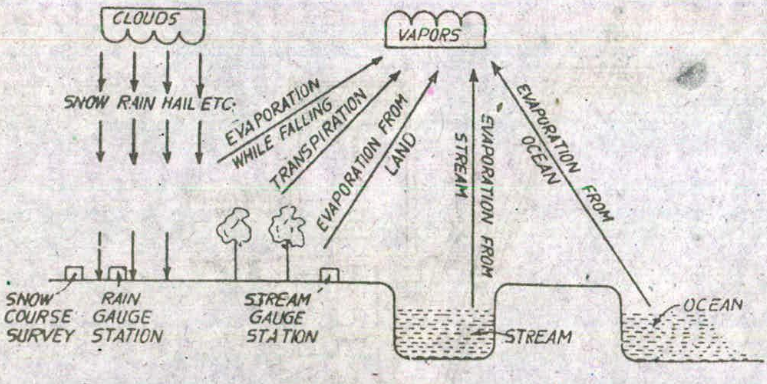


Fig. 6.42

where P = Precipitation
R = Run off
E = Evaporation.

Precipitation. It includes all the water that falls from atmosphere to the earth surface. Mainly precipitation is of two types.

(*i*) Liquid precipitation (Rainfall)
(*ii*) Solid precipitation (Snow, Hail storm).

Run-off. Run-off is that portion of precipitation which makes its way towards streams, lakes or oceans. Run off occurs only if the rate of precipitation exceeds the rate at which water infiltrates into the soil and after depressions small and large on the soil surface get filled with water. Rainfall duration, its intensity and a real distribution influence the rate and volume of run-off.

Evaporation. Transfer of water from liquid to vapour state is called evaporation.

Transpiration. It is a process by which water is released to the atmosphere by the plants.

6.37 Hydrograph

It is a graphical representation between discharge (cubic metres per second) through a river and time.

A hydrograph may be plotted for several weeks or even months. Hydrograph indicates the power available from the stream at different times of the day, week or year. Extreme conditions of flow can also be studied from a hydrograph. Hydrograph of stream of a river will depend on the characteristics of the catchment and precipitation over the catchment. Hydrograph will assess the flood flow of rivers hence it is essential that anticipated hydrograph could be drawn for river for a given storm. A typical hydrograph is shown in Fig. 6.43. A hydrograph has a rising limb, peak and receding limb or recession curve.

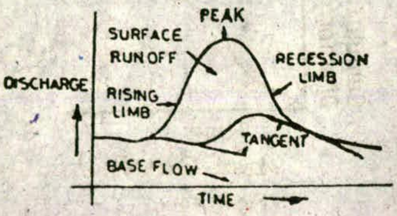


Fig. 6.43

6.37.1 Flow Duration Curve

It is a method to represent the run off graphically. This curve is plotted between flow available during a period versus the fraction of time. The total power available at the site may be known by this curve which can be drawn with the help of hydrograph from the available run off data. Fig. 6.43 (*a*) shows a typical flow duration curve.

This curve is nearly useful in the analysis of the development of water power.

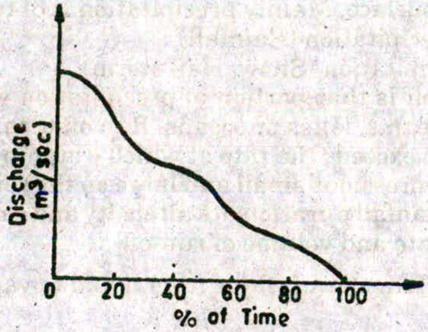
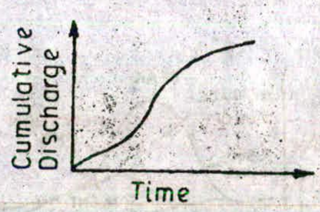


Fig. 6.43 (*a*).

6.38 Mass Curve

A reservoir is used to conserve water which can be used during the period of deficiency. A mass curve is a convenient device to determine storage requirement that is needed to produce a certain dependable flow from fluctuating discharge of a river by a reservoir. Mass curve is a plot of cumulative volume of water that can be stored from stream flow *versus* time in days, weeks or months. The slope of the mass curve at any point represents the change of volume per change of time in other words the rate of flow at the moment. Hence the mass curve is steep when the river flow is large and flat when the river flow is small. Fig. 6.44 shows a mass curve.



Mass Curve

Fig. 6.44

6.38.1 Unit Hydrograph

This type of hydrograph represents a volume of one inch of run off resulting from a rainfall of some unit duration and specified a real distribution.

Unit hydrographs of very large floods differ some what from those of small rainfalls. A unit hydrograph can be constructed from a hydrograph of the actual run off when there is uniform rainfall intensity and uniform a real distribution. The number of unit hydrographs for a given basin is theoretically infinite as there may be one unit hydrograph for every possible duration of rainfall and every possible distribution pattern of rainfall in the basin. In prac tice only a limited member of unit hydrographs are used for a given basin.

A unit hydrograph is constructed as follows :

(*i*) Measure the total volume of run off from actual hydrograph.

(*ii*) Determine the ordinates of unit hydrograph by dividing the ordinates of actual ran off by the total volume of run off in cms. over the drainage area. This gives unit hydrograph for the basin.

(*iii*) Determine effective duration of run off producing rain for which the unit hydrograph (UH) is applicable by a study of the rainfall records.

Unit hydrograph is a very useful tool in estimating the run off from a basin for a storm of given duration. It helps to predict the expected flood flow from a catchment if rainfall intensity in the catchment area is known.

Fig. 6.44.1 shows a typical unit hydrograph obtained from actual hydrograph of run off.

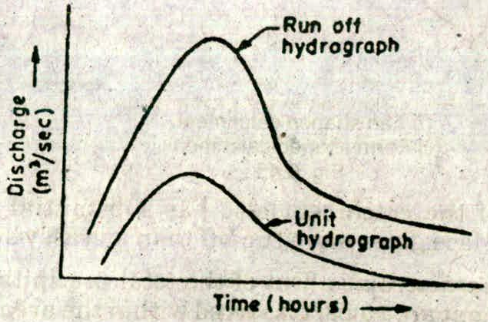


Fig. 6.44.1

6.38.2 Factors affecting run off

Run-off from an area depends upon the following factors :

(*i*) *Precipitation characteristics.* They include type of storm, its intensity, extent and duration.

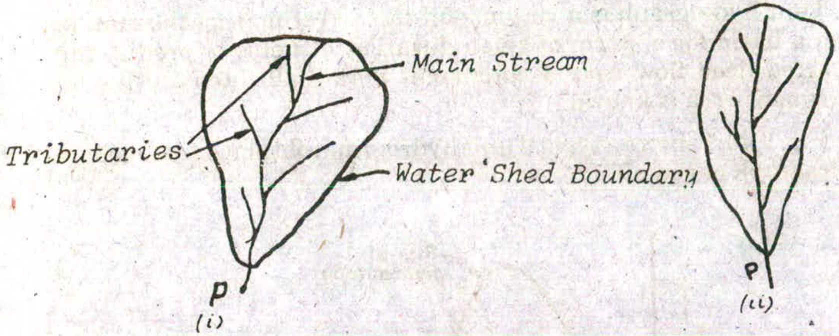
(*ii*) *Meterological characteristics.* They include temperature humidity, wind, pressure variation etc. Greater temperature and wind velocity help evaporation.

(*iii*) *Catchment characteristics.* Geographical features of catchment such as size, shape and location of catchment produce significant effects on the run-off.

Two types of catchment shapes with different arrangement of drainage channel in the area shown in Fig. 6.45. The fan shaped catchment produces greater flood intensity than a fern shaped catchment.

When rainfall takes place over the catchment water from the tributaries reach the point P simultaneously creating a sudden rise of discharge at P in case of fan shaped catchment.

On the other hand, in case of fern shaped catchment when rainfall takes place the tributaries are so distributed that water from different points takes different time to reach the point P. Hence rate of discharge at P is slow and takes place over a longer period.



(*i*) Fan shaped catchment.
(*ii*) Form shaped catchment.
Fig. 6.45

The surface of the catchment also has substantial effect on run-off. A base surface gives more run-off than a grassy surface.

(*iv*) *Storage characteristics.* Out of the total precipitation that falls on the catchment area a part is stored within the area and does not appear as run off. There may be a number of depressions, pools and lakes which store part of the precipitation and detain it either temporarily or permanently.

6.38.3 Run-off Estimation

The following three kinds of informations are generally required for run-off statistics :

(*i*) Annual, monthly or seasonal run-off
(*ii*) Extreme low flows
(*iii*) Flood run-off.

The following methods are used to determine the runoff from a catchment :

(*i*) Empirical method (*ii*) Rational method
(*iii*) From hydrograph.

(*i*) **Empirical Method.** The following few formulae are used to determine run-off. These formulae have been derived from limited regional use.

(*i*) Lacey formula $R = \frac{P^2}{Y + \frac{3048F}{S}}$

(*ii*) Inglis = De Souza formula.

$R = 0.85P - 304.8$ for Ghat area

$= \frac{P(P - 177.8)}{2540}$ For non Ghat area

(*iii*) Khosla formula $R = P - 4.811T$

where R = Run off in mm

P = Rainfall in mm

T = Mean temperature in °C

F = Monsoon duration factor

= 0.5 to 1.5 depending upon type of catchment

S = Catchment factor

= 0.25 for flat lands to 3.5 for hilly areas.

(*ii*) **Rational Method.** The following rational formula is used to give a rainfall run-off relationship :

$R = K.A.P.$

where R = Run off in hectare cm

A = Area of catchment in hectares

P = Precipitation in cm

K = Coefficient taking losses into account.

(*iii*) **Hydrograph method.** It is a graphical representation showing discharge (run-off) of flowing water respect to time for a specified time. The time period for discharge may be hour, day, week or month. The rate of flow at any instant can be read from hydrograph.

6.38.4 Flood Run-off

It involves estimating the maximum peak value of the flow. Few empirical formulae listed below are used for finding maximum discharge.

(*i*) Dicken's formula $Q = CA^{0.75}$

(*ii*) Inglis formula $Q = \frac{123A}{\sqrt{A + 10}}$

where Q = Discharge in m³/sec.

A = Catchment area in km^2.

Calculation of H.P. and kW Power

Let H = net head of water in metres

ϕ = discharge m^3/sec

η = overall efficiency of hydro power plant

ω = specific weight of water in kg/m^3

H.P. = horse power developed.

$$\text{H.P.} = \frac{\omega\phi H \,.\, \eta}{75}$$

(Taking 1 metric H.P. = 75 kg m/sec)

$$\text{kW power} = 0.746 \times \text{H.P.}$$

6.39 Controls in Hydro-electric Plants

The various controls provided in a hydraulic power plant are as follows :

(*i*) Hydraulic controls
(*ii*) Machine starting and stopping controls
(*iii*) Machine loading and frequency controls
(*iv*) Generator and system voltage control
(*v*) Machine protection.

Hydraulic controls. All water levels are indicated on the control panels. Water passing through the turbine is recorded in the control room through water flow indicator and recorder for individual units. The various hydraulic controls are as follows :

(*a*) Primary and secondary storage level indicators.
(*b*) Flood control. (*c*) Intake gate control.
(*d*) River flow control.

Machine starting and stopping controls. The water flowing to the turbine is controlled by means of gates and valves provided in the supplying conduit and at the turbine inlet. The water supply to the turbine is regulated in accordance with generator load through a governor system. During starting of turbines filling of casing should be done gradually and by pass valves are provided to limit the rate of water flow.

Machine loading and stopping controls. The load on the machine is controlled by adjusting the governor speeder control or by controlling the system frequency.

Generator and system voltage control. The electric power should be supplied at proper voltage. The voltage control is exercised through voltage regulators.

Machine protection. In a power plant the protective devices should be provided to guard against breakdown of turbo generator and auxiliary services, like transformers, switchgear, overhead lines etc. Protection measures are also needed to guard against incorrect operation and failure of control system.

Automatic controls are more reliable, safe and efficient. The control room should be designed for convenience of operation and the equipment should be spaced to permit easy access.

6.40 Surveys needed for hydro-power plants

The following surveys are carried out for a hydro plant installation.

(A) **General surveys** – They constitute the following :

1. Topographical surveys such as

(*i*) The dam site topographical survey plans including the area of accommodate dam, spillway, outlet works, diversion works etc.

(*ii*) The reservoir submergence plans

(*iii*) Contour plan of

(*a*) surge tanks (*b*) tunnels

(*c*) penstock (*d*) tail race channels.

(*iv*) River surveys

(*v*) For a barrage structure detailed survey maps to cover the area under the barrage.

2. **Geological and foundation investigations.** A study should be carried out for the following :

(*i*) Secismic condition of the region

(*ii*) Water flow in reservoir

(*iii*) Sub-surface conditions

(*iv*) Foundation investigations for dams.

3. **Metrological and hydrological studies**

The following data should be collected

(*i*) Precipitation, evaporation.

(*ii*) Water flows such as maximum and minimum water flows.

(*iii*) Rainfall–run off relation data.

(*iv*) Mean latitude, and longitude, mean elevation, mean monthly temperature.

(*v*) Location of raingauge station near power plant site.

4. **Construction material investigations**

Data should be collected for the following :

(*i*) Materials to be used for

(*a*) Concrete and masonary dams

(*b*) Earth and rock fill dams.

(*ii*) Tests to be carried out for materials.

5. Transportation and communication. Data should be collected for the following :
   - (*a*) Road, water and rail routes
   - (*b*) Telephone and telegraph lines.
6. **Environmental considerations**
   - (*i*) Navigation
   - (*ii*) Fish culture.

(B) Special surveys

Special surveys include the following :

1. **Load surveys**

They are made of

- (*i*) Power-station capacity
- (*ii*) Power to be generated
- (*iii*) Details for major loads to be served
- (*iv*) Peak load
- (*v*) Load factor
- (*vi*) Future energy demand
- (*vii*) Inter connection with other power systems

2. **Lay-out studies.** This includes the following
   - (*i*) Type of power plant such as storage type, run of river plant pumped storage type etc.
   - (*ii*) Structural components like
     - (*a*) Dams
     - (*b*) Canals
     - (*c*) Tunnels
     - (*d*) Penstock
     - (*e*) Draft tube
     - (*f*) Surge tanks
     - (*g*) Power house
     - (*h*) Switch yard.

6.41 Control room functions

The control room is used to perform the following functions :

- (*i*) Machine starting and stopping
- (*ii*) Machine loading
- (*iii*) Frequency control
- (*iv*) Generator and system voltage control
- (*v*) Machine running supervision
- (*vi*) Hydraulic control.

The control room is generally situated in the power house. Automatic and semiautomatic together with push–button control systems are preferred.

6.42 Mechanical Equipment

The mechanical equipment in a hydro power plant consists of the following :

- (*i*) Pumps for different uses
- (*ii*) Bearings of turbine and generator
- (*iii*) Ventilation and cooling equipment with
  - (*a*) fans (*b*) blowers (*c*) compressors
- (*iv*) Brake circuits for the generator

(*v*) Lifting cranes
(*vi*) Governors for turbines

6.43 Switch gear

It is used for making and breaking the circuits. It may consist of the following :

(*i*) Switches (*ii*) Isolators
(*iii*) Surge-arrestors (*iv*) Circuit breakers.

If the switch gear is at the generated voltage it is normally located indoors whereas if it is at the transmission voltage it is usual to locate it outdoors in switch yard. Switch gear and transformers located outside should be provided with adequate lightning protection.

Example 6.5. *A reaction turbine is supplied with 100 cu m of water per second and works under a maximum head of 120 m at 350 R.P.M. Assuming overall efficiency of the plant 80% and specific weight of water 1000 kg/m^3; calculate the horse power developed and power in kW.*

Solution. $H = 150$ m

$\phi = 100$ m^3/sec

$\omega = 100$ kg/m^3

$\eta = 0.8$

$\therefore$ Horse power developed

$$= \frac{\omega \phi H \,.\, \eta}{75} = \frac{1000 \times 100 \times 120 \times 0.8}{75}$$

$$= 128{,}000$$

Power in kW $= 128{,}000 \times 0.746 = 95{,}488$ kW. **Ans.**

Example 6.6. *(a) Calculate the total energy in kWh which can be generated from a hydro power station having following data :*

Reservoir area = *2.5 sq. km*
Capacity = *5* × *10*^{6} *m*^{3}
Net head of water at the turbines = *80 m*
Turbine efficiency = *80%*
Generator efficiency = *90%*

(*b*) *Also find by how many metre the level of reservoir will fall if a load of 20,000 kW is supplied for 5 hours ?*

Solution. (*a*) Work done/sec.

$$= 1000 \times 5 \times 10^6 \times 80 \text{ kg m/sec.}$$

$$= 40 \times 10^{10} \text{ kg m/sec.}$$

H.P. Developed $= \dfrac{40 \times 10^{10} \times 0.8 \times 0.9}{75} = 0.38 \times 10^{10}$

Energy produce kW sec $= 0.38 \times 10^{10} \times 0.746 = 0.28 \times 10^{10}$

Energy produced (kWh)

$$= \frac{0.28 \times 10^{10}}{3600} = 7.78 \times 10^{5} \text{ kWh.}$$

(*b*) Let the fall in level of reservoir = *h* metre.

Time = 5 hours.

Area of reservoir = (2.5 × 1000 × 100) sq. m.

$$\text{Discharge/sec.} = \frac{2.5 \times 1000 \times 1000 \times h}{5 \times 3600} = \frac{10^4 \times h}{72}$$

$$\text{Work done/sec.} = \frac{1000 \times 10^4 \times h \times 80}{72}$$

$$\text{H.P. developed} = \frac{1000 \times 10^4 \times h \times 80}{72 \times 75} \times 0.8 \times 0.9$$

$$\text{kW produced} = \frac{1000 \times 10^4 \times a \times 80 \times 0.80 \times 0.9}{72 \times 75} \times 0.746$$

$$= 1.05 \times 10^5 \times h$$

But kW produced = 20,000 (given)

$$\therefore \quad 20{,}000 = 1.05 \times 10^5 \times h$$

$h = 0.2$ metre. **Ans.**

Example 6.7. *For a hydroelectric power plant the following data is supplied :*

Annual rainfall = *1000 mm.*
Catchment area = *120 sq. km.*
Effective head = *250 m.*
Load factor = *40%*

Yield factor to allow for run-off and evaporation loss = 50%

Efficiency of power plant = 70%

Determine the following :

(*a*) *Average power produced*
(*b*) *Capacity of the power plant.*

Solution. Volume of water available per year

= Catchment area × Annual rainfall × Yield factor

Now catchment area = 120 sq. km. = $120 \times (1000)^2$ m^2

$$\text{Annual rainfall} = \frac{1000}{10 \times 100} = 1 \text{ metre}$$

Volume of water available per year $= 120 \times (1000)^2 \times 1 \times 0.5$

Volume of water available per second

$$Q = \frac{120 \times (1000)^2 \times 0.5}{8760 \times 60 \times 60}$$

$$\therefore \text{ H.P. developed } = \frac{\omega . \phi H. \eta}{75}$$

where ϕ = water available/sec.

$$= \frac{120 \times (1000)^2 \times 0.5}{8760 \times 60 \times 60}$$

ω = specific weight of water = 1000 kg/m^3

H = head = 250 metre

η = efficiency = 0.7

k = yield factor = 0.5

$$\therefore \text{ H.P. developed } = \frac{1000 \times 120 \times (1000)^2 \times 250 \times 0.7 \times 0.5}{8760 \times 60 \times 60 \times 75}$$

$$= \frac{35 \times 10^6}{876 \times 9} = 4328$$

$\therefore$ Average Power $= 4328 \times 0.746 = 3228$ kW

$$\text{Load factor} = \frac{\text{Average power}}{\text{Maximum demand}}$$

$\therefore$ Maximum demand

$$= \frac{\text{Average power}}{\text{Load factor}} = \frac{3228}{0.4} = 8070 \text{ kW.}$$

The capacity of the power plant can be taken equal to maximum demand

$\therefore$ Capacity = 8070 kW.

Example 6.8. *Calculate the power that can be developed from a hydro-electric power station having the following data :*

Catchment area = *100 sq. km.*
Average rain fall = *120 cm*
Run-off = *80%*
Available head = *300 m*
Overall efficiency of the power station = *75%.*

Solution. Run-off available (ϕ)

$$= \frac{100 \times 10^3 \times 1.2 \times 0.8}{365 \times 24 \times 60 \times 60} = 3.4 \text{ cu-m/sec.}$$

$$\omega = 1000 \text{ kg}$$

(as 1 cum of water weight = 1000 kg)

$$H = \text{Available head} = 300 \text{ m}$$

$$\eta = \text{Efficiency} = 0.75$$

$$\text{H.P. developed} = \frac{\omega.\ \phi H \times \eta}{75} = \frac{1000 \times 3.4 \times 300}{75} \times 0.75$$

$$\text{Power in kW} = \frac{1000 \times 3.4 \times 300 \times 0.75 \times 0.746}{75}$$

$$\text{Power in MW} = \frac{1000 \times 3.4 \times 300 \times 0.75 \times 0.746}{75 \times 1000}$$

$$= \frac{3.4 \times 300 \times 0.75 \times 0.746}{75}$$

$$= 7.48 \text{ MW.} \quad \textbf{Ans.}$$

Example 6.9. *Determine the H.P. that can be developed from a hydroelectric power plant with following data :*

Catchment area of reservoir = 3×10^8 *sq. metre*
Mean head = *40 m*
Annual average rainfall = *110 cm*
Efficiency of turbine = *80%*
Efficiency of generator = *85%*
Load factor = *45%*

Assume that 25% of the rainfall is lost due to evaporation and 4% head lost in penstock.

Solution. Quantity of water available per annum

$$Q = 3 \times 10^3 \times 1.10 \times 0.75 = 2.475 \times 10^8 \text{ cu-m.}$$

Quantity of water available per second

$$Q = \frac{2.475 \times 10^8}{365 \times 24 \times 60 \times 60} = 7.85 \text{ cu-m/sec.}$$

Head $H = 40$ m

Overall efficiency (η) = Turbine efficiency × Generator efficiency × Penstock efficiency

$$= 0.8 \times 0.85 \times 0.96 = 0.65$$

$$\text{H.P. developed} = \frac{\omega Q H \eta}{75 \times \text{load factor}}$$

$$= \frac{1000 \times 40 \times 7.85 \times 0.65}{75 \times 0.45} = 6032. \textbf{ Ans.}$$

Example 6.10. (*a*) *In a hydropower plant the reservoir is 200 m above the turbine house. The annual replenishment of reservoir is 40 × 10^{10} kg. Calculate the energy available at the generating station bus bars if the loss of head in the hydraulic system is 20 m and the overall efficiency of the station is 80%.*

(*b*) *Also determine the diameter of two steel penstocks if maximum demand of 50 MW is to be supplied.*

Solution. (*a*) n = Efficiency = 0.8

h^1 = Loss in head = 20 m

h = Actual head available

$= 200 - h_1 = 200 - 20 = 180$ m

E = Energy available at the turbine house

$= mgh = 40 \times 10^{10} \times 9.81 \times 180$

$= 70.63 \times 10^{13}$ J

$$= \frac{70.63 \times 10^{13}}{36 \times 10^5} = 16.84 \times 10^7 \text{ kWh.}$$

(As 1 kWh = 36×10^5 J)

Energy output $= E \times \eta = 16.84 \times 10^7 \times 0.8$

$= 13.48 \times 10^7$ kWh. **Ans.**

(*b*) Kinetic energy of water

$= \frac{1}{2} mV^2$ = Loss of potential energy of water

$$\therefore \quad \frac{1}{2} mV^2 = mgh$$

$$V = \sqrt{2gh} = \sqrt{2 \times 9.81 \times 180} = 59.4 \text{ m/sec.}$$

E_1 = Energy available from a mass m kg of water when it flows with the velocity 59.4 m/sec.

$$= \frac{1}{2} mV^2 = \frac{1}{2} m \times 59.4^2 \text{ J/s or Watts.}$$

But energy to be supplied = 50 × 10^6 watts.

m = 22,700 kg.

ω = Specific weight of water = 1000 kg/m^3.

A = Total area of two penstocks (m^2)

$$A \times V \times \omega = m$$

$$A \times 59.4 \times 1000 = 22{,}700$$

$$A = 0.38 \text{ m}^2$$

A_1 = Area of each penstock

$$= \frac{A}{2} = \frac{0.38}{2} = 0.19 \text{ m}^2$$

Let D = Diameter of penstock

$$\frac{\pi}{4} D^2 = 0.19$$

$$\therefore \quad D = 0.242 \text{ m.} \quad \textbf{Ans.}$$

6.43(a) Hydro Power Plants in India

Some of the hydro power plants installed in our country are mentioned in Table 6.4.

6.43.1 Hydro Power in India

Hydro power represents a renewable source of energy which enjoys many intrinsic advantages. Our country has large hydropotential.

It is essential to produce cheap power for alround development of the country. Our fossil fuel reserve is limited and we are still at infancy in developing nuclear power and hence as far as possible the long term planning for power development should be hydropower oriented. As no fuel is required to produce power therefore, power produced will be cheaper than other conventional means in the long run. In India the scope of water power development is tremendous. Only a part of the easily available water power potential has been developed so far Hydro power plants do not pollute the atmosphere. Hence in order to keep the atmosphere free from harmful pollution, water power is the ideal source of power. Being endowed by nature with a variety of sources its tropical geographical position, its rivers and wind power mark out for India much hydro power potential. Hydro power being a renewable source of energy must undoubtedly receive a high priority in our energy development programme. Total hydro potential in our country is estimated to be equivalent to about 75,400 MW at 60% load factor of which only 11 to 12% has been exploited so far. The assumption that hydel generation despite its high capital costs and long gestation period, is cheap and clean has rarely been questioned.

Table 6.4

S.No.	*Name of the project*	*River and the State*	*Type of dam*	*Power development (MW)*
1.	Srisailam Hydel Project	Andhra Pradesh	Masonry and gravity	770
2.	Upper Sileru Hydro Electric Project	Andhra Pradesh	Masonry Division Weir	120
3.	Umiam Hydel Power Project	Umaim River, Assam	Concrete Earthen	39
4.	Subarnarekha Hydel-cum-Water Supply Project	Subarnarekha, Bihar	Masonry Earthen	120
5.	Ukar Project	Tapi, Gujarat	Masonry Earthen	160
6.	Chonani Hydel Project	Tawi, Jammu and Kashmir	Masonry Division Weir	37
7.	Salal Hydel Project	Chenab, Kashmir	Concrete Gravity	960
8.	Iddiki Hydel Project	Iddiki, Kerala	Concrete Arch Concrete Gravity Masonry Gravity	800
9.	Pambki	Pamba and Kakhi river, Kerala	Concrete Gravity Stone Masonry Stone Masonry	300
10.	Chambal Valley Project	Chambal, river		
	(*i*) Gandhi Sagar	Madhya Pradesh	Concrete Gravity	115
	(*ii*) Jawahar Sagar, Kotah Dam	Chambal (M.P.)	"	99
	(*iii*) Rana Pratap Sagar Dam			128
11.	Kodayar Hydro-Electric Project	Kodayar, Tamil Nadu	—	100
12.	Kundah Basin Development Project	On different rivers, Kundah Basin, Tamil Nadu	—	425
13.	Mettur Hydro-Electric Project	Mettur Tamil Nadu	Concrete Gravity	200
14.	Periyar Hydro-Electric Project	Periyar, Tamil Nadu	Forebay Dam	140
15.	Koyna Hydro-Electric Project	Koyna, Maharashtra	Rubble Concrete	900
16.	Sharavathi Hydro-Electric Project			
	(*i*) Linga Makki Dam	Sharavathi, Karnataka	Masonry Earthen	891
	(*ii*) Talakalala Dam	"	"	
17.	Tungabhadra Project	Tungabhadra, Karnataka	Masonry Gravity	126

18.	Balimela Hydro-Electric Project	Silera, Orissa	—	480
19.	Hirakund Project	Mahanadi, Orissa	Concrete Gravity Earthen	427
20.	Beas Dam at Pong	Beas, Punjab-Himachal	Gravel	360
21.	Beas Sutlej Link Project			
22.	Bhakra Nangal Project	Beas, Punjab-Himachal Pradesh	Concrete Gravity	633
	(*i*) Bhakra Dam	Sutlej, Punjab	Concrete Gravity	1156
	(*ii*) Nangal	" "	" "	
23.	Doab Canal Hydro Project	Punjab	— —	45
24.	Orba Hydro-Electric Project	Rehand, U.P.	—	99
25.	Ram Ganga Project	Ram Ganga, U.P.	Earth	165
26.	Rihand Hydro-Electric Project	Rihand, U.P.	Concrete Gravity	300
27.	Yamuna Hydro-Electric Project	Yamuna, U.P.	Concrete Gravity	444
28.	Jaldala Hydro-Electric Schemes	Jaldala, W. Bengal	Concrete	36

So far as river-wise potential is concerned the two great rivers namely Ganga and Brahmaputra have an unexploited power potential of 5000 MW and 15000 MW respectively. The river Godavari and its tributaries have a power potential of 6000 MW, which is still to be exploited.

The gestation period of hydro power plants is more. To ensure timely implementation of such projects the following steps are required :

(*i*) A better assessment of geological and environmental factors.

(*ii*) Strengthening of construction agencies in terms of
- (*a*) organisation
- (*b*) equipment
- (*c*) skilled man power
- (*d*) technical know-how.

(*iii*) Making available optimal equipment both qualitatively and quantitatively.

(*iv*) Regular flow of funds.

6.43.2 Preventive Maintenance of Hydro Electric Power Plant

Preventive Maintenance is based on schedule inspections of plant and equipment. Its purpose is to minimise break down and excessive depreciation resulting from neglect. The various parts of a hydro plant using reaction turbine are inspected and maintained monthly, quarterly, half yearly and yearly are as follows :

(*a*) Monthly inspection and maintenance is carried out for the following parts :

(*i*) Turbine cover parts such as drainage holes, leakage unit, servomotor connections, turbine shaft and cover, oil pump its auxiliaries and ejector cabinet.

(*ii*) Guide vane mechanism.

(*iii*) Operating ring of turbines.

(*b*) Quarterly maintenance is carried out in case of following parts :

(*i*) Governor oil system

(*ii*) Ejector cabinet

(*iii*) Servomotor

(*iv*) Feedback system.

(*c*) The following parts are inspected half yearly :

(*i*) Gauges.

(*ii*) Grease pumps for guide vanes and guide bearings.

(*iii*) Governor mechanism.

(*iv*) Grease pipes connected to grease pumps.

All gauges are recalibrated once in two years.

(*d*) Yearly maintenance is carried out in case of following parts :

(*i*) Turbine auxiliaries such as turbine guide bearing, and water both, oil pressure tank, and turbine instruments.

(*ii*) Scroll casing runner with cone guide vanes.

(*iii*) Draft tube.

(*iv*) Emergency slide valve.

(*v*) Runner blades checked for cavitational effects, cracks and we aring out.

(*vi*) Pit liner.

6.43.3 Electrical and Mechanical Equipment

The electrical and mechanical equipment in a hydro power plant consists of the following :

(*a*) Electrical equipment.

(*i*) Generators

(*ii*) Exciters and voltage regulators

(*iii*) Transformers (*iv*) Switchgear

(*v*) Control room equipment including switch boards.

The generators used in hydro power plants are usually three phase synchronous machines. The generators have a speed range of 70–1000 R.P.M. Generators have either a vertical shaft arrangement or horizontal shaft arrangement. But vertical shaft arrangement is preferred. The generator cooling can be achieved by air circulation through the stator ducts. Cooling by water cooled heat exchangers in common. The out put power of a three phase alternator is given by

$$P = \sqrt{3}\ \text{V.I.P.} \times 10^{-6}\ \text{MW}$$

where P = Power

V = Voltage in volts

I = Current in amperes

p = Power factor = 0.9 to 0.95

Thrust bearing is used to carry all the axial loads of the machine including the weight of runner, the turbine and generator shaft and rotor weight.

Transformers may be of three phase or single phase type. The transformers are oil-filled for insulation purposes as well as for cooling purposes. The generated voltage is usually below 18 kV while transmission voltage may be as high as 400 kV. This is achieved by using step up transformers.

Switch gear is used to make and break the circuits. It consists of switches, isolators, surge arrestors and circuit breakers. For generated voltage it is preferred to locate switch gear indoors whereas out door location is used for transmission voltage. Both transformers and switch gears particularly located outside should be provided with adequate lighting protection.

The control room equipment is used to perform the following functions :

(*i*) Machine starting and stopping
(*ii*) Generator and system voltage control
(*iii*) Machine loading control
(*iv*) Frequency control
(*v*) Hydraulic control
(*vi*) Machine running control

(*b*) Mechanical equipment

(*i*) Shaft, couplings, bearings etc.
(*ii*) Compressors and air ducts
(*iii*) Braking equipment for the generator
(*iv*) The oil circuits and pumps
(*v*) Ventilation and cooling systems
(*vi*) Cranes and other lifting equipment
(*vii*) Equipment for power houses lighting
(*viii*) Equipment for water supply and drainage.

6.43.4. Hydel-Thermal Mix

A judicious combination of both hydro and thermal power is the optimum solution to meeting the increasing power demand and to reduce the cost of electrical power. Hydro-power represents a renewable source of energy which enjoys many intrinsic advantages as compared to thermal power. Although the cost of construction of a hydro power plant is nearly same as that of a coal based steam power plant in terms of investment for MW, but hydro-power plant uses water for power generation which is available in abundance in nature. Our country's full hydro potential is estimated to be 135000 MW at 40 per cent load factor.

While the hydel thermal mix stood at 51 : 49 in 1962-63 it went down to 40 : 60 at the end of Fifth plan, declined at 34 : 66 at the end of Sixth plan and declined to 30 : 70 at the end of Seventh plan. This ratio may be 20 : 80 at the end of Eighth plan if proper measures are not taken to make use of hydro power properly. It is observed that to produce electrical power economically the hydel thermal mix ratio must be 40 : 60 by the end of Ninth plan.

Central Electricity Authority (CEA) has projected that by the end of Ninth Plan period the hydro component will be 34% thermal 60.2% and nuclear 5.8%. Without adequate hydel back up the over al. cost of meeting the power is more expensive. This is further supported by the fact that the hydel generation is based on renewable source of energy and is pollution free.

In our country's power scenario coal still occupies the prime position accounting for 68% of commercial energy generation. This trend has led to the distortion of hydel-thermal mix ratio in the installed capacity over the years. In view of the availability of natural resources, a generation mix of 40% hydel and 60% thermal is considered fairly good for Indian systems.

In our country the present ratio of hydrothermal mix is poor particularly in respect of Eastern and Northern regions (which are endowed with large economically harnessable hydro-potential). Priority should be given for tapping of the same.

6.44 Economic Loading of Hydro-Power Plants

For economic loading of hydro power plants, following data is needed :

(*i*) Efficiency curve of each unit.

(*ii*) Input and output curves showing total rate of flow of water against the load.

(*iii*) Incremental rate curve showing the change in the rate of flow required per unit change in load.

(*iv*) Capacity of each unit. The use of hydro power plant as base-load plant or peak load plant depends on storage available at the plant.

6.44.1 Run-of-river plant in combination with steam power plant

In a run-of-river plant the quantity of water available is not steady throughout the year. The run of river plant can be used as base load plant during the rainy season when enough water is available and thermal power plant is used to take up the peak load. During dry season the thermal power plant should be used as base load plant and run-of-river plant can be used to take peak load.

In a combined system it is always desirable to use the hydropower plant to the best extent possible when enough water is available. Load duration curve for the combined system should be plotted to know the power to be supplied at different intervals of time (duration) similarly power available curve for run-of-river plant should also be plotted for the same duration. By combining these two curves it can be found out during which period of the given duration the run-of-river plant will act as base load power plant.

6.44.2 Pump storage plant in combination with steam power plant

The pumped storage power plant is useful in an inter-connected system to supply sudden peak loads of shorter duration. In pump storage power plant water is pumped from tail water pond to head water pond.

The various advantages of inter-connecting pumped storage plant with steam power plant are as follows :

(*i*) During off-peak period the extra energy available from steam power plant is used to pump water from tail water pond to head water pond. This stored hydraulic energy is used during peak load period.

(*ii*) It provides added power to meet the peak load and thus :

(*a*) helps in reducing the installed capacity of the steam power plant.

(*b*) allows the steam power plant to run at high load factor.

This will reduce power generation cost.

Example 6.11. *A hydel power plant produces 18 × 10³ kW under a head of 14 metres. Determine the following :*

(*a*) *Type of turbine.*

(*b*) *Synchronous speed of generator.*

Assume overall efficiency of plant 70%.

Solution. (*a*) H = head = 14 metres.

$$P = \text{Power} = 18 \times 10^3 \text{ kW}$$

$$= 18 \times 10^3 \times \frac{1000}{735.5} = 2.447 \times 10^4 \text{ H.P.}$$

$$P = \frac{\omega . Q . H . \eta}{75}$$

where ω = Specific weight of water = 1000 kg/m^3

Q = Discharge

η = Efficiency = 0.7

$$2.447 \times 10^4 = \frac{1000 \times Q \times 14 \times 0.7}{75}$$

$$Q = 187.3 \text{ m}^3/\text{sec.}$$

As the head is low and discharge is high so a propeller type of turbine should be used.

(*b*) N_s = Specific speed

$$= \frac{1150}{H^{1/4}} \text{ (Approx.)} = \frac{1150}{14^{1/4}} = \frac{1150}{1.93}$$

$$= 596$$

N = Speed of rotation

$$= \frac{N_s \, . \, H^{5/4}}{\sqrt{P}} = \frac{596 \times 14^{5/4}}{\sqrt{2.447 \times 10^4}}$$

$$= 103 \text{ R.P.M.}$$

For generator $N = \dfrac{120f}{p}$

where f = Frequency in cycles per second.

= 50 cycles/sec

p = Number of poles

$$103 = \frac{120 \times 50}{60}$$

$$p = 58.3 = 60 \text{ (say)}$$

As the number of poles is necessarily an even number.

Again $N = \dfrac{120f}{p} = \dfrac{120 \times 50}{60} = 100$ R.P.M.

Example 6.12. *A steel penstock carries 12 m^3/sec of water under a head of 240 m. The penstock diameter is 2.8 m and the allowable stress in penstock material is 1400 kg/m^2. Determine the following :*

(*a*) *Water hammer pressure assuming velocity of pressure wave 1425 m/sec.*

(*b*) *Thickness of penstock.*

(*c*) *Describe water hammer.*

Solution.

(*a*) Q = Discharge = 12 m^3/sec.

d = Diameter of penstock = 2.8 m

H = Head = 240 m

V_1 = Velocity of pressure wave = 1425 m/sec.

V_2 = Velocity of water

$$Q = V_2 \times \frac{\pi}{4} d^2$$

$$12 = V_2 \times \frac{\pi}{4} \times (2.8)^2$$

V_2 = 1.95 m/sec.

p_1 = Water hammer pressure

$$= \frac{V_1 \,.\, V_2}{g} = \frac{1425 \times 1.95}{9.81} = 283 \text{ m.}$$

(*b*) f = Safe stress in penstock material

= 1400 kg/cm^2

h = Total pressure head = $H + p_1$

= 240 + 283 = 523 m

p = Total pressure = $w.h.$ = 1000 × 523 kg/m^2

t = Thickness of penstock

$$= \frac{pd}{2f} = \frac{1000 \times 523 \times 2.8}{2 \times 1400 \times 10^4} \times 100 = 5.23 \text{ cm.}$$

(*c*) **Water hammer.** When the load on the generator is suddenly reduced the valves admitting water to the turbines are to be closed suddenly. This sudden stoppage brings the water near the valve to stand still but the along column of water in the pipe line is still moving. The momentum of this water causes sudden increase in pressure in pipe section. This sudden rise of pressure above normal is called water hammer. Surge tanks help in releasing and dissipating the excessive water hammer pressure built up in a penstock.

Example 6.13. *For a hydro-electric power station the following data is available :*

Head = 380 m.

Discharge = 4 m^3*/sec.*

Efficiency of turbine = 80%

Generator frequency = 50 c/s

Determine the following :

(a) Output *(b) Type of turbine*

(c) Speed of turbine.

Solution. Q = Discharge = 4 m^3/sec

N = Head = 380 m

ω = Unit weight of water = 1000 kg/m^3

n = Efficiency of turbine = 0.8

Output $= \dfrac{w.Q.H.\eta}{75} = \dfrac{1000 \times 4 \times 380 \times 0.8}{75}$

= 16,200 metric H.P.

Pelton turbine should be used for a head of 380 m.

N = Actual speed of turbine.

N_s = Specific speed of turbine.

Choosing an approximate specific speed of about 26 (metric unit).

$$N = \frac{N_s \,.\, H^{5/4}}{P^{1/2}} = \frac{26 \times 380^{5/4}}{16200^{1/2}}$$

= 342 R.P.M.

p = Number of poles

f = Generator frequency = 50 cycle/sec.

$$p = \frac{120f}{N} = \frac{120 \times 50}{342}$$

= 17.54 = 18 (say)

Corrected speed $= \dfrac{120f}{p} = \dfrac{120 \times 50}{18}$

= 333 R.P.M.

Example 6.14. *(a) What is a flow duration curve ?*

(b) The mean weekly discharge at a hydro power plant site is as follows :

Week	*Discharge*	*Week*	*(Discharge m^3/sec.)*
1	*160*	*7*	*700*
2	*200*	*8*	*600*
3	*300*	*9*	*1000*
4	*1100*	*10*	*600*
5	*700*	*11*	*400*
6	*900*	*12*	*300*

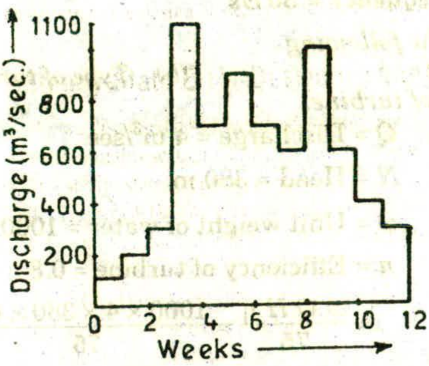


Fig. 6.46

(*i*) *Draw the hydrograph and find average discharge available for the whole period.*

(*ii*) *Develop the flow duration curve and plot it.*

Solution. (*a*) A flow duration curve is used to determine the available power at the site. It indicates the daily, weekly, or monthly flows available as ordinates plotted against percentage of time.

(*b*) The hydrograph is plotted between discharge (m^3/sec.) and number of weeks as shown in Fig. 6.46.

$$\text{Average discharge} = \frac{\text{Total discharge}}{\text{Total weeks}} = 580 \text{ m}^3/\text{sec}$$

$$= \frac{6960}{12}$$

In order to draw flow duration curve it is essential to find the lengths of time during which certain flows are available. This information is indicated in table shown below.

Discharge (m^3/sec)	*Total number of week*	*Percentage time*
160 (and more)	12	100
200 (and more)	11	91.7
300 (and more)	10	83.3
400 (and more)	8	66.7
600 (and more)	7	58.3
700 (and more)	5	41.7
900 (and more)	3	25
1000 (and more)	2	16.7
1100 (and more)	1	8.3

Fig. 6.47 shows a flow duration curve. When selecting a suitabl site for a hydro power plant the flow data for a number of years are collected and hydrographs and flow duration curves and the various periods are determined.

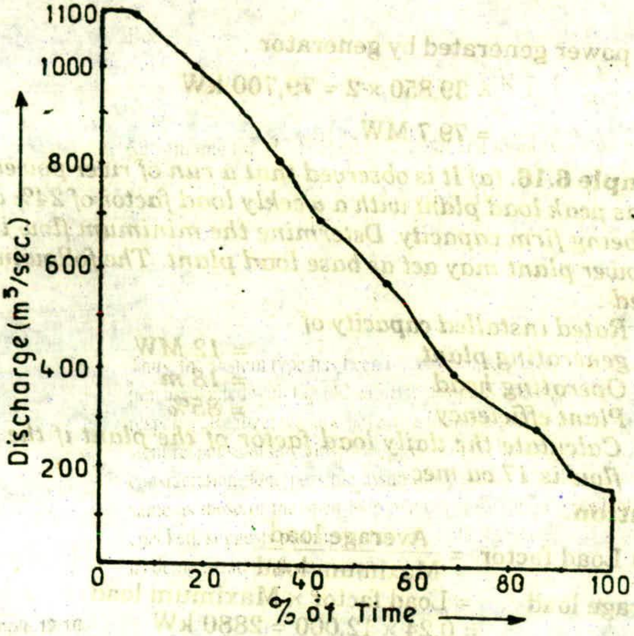


Fig. 6.47

Example 6.15. *At a site for a hydro power plant a flow of 80 m³/sec is available at a head of 120 m. If turbine efficiency is 90% and generator efficiency is 94% determine the following :*

(*a*) *Power that can be developed*

(*b*) *No. of units required and their capacities.*

Solution. Q = Discharge = 80 m³/sec

H = Head = 120 m

η = Efficiency of turbine = 0.9

P = Power developed

$$= \frac{\omega Q H \eta}{75} = \frac{100 \times 80 \times 120 \times 0.9}{75}$$

= 115,200 Metric H.P.

Two turbines each of $\frac{115,200}{2}$ = 57,600 metric H.P. capacity should be used

η_g = Generator efficiency = 0.94

Generator capacity of each unit = 57,600 × 0.94 × 0.736

= 39,850 kW.

- Total power generated by generator

$= 39{,}850 \times 2 = 79{,}700$ kW

$= 79.7$ MW.

Example 6.16. *(a) It is observed that a run of river power plant operates as peak load plant with a weekly load factor of 24% all this capacity being firm capacity. Determine the minimum flow in river so that power plant may act as base load plant. The following data is supplied :*

Rated installed capacity of generating plant = *12 MW*
Operating head = *18 m*
Plant efficiency = *85%*

(b) *Calculate the daily load factor of the plant if the stream flow is 17 cu mec.*

Solution.

(a) Load factor $= \dfrac{\text{Average load}}{\text{Maximum load}}$

Average load = Load factor × Maximum load

$= 0.24 \times 12{,}000 = 2880$ kW

E = Total energy generated in one week

= Average load × Time

$= 2880 \times 24 \times 7 = 48.4 \times 10^4$ kWH

Let Q = Minimum flow rate (m^3/sec)

P = Power developed $= \dfrac{\omega Q H \eta}{75}$

where ω = Specific weight of water

$= 1000$ kg/m^3

H = Head = 18 m

η = Efficiency of plant = 0.85

(b) $P = \dfrac{1000\, QH\eta}{75} = 13.3\, Q H \eta$ (HP)

$= 0.736 \times 13.33\, QH\eta$ (kW)

$= 9.8 \times QH\eta$ (kW)

$= 9.8 \times Q \times 18 \times 0.85$ kW

$= 149.9\, Q$ kW

E_1 = Total energy generated in one week

$= P \times \text{Time} = 149.9\, Q \times 24 \times 7$

$$= 2.5Q \times 10^4 \text{ kWh}$$

Now $E = E_1$

$$48.4 \times 10^4 = 2.5\, Q \times 10^4$$

$$Q = 19.36 \text{ cumec.}$$

P_1 = Power developed when stream flows is .7 cumec.

$$= 149.9 \times 17 = 2548.3 \text{ kW}$$

E_2 = Energy generated per day

$$= P_1 \times \text{Time} = 2548.3 \times 24$$

$$= 61{,}159 \text{ kWh.}$$

$$\text{Daily load factor } = \frac{\text{Average load}}{\text{Max. load}}$$

$$= \frac{61{,}159}{24 \times 12{,}000} = 0.212 \text{ or } 21.2\%.$$

Example 6.17. *(a) What is pondage factor ?*

(b) Determine the firm capacity of a run-of-river hydro power plant to be used as 9 hours peaking plant assuming daily flow in a river to be constant at 16 m^3/sec.

Also calculate pondage factor and pondage if the head of the plant is 12 m and overall efficiency is 80%.

Solution.

(*a*) Pondage factor is the ratio of total in flow hours in a given period to the total number of hours plant running during the same period.

(*b*) P = Firm capacity without pondage

$$= \frac{\omega . Q . H . \eta}{75}$$

where ω = Specific weight of water

$$= 1000 \text{ kg/m}^3$$

Q = Discharge = 16 m^3/s

H = Head = 12 m

η = Overall efficiency = 0.8

$$P = \frac{1000 \times 16 \times 12 \times 0.8}{75} = 2048 \text{ H.P.}$$

$$P.F. = \text{Pondage factor} = \frac{t_1}{t_2}$$

where t_1 = Total hours in one day = 24

t_2 = No. of hours of power plant running = 9

$$P.F. = \frac{24}{9} = 2.67$$

$$Q_1 = 9 \text{ hours flow} = \frac{16 \times 24}{9}$$

$$= 42.67 \text{ m}^3/\text{s}$$

P_1 = Firm power with pondage

$$= 2048 \times 2.67$$

$$= 5468 \text{ H.P.}$$

S = Magnitude of pondage

$$= (24 - 9) = 15 \text{ hours flow}$$

$$= 15 \times 60 \times 60 \times 16$$

$$= 864 \times 10^3 \text{ m}^3.$$

Example 6.18. *The following data is supplied for a hydropower plant.*

Catchment area = 2200 sq km

Annual average rain fall = 150 cm

Available head = 130 m

Turbine efficiency = 0.86

Generator efficiency = 0.91

Percolation and evaporation losses = 18%

Determine :

(*a*) *Power development in kW taking load factor as Unity.*

(*b*) *Suggest type of turbine to be used if the speed of runner is to be maintained below 260 R.P.M.*

Solution.

A = Area = 2200 sq km

$$= 2200 \times 10^6 \text{ m}^2$$

h = Annual average rainfall = 150 cm

$$= \frac{150}{100} = 1.5 \text{ m}$$

y = Percolation and evaporation losses

$= 0.18$

H = Head available = 130 m

Q_1 = Quantity of water available for power generation per year

$$= A \times h \times (1 - y)$$

$$= 2200 \times 10^6 \times 1.5\,(1 - 0.18)$$

$$= 2.7 \times 10^8 \text{ m}^3$$

Q = Quantity of water available per second

$$= \frac{2.7 \times 10^8}{365 \times 24 \times 60 \times 60}$$

$$= 8.56 \text{ m}^3/\text{sec.}$$

η_t = Turbine efficiency = 0.86

η_g = Generator efficiency

$= 0.91$

P = Power developed

$$= \frac{\omega Q H}{75} \times \eta_t \times \eta_g$$

$$= \frac{1000 \times 8.56 \times 130}{75} \times 0.86 \times 0.91$$

$$= 11612 \text{ H.P.} = 11612 \times 0.736$$

$$= 8546 \text{ kW} = 8.546 \text{ MW}$$

N = 260 R.P.M.

$$NS = \frac{N\sqrt{P}}{H^{5/4}} = \frac{260\sqrt{8546}}{130^{5/4}}$$

$$= 54.75.$$

Single Pelton turbine with 4 jets can be used. Further since head available is large and discharge is low, Pelton turbine will work satisfactorily.

Example 6.19. *The available discharge for a hydro-electric power plant is 320 m^3/sec under a head of 28 metre. The turbine efficiency is 90% and the generator is directly coupled to the turbine. The frequency of generation is 50 cycles / sec. and number of poles used are 26. Find the number of machines required when :*

(*a*) *A francis turbine with a specific speed of 280 is used.*

(*b*) *A Kaplan turbine with a specific speed of 500 is used.*

Solution. N = Speed of generator

$$= \frac{120.f}{p}$$

f = frequency

= 50 cycles/sec.

p = Number of poles = 26

$$N = \frac{120 \times 50}{26} = 230 \text{ R.P.M.}$$

Since the generator is directly coupled to the turbine the speed of turbine used must be equal to the synchronous speed of the generator.

$$P = \text{Power} = \frac{\omega.Q.H}{75} \times \eta$$

where ω = 1000 kg/m^3

Q = Discharge = 320 m^3/sec.

H = Head = 28 m

η = Efficiency of turbine = 0.9

$$P = \frac{1000 \times 320 \times 28 \times 0.9}{75} = 107 \times 10^3 \text{ H.P.}$$

(*a*) Let P_1 = Power capacity of each Francis turbine

$$N_s = \frac{N\sqrt{P}}{H^{5/4}}$$

$$280 = \frac{230\sqrt{P_1}}{28^{1.25}}$$

$$P_1 = 6400$$

Number of Francis turbines required

$$= \frac{P}{P_1} = \frac{107 \times 10^3}{6400} = 17. \quad \textbf{Ans.}$$

(*b*) Let P_2 = Power capacity of each Kaplan turbine

$$N_s = \frac{N\sqrt{P_2}}{N^{5/4}}$$

$$500 = \frac{230\sqrt{P_2}}{28^{1.25}}$$

$$P_2 = 196 \times 10^2$$

Number of Kaplan turbines required

$$= \frac{P}{P_2} = \frac{107 \times 10^3}{196 \times 10^2} = 6. \quad \textbf{Ans.}$$

Example 6.20. *A pump storage power plant has a gross head of 300 m. The head race tunnel is 3.8 m diameter and 650 m long. The flow velocity is 7 m/sec. and friction factor is 0.017. If the overall efficiency of pumping and generation are 84% and 89% respectively determine the plant efficiency. The power plant discharges directly in the lower reservoir.*

Solution. f = Friction factor = 0.17

η_p = Pumping efficiency = 0.84

η_g = Generation efficiency = 0.89

L = Tunnel length = 650 m

H = head = 300 m

V = Flow velocity = 7 m/s

D = Diameter of head race tunnel

= 3.8 m

h_f = Frictional head loss

$$= \frac{f.L.V^2}{2gD} = \frac{0.017 \times 650 \times 7^2}{2 \times 9.81 \times 3}$$

$$= 7.26 \text{ m}$$

Now $h_f = \text{kH}$

$$7.26 = k \times 300$$

$$k = 0.024$$

Plant efficiency (η) is given by

$$\eta = \frac{1-k}{1+k} \times \eta_p \times \eta_g$$

$$= \frac{1-0.024}{1+0.024} \times 0.84 \times 0.89$$

$$= 0.712 = 71.2\%.$$

Example 6.21. *A run off river hydro-power plant with an effective head of 20 m and plant efficiency 78% supplies a variable load as shown below :*

Time (Hours)	*Load ($\times 10^3$ kW)*
0—4	*8*
4—8	*15*

8—12	*28*
12—16	*32*
16—20	*42*
20—24	*50*

Draw load duration curve and determine

(a) Flow required for average load

(b) Load factor.

Solution. The load duration curve is shown in Fig. 6.48.

H = head = 20 m

η = Efficiency = 0.78

E = Energy supplied during 24 hours

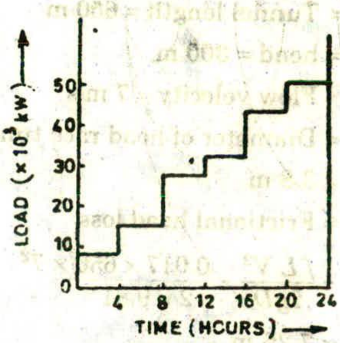


Fig. 6.48

$$= (8 + 15 + 28 + 32 + 42 + 50) \times 4 \times 10^3$$

$$= 700 \times 10^3 \text{ kWh}$$

$$\text{Average Load} = \frac{700 \times 10^3}{24}$$

$$= 29 \times 10^3 \text{ kW}$$

$$\text{Load factor} = \frac{\text{Average Load}}{\text{Maximum demand}}$$

$$= \frac{29 \times 10^3}{50 \times 10^3}$$

$$= 0.58$$

$$= 58\%$$

Let Q = Flow (m^3/sec)

$$\text{Average Power (kW)} = \frac{\omega . Q . H}{75} \times \eta \times 0.736$$

$$29 \times 10^3 = \frac{1000 \times Q \times 20}{75} \times 0.78 \times 0.736$$

$$Q = 189 \text{ m}^3/\text{second.}$$

Example 6.22. ***A penstock supplies water at a head equivalent to 18 kg/cm^2. There is a possibility of 15% increase in pressure due to transient conditions. The design stress and efficiency of joint may be taken as 1000 kg/cm^2 and 88% respectively. If internal diameter of penstock is 1.3 m find wall thickness of penstock.***

Solution. p = Total pressure

$= 18 + 0.15 \times 18$

$= 20.7$ kg/cm^2

D = Internal diameter

$= 1.3$ m

R = Internal radius

$= 0.65$ m.

$= 65$ cm

f = Design stress

η = Efficiency

$= 0.88$

t = Wall thickness of penstock

It is given by the following formula

$$t = \frac{pR}{f \cdot \eta - 0.6\,p} + 0.15 \text{ cm}$$

$$= \frac{20.7 \times 65}{1000 \times 0.88 - 0.6 \times 20.7} + 0.15$$

$$= 1.7 \text{ cm.}$$

6.45 Power House Planning

The basic requirement for power house planning is functional efficiency coupled with aesthetic beauty. Two types of power plants may be used.

(*i*) **Surface power plants.** The building of such power plants is located above the ground.

(*ii*) **Underground power plants.** The building of these power plants is situated in caverns excavated below the ground. Surface power plants are quite commonly used.

After the choice of the type of power plant is made, the following decisions may then be taken.

(*i*) The size of power plant and the arrangement of various units.

(*ii*) The equipment to be located indoors and outdoors. For example transformers and inlet valves can be located either inside or outside the power plant.

6.46 Surface Power Plants

They have less space restrictions than the underground power plants. The following parts of the power plant should be properly designed.

1. **Power house structure.** Power house structure can have following three divisions :

(*i*) Sub structure (*ii*) Intermediate structure
(*iii*) Super structure.

The sub-structure is that part of power house structure which is situated below the turbine level. The sub-structural transmits the load of the structure to the foundation. Sub-structure is usually below the ground level and houses the following

(*i*) Draft tube (*ii*) Tail water channel
(*iii*) Drainage pipes of waste water
(*iv*) Drainage galleries (*v*) Grout galleries

The intermediate structure extends from the top of the draft tube to the top of the generator foundation. It houses the following:

(*i*) Turbine including its casing
(*ii*) Galleries for the auxiliary machines
(*iii*) Governor servo-motor system.

The turbine flour is below the generator floor and is accessible through stairs from the generator floor.

The super structure is the portion extending from the generator floor called the main floor up to the roof top.

It houses the following

(*i*) Generators (*ii*) Governors
(*iii*) Control room (*iv*) Exciters
(*v*) Auxiliary equipment. Such as needed for
(*a*) ventilation (*b*) cooling
(*vi*) Main travelling gantry crane at the roof level.
(*vii*) Control room (*viii*) Offices and stores.

2. **Power house dimensions.** The super structure of the power plant has the following three bays.

(*i*) Machine hall or unit bay (*ii*) Erection or loading bay
(*iii*) Control bay.

Machine hall size depends on the number of units, the distance between the units and size of machines. The machine hall must have a height which will enable the cranes to lift the rotor of the generator or runner of the turbine clear off the floor.

The loading bay is used to load and unload the vehicles and where dismantled parts of the machines can be placed and where small assembling of the equipment can be done.

The control bay houses the main control consisting of control switches, panels etc. The control bay should be quite spacious.

3. **Cables and Bus Bars.** High voltage and low voltage cables should be carried separately cables and bus bars are placed in cable ducts provided in the floor of the generator or placed in the bus bar galleries.

4. **Operation room.** The operation room may be located inside the turbine room. The instructions are sent to the operation room from the control room. The operation room is the centre from where the machines are controlled and switch gear operated.

5. **Miscellaneous equipment.** Proper planning for the following should be carried out

(*i*) Transformers (*ii*) Service cranes
(*iii*) Lighting (*iv*) Ventilation.

6.47 Under ground power plants

They are safe against earth tremors, rock slides and snow avalanches. The various factors which affect the choice are as follows :

(*i*) Rock quality (*ii*) Tunneling ease
(*iii*) Over all economy.

An aesthetically significant advantage offered by an underground power plant is the preservation of the natural land scape features. The surface power plants would necessitate the deforestation, interference with natural landscape on account of the material transportation and constructional activities.

6.48 Components of underground power plant

The various components of an underground power plant are as follows :

(*i*) *Machine hall* : It houses the turbines and generators

(*ii*) Transformer hall

(*iii*) Control room

(*iv*) *Erection bay* : It is used for the assembly of rotor stator. It is also used to serve as repair bay.

(*v*) Cable gallery

(*vi*) *Valve chamber* : It is used to house control valves (*vii*) Ventilation tunnel

(*viii*) Access gallery.

6.49 Types of underground power plants

The layout of an underground power plant depends on the following factors

(*i*) Head and tail race water levels

(*ii*) Turbines	(*iii*) Generators
(*iv*) Transformers	(*v*) Control valves
(*vi*) Control room	(*vii*) Access gallery
(*viii*) Ventilation shaft	(*ix*) Topography and geology.

The underground power plants required a good sound rock. Heavy expenditure is incurred in supporting penstocks and on rock supports and rock bolting various types of underground power plants are as follows :

(*i*) Upstream power plant

(*ii*) Downstream power plant

(*iii*) Intermediate station development.

The upstream power plant also known as head development is located close to the intake and thus water is directly fed from the head pond to the generating units.

In down stream power plant also called tail race development has a long and nearly horizontal pressure tunnel together with pressure shafts and a short tail race tunnel. The intermediate power plant has a long head race tunnel and a long tail race tunnel.

6.50 Largest Underground Power Plant (Nathpa Jhakhri Hydel Power Project)

Nestled amidst the snow-capped mountains of Himachal Pradesh and surrounded by an inhospitable terrain, the country's largest underground power house, the Nathpa Jhakhri hydel power project, promises to solve the northern region's power problem.

The hydel project, estimated to produce an aggregate capacity of 1500 MW of hydel power in a single underground cavern, is situated in the Kannaur and Shimla district. The cavern is to house six units of 250 MW each.

While the first unit is to be commissioned by June, 1998 the subsequent second, third, fourth, fifth and sixth units have been scheduled for completion by December 1998.

The Nathpa Jhakhri project envisages to harness the hydropower potential in the upper reaches of river Satluj in the form of a "largest run-of-the river underground development in the south-west Himalayas".

The reservoir at Nathpa has virtually no impoundment of water and related problems associated with ecology displacement of population and deforestation.

Some of the unique features of this project, one of the largest underground complexes in the world is that it has 301-metre-deep surge shaft to produce hydel power. This will be the deepest surge shaft in the world.

The cavern six of this power house alone is 216 M × 20 M × 49 M and is to utilise a design discharge of 405 cubecs of water with a design head fall of 425 metres at Jhakhri.

The Nathpa Jhakhri Power Corporation (NJPC) proposes a 60.40 metre-high concrete dam on Satluj river at Nathpa to divert 405 cubecs of water through four intakes. Tunnelling and drilling work relating to this diversion dam is under completion.

6.51 Advantages and Dis-advantages of Underground Power Plant

Various advantages of under ground hydro power plant are as follows :

(*i*) Shorter power conduit reduces cost and head losses. It also reduces pressure developed due to water hammer ; (*ii*) The power plant construction period is less ; (*iii*) The underground power house is safe against air-raids ; (*iv*) Governing of turbines is easier ; (*v*) The plant is free from land slides ; (*vi*) Regular maintenance cost is low.

The various disadvantages are as follows :

(*i*) Construction cost is more ; (*ii*) Special ventilation and air conditioning is needed ; (*iii*) Construction of air ducts and bus galleries increase the cost ; (*iv*) Operational cost is more.

Example 6.23. *A pelton turbine is to satisfy the following requirements.*

Head $= T\ m$

Power $= 9.5 \times 10^3\ kW$

Speed $= 740\ RPM$

Jet diameter $= \frac{1}{6}$ *of wheel diameter*

Overall efficiency $= 87\%$

Determine (*a*) *Wheel diameter*
(*b*) *Jet diameter*
(*c*) *Number of jets required*

Given : Speed ratio $= 0.48$

$C_v = 0.986$

Solution.

H = Head = 340 m

P = Power = 9.5×10^3 kW

C_v = Coeff. of velocity = 0.986

V_1 = Velocity of jet

$= C_v \sqrt{2gH}$

$= 0.986 \sqrt{2 \times 9.81 \times 340} = 80.53$ m/s

V_2 = Velocity of wheel

= Speed ratio × $\sqrt{2gH}$

$= 0.48 \times \sqrt{2 \times 9.81 \times 340} = 39.2$ m/s

N = RPM = 740

D = Wheel diameter

$$V_2 = \frac{\pi DN}{60}$$

$$39.2 = \frac{\pi \times D \times 740}{60}$$

$D = 1.01$ m

d = Jet diameter

$$= \frac{1}{6} \times D = \frac{1}{6} \times 1.01$$

$= 0.168$ m

n = Number of jets required

q = Discharge throughout jet

$$= \frac{\pi}{4} \times d^2 \times V_1 = \frac{\pi}{4} \times (0.168)^2 \times 80.53$$

$= 1.78$ m^3/sec

η = Overall efficiency = 0.87

$$\eta = \frac{P}{\text{Water}}$$

$$= \frac{9500}{W.Q.H}$$

where w = Specific weight of water

$$= 9.81 \text{ kN/m}^3$$

$$Q = \text{Total discharge}$$

$$0.87 = \frac{9500}{9.81 \times Q \times 340}$$

$$Q = 3.273 \text{ m}^3\text{/sec}$$

$$3.273 = n \times q = n \times 1.78$$

$$n = 1.838 = 2 \text{ (say)}$$

Example 6.24. *For a river having a discharge of 230 litres / sec and available head of 43 metres.*

(*a*) *Calculate specific speed of turbine.*

(*b*) *Suggest type of turbine for the river.*

Take efficiency of turbine as 80% and speed as 480 RPM.

Solution.

$$H = \text{Head} = 43 \text{ m}$$

$$Q = \text{Discharge} = 230 \text{ litres/sec} = \frac{230}{1000} = 0.23 \text{ m}^3\text{/s}$$

$$N = \text{Speed} = 480 \text{ RPM}$$

$$\eta = \text{Turbine efficiency} = 0.8$$

$$P = \text{Power developed}$$

$$w = \text{Weight density of water} = 9.81 \times 10^3 \text{ N/m}^3$$

$$\eta = \frac{P}{W.Q.H.}$$

$$0.8 = \frac{P}{9.81 \times 0.23 \times 43}$$

$$P = 77.6 \text{ kW}$$

$$\text{NS} = \text{specific speed}$$

$$= \frac{N \,.\, \sqrt{P}}{H^{5/4}} = \frac{480 \times \sqrt{77.6}}{43^{5/4}} = 38.4$$

Therefore Pelton turbine is suitable.

Example 6.25. *A hydro-electric power plant is to be built across a river having a discharge of 320 m³/s and head of 30 m. The generator is directly coupled to the turbine. The frequency of generator is 50 Hz and number of poles used are 24. The turbine efficiency is 82%. Find the number of turbines required if*

(*a*) *A Francis turbine with a specific speed of 250 is used.*

(*b*) *A Kaplan turbine with a specific speed of 710 is used.*

Solution.

f = Frequency = 50 Hz

p = Number of poles = 24

(*a*) H = Head = 30 m

Q = Discharge = 320 m^3/s

η = Efficiency of turbine = 0.82

$$N = \frac{120f}{p} = \frac{120 \times 50}{24} = 250 \text{ RPM}$$

$$\eta = \frac{P}{W.Q.H.} \quad \text{where } P = \text{Power}$$

$$0.82 = \frac{P}{9.81 \times 320 \times 30}$$

$$P = 77224 \text{ kW}$$

N_s = specific speed = $\dfrac{N\sqrt{P_1}}{H^{5/4}}$ where P_1 = Power of each Francis turbine

$$250 = \frac{250\sqrt{P_1}}{30^{5/4}}$$

$$P_1 = 4512 \text{ kW}$$

Number of Francis turbines required

$$= \frac{P}{P_1} = \frac{77224}{4512}$$

$$= 17.1 = 18 \text{ (say)}$$

(*b*) For Kaplan turbine

$$N_s = \frac{N\sqrt{P_2}}{H^{5/4}}$$

$$710 = \frac{250\sqrt{P_2}}{30^{5/4}}$$

$$P_2 = 32618 \text{ kW}$$

Number of Kaplan turbines required

$$= \frac{77224}{32618} = 2.36 = 3 \text{ (say).}$$

Example 6.26. *Determine the firm capacity of a run of river hydropower plant to be used as 7 hours peaking load plant assuming daily flow in the river to be constant at 16 m³/sec.*

If head of power plant is 12 m and over all efficiency is 80% calculate

(*i*) *Pondage factor*

(*ii*) *Pondage.*

Solution.

H = Head = 12 m

w = specific weight of water

= 9.81 kN/m^3

Q = Discharge = 16 m^3/s

η = Efficiency = 0.8

P = Firm capacity without pondage

$= \eta \times W.Q.H.$

$= 0.8 \times 9.81 \times 16 \times 12$

= 1506.8 kW

$$\text{Pondage factor} = \frac{t_1}{t_2}$$

where t_1 = Total hours in a day = 24

t_2 = Number of hours for which plant remains in operation = 7

$$\text{Pondage factor} = \frac{24}{7} = 3.43$$

$Q_1 = Q \times 3.43$

$= 16 \times 3.43 = 55$ m^3/s

P_1 = Firm power with pondage

$= P \times$ Pondage factor

$= 1506.8 \times 3.43 = 5168.3$ kW

Pondage = (24 − 7) = 17 hours flow

$= 17 \times 60 \times 60 \times Q$

$= 17 \times 60 \times 60 \times 16$

$= 9.8 \times 10^5$ m^3.

Example 6.27. (*a*) *A run of river plant is used as a peak load plant with weekly load factor of 26% all the capacity being firm capacity. Determine the minimum flow in river so that power plant may act as base load plant when rated installed capacity is 12 MW and operating head is 17 m with plant efficiency 85%.*

(*b*) *Also determine the laity load factor when stream flow is* 16 m^3/sec.

Solution.

(*a*) C = Capacity of plant = 12 MW

H = Head = 17 m

η = Plant efficiency = 85%

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$0.26 = \frac{\text{Average load}}{12 \times 1000}$$

Average load = 3120 kW

E = Electrical energy generated in one week

= Average load × 24 × 7

$= 3120 \times 24 \times 7 = 52 \times 10^4$ kWh

Now $$\eta = \frac{P}{W.Q.H}$$

where P = Power developed

$$0.85 = \frac{P}{9.81 \times Q \times 17}$$

$P = 141.75\, Q$ kW

E_1 = Total energy generated in one week

$= P \times 24 \times 7$

$= 141.75 \times 24 \times 7 \times Q$

$= 23814 \times Q$ kWh

Now $E = E_1$

$52 \times 10^4 = 23814 \times Q$

$Q = 21.8$ m^3/s

(*b*) When Q = Flow rate
= 16 m^3/s

P_1 = Power developed = 141.75×16

= 2268 kW

E_2 = Energy generated per day

$= P_1 \times 24$

$= 2268 \times 24$

$$= 54432 \text{ kWh}$$

$$\text{Daity load factor } = \frac{\text{Average load}}{\text{Maximum load}}$$

$$= \frac{54432}{24 \times 12 \times 1000} = 0.19 = 19\%.$$

PROBLEMS

6.1. (*a*) What are the essential features of a hydroelectric power plant? Describe the various types of dams used in such plants.
(*b*) Discuss the working principle of hydro power plant.

6.2. Name the different types of hydroelectric power plants. Describe the pumped storage power plant and high head hydroelectro power plant.

6.3. What is the function of draft tube ? Describe the various types of draft tube.

6.4. How a surge tank helps in reducing water hammer effect ? Describe the various types of surge tanks.

6.5 (*a*) Classify the water turbines. What type of water turbine is used in high head hydro electric plant and why ? Discuss the various factors to be considered while selecting a water turbine.
(*b*) Sketch an impulse turbine installation.

6.6. What are the different factors to be considered while selecting the site for hydroelectric power plant ?

6.7. State the advantages and disadvantages of hydro-electric power plant. Compare it with steam power plant.

6.8. Write short notes on the following :
(*a*) Penstock
(*b*) Low head hydro-electric power plant
(*c*) Francis turbine
(*d*) Hydraulic Accumulator
(*e*) Drum Gate
(*f*) Fore bay.

6.9 Explain the terms 'Hydrology'. Describe Hydrologic cycle.

6.10. What is meant by waterway ? Describe the various types of tunnels and flumes.

6.11. What is the function of a gate in hydro-power station ? Describe Rolling Gate and Tainter Gate.

6.12. Write short notes on the following :
(*a*) Cavitation. (*b*) Cost of hydro Power Plant.
(*c*) Stoney Gate. (*d*) Needle valve.
(*e*) Turbine governing.
(*f*) Micro and mini hydro-power plant.

(*g*) Trash rack. (*h*) Butterfly valve.

6.13. What is the function of a spillway ? Discuss the various types of spillways commonly used.

6.14. Tick mark the correct answer. Francis turbine is used for :
(*a*) Low head. (*b*) Medium head.
(*c*) High head.

[**Ans.** Medium head]

6.15. Fill in the blanks :
(*i*) The overall efficiency of a Francis turbine is....
(*ii*) Pelton turbine is used for....heads.
(*iii*) In axial flow turbines the water flows through the vanes....to the axis of the runner shaft.
(*iv*) The maximum cone angle of a straight divergent draft tube is.....
(*v*) The running cost of hydro-electric power plant is....

[**Ans.** (*i*) 85 to 90% ; (*ii*) High ; (*iii*) Parallel (*iv*) 8° (*v*) Low]

6.16. State the head of water for which the following types of turbine are used :
(*a*) Pelton turbine (*b*) Francis turbine
(*c*) Kaplan turbines.

[**Ans.** (*a*) 150 to 300 m ; (*b*) 60 to 150 m ; (*c*) up to 60 m].

6.17. A turbine develops 30,000 H.P. under a head of 28 m when running at 150 R.P.M. Determine the specific speed of the turbine and specify the type of turbine to be used.

6.18. What is unit power ? Unit discharge and Unit Speed ? Derive the expressions for these quantities and explain their importance in determining the performance of a turbine.

6.19. A proposed hydroelectric power station has catchment area 520 sq. km with an average annual rainfall of 480 cm. The average head is 460 metres. Assuming 40% energy losses and 50% load factor, estimate the installed capacity of the power station.

6.20. Describe the various controls used in hydro power plants.

6.21. Write short notes on the following :
(*a*) Hydro-steam inter-connected system.
(*b*) Mass curve.

6.22. Write a short note on future of hydro power in India.

6.23. Define firm power and secondary power of a hydro-electric power plant.

6.24. Write short notes on the following :
(*a*) Water hammer.
(*b*) Synchronous speed of a turbine.
(*c*) Methods of coupling turbine with generator. Sketch and discuss turbine generator coupling for a low head power plant.

6.25. For a hydro power plant the following data is available.
Head = 180 m
Discharge = 2.5 m^2/sec.
Efficiency of turbine = 85%
Generator frequency = 50 cycles/sec.

Determine the following :

(*a*) Output (*b*) Type of turbine

(*c*) Speed of turbine.

6.26. A steel penstock carries a discharge of 24 m^2/sec under a head of 48 m. The velocity of water is 4 m/sec. The efficiency of joints is 88% and the permissible stress in penstock material is 1100 kg/cm^2. Determine the following :

(*a*) Diameter of penstock.

(*b*) Thickness of penstock.

6.27. A hydro-electric power plant has a capacity of 40 × 10^3 kW. The cost of development is Rs. 1400 per kW. The fixed cost is 10% per year and operation and maintenance cost is Rs. 12 per kW per year. If the transmission liability is Rs. 16 per year and load factor is 65% determine the cost per kilowatt hour.

6.28. Run-off rate of 400 m^3/sec and head of 45 m is available at a site proposed for hydroelectric power plant. Assuming the turbine efficiency of 90% and speed of 50 r.p.m. find out the least number of machines, all of equal size required if Francis turbine not greater than 2000 specific speed is used.

[*A.M.I.E. 1981*]

6.29. (*a*) What are 'hydrographs' and 'flow duration curves, and what are their uses ? Describe unit hydrograph.

(*b*) Name the different types of water turbines and explain the basis of selection of turbines for hydroelectric power stations.

(*c*) The catchment area for the reservior of a hydro-electric power plants is 14 × 10^8 sq m having an average rain-fall per annum of 125 cm 70% of the rain-fall is available for power generation and the mean operating head is 30 metre. Calculate the maximum plant capacity h.p. to be installed. Assume that 5% of the head is lost is penstock, the turbine efficiency is 85%, the generator efficiency is 90% and the annual load factor is 50%. [*A.M.I.E. 1979*]

6.30. Describe a typical layout of a hydro power plant.

6.31. (*a*) How are specific speed, capacity and head related in a turbine. Explain the significance of specific speed in selecting the type of hydroelectric turbine in a hydro-electric power station.

(*b*) It is proposed to develop 2000 h.p. at a size where 150 m of head is available. What type of turbine would be suitable if it had to run at 300 r.p.m. ?

(*c*) Draw a line sketch of a typical high pressure intake head works for a hydro-electric power station. Explain briefly its features. [*A.M.I.E. 1975*]

6.32. Compare a Pelton wheel and Francis turbine.

6.33. (*a*) Define run off. Discuss the factors affecting run-off.

(*b*) Describe the methods to find run-off.

6.34. Write short notes on the following :

(*i*) Flood run-off. (*ii*) Types of catchment areas.

(*iii*) Hydrologic cycle.

6.35. Write short notes on the following :
(*a*) Pondage factor
(*b*) Rain-fall and its measurement.

6.36. Discuss the investigations to be carried out while selecting the site for hydro-power plant.

6.37. Discuss electrical and mechanical equipment of a hydro-power plant.

6.38. Write short notes on the following :
(*a*) Site selection for a dam.
(*b*) Advantages of pumped storage plants.
(*c*) Hydel–Thermal mix.

6.39. The average weekly discharge at the site of a hydel plant is 240 m^3/sec. If the head at the installation is 28 m and the over all efficiency of the hydraulic turbine generator unit is 88% find the maximum average power in MW which can be developed.

6.40. Write short notes on the following :
(*a*) Functions of anchor blocks used for penstocks.
(*b*) Selection of number of penstocks.

6.41. Name the main component parts of a high head hydro-power plant.

6.42. Discuss economic loading of hydro-power plant.

6.43. Write short notes on the following
(*i*) Power house planning (*ii*) Surface power plant
(*iii*) Underground plant.

6.44. Describe the salient features of Nathpa Jhakhri Hydro-power plant.

6.45. Write short notes on the following
(*i*) Run-of-river plant in combination with steam power plant.
(*ii*) Pump storage plant in combination with steam power plant.
(*iii*) Speed and pressure regulation in turbines.

7

Gas Turbine Power Plant

7.0 Introduction

Gas turbine power plant has relatively low cost and can be quickly put into commission. It requires less space. This plant is of smaller capacity and is mainly used for peak load service.

Gas turbine power plants are very promising for regions where liquid or gaseous fuel is available in large quantities. Gas turbine installations require only a fraction of water used by their steam turbine counterparts. Gas turbine has made rapid progress during the past decade due mainly to the large amount of research. The size of gas turbine plants used in a large system varies normally from 10 to 25 MW and the largest size used is about 50 MW. The thermal efficiency of gas turbine plant is about 22% to 25%.

In our country it may be expected that by 1995 installation of medium and large size combined cycle plants (CCP) will pick up and gas turbines will record a faster growth rate. In C.C.P. plants atmospheric pollution by fly ash will be corresponding lower, cooling water requirement will be reduced combined cycle gas based power plants are more economical than coal based power plants as coal transportation was exorbitantly expensive. Moreover the gas based power plant has the shortest gestation period as it could be put on stream in barely two years. In any other system it takes at least five years to commission a project. More gas power plants would ensure utilisation of natural gas.

7.0 (A) : Classification of Gas Turbine Plants

Gas turbine plants may be classified according to the following criteria :

1. *Type of load :*
   (*a*) Peak load plants (*b*) Standby plants
   (*c*) Base load plants.

2. *Application :*
    (*a*) Aircraft (*b*) Locomotive
    (*c*) Marine (*d*) Transport.
3. *Cycle :*
    (*a*) Open cycle plants (*b*) Closed cycle plants.
4. *Number of shafts :*
    (*a*) Single shaft (*b*) Multi-shaft.
5. *Fuel :*
    (*a*) Liquid (*b*) Solid
    (*c*) Gas.

7.1 Elements of a Simple Gas Turbine Plants

A simple gas turbine plant is shown in Fig. 7.1. It consists of compressor combustion chamber and turbine. When the units runs the atmospheric air is drawn into the compressor, raised to static pressure several times that of the atmosphere. The compressed air then flows to the combustion chamber, where the fuel is injected. The produces of combustion, comprising a mixture of gases at high temperature and pressure, are passed through the turbine where they expand and develop motive force for turning the turbine rotor. After expansion the gases leave the turbine at atmospheric pressure. The temperature of the products of combustion is nearly 1000° to 1500°F. The temperature of the exhaust gases is in the range of 900° to 1100°F. The compressor is mounted on the same shaft as that of turbine. Major portion of the work developed in the turbine is used to drive the compressor and the remainder is available as net power output.

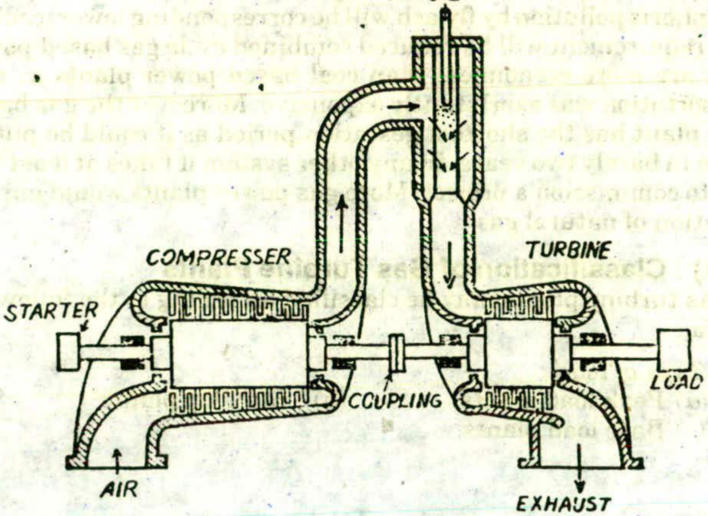


Fig. 7.1

Turbine. Turbine drives the compressor and the load. Both impulse and reaction turbines can be used in gas turbine plants. As compared to steam turbines gas turbines have few stages because they operate on smaller pressure drops.

Axial flow type turbines are commonly used. The various requirements of turbines are as follows :

(*i*) Light Weight
(*ii*) High Efficiency
(*iii*) Reliability in operation
(*iv*) Long working life.

Combustion Chamber. In the combustion chamber, combustion of fuel takes place. The combustion process taking place inside the combustion chamber is quite important because it is in this process that energy, which is later converted into work by the turbine, is supplied. Therefore, the combustion chamber should provide thorough mixing of fuel and air as well as combustion products and air so that complete combustion and uniform temperature distribution in the combustion gases may be achieved. Combustion should take place at high efficiency, because losses incurred in the combustion process have a direct effect on the thermal efficiency of the gas turbine cycle. Further the pressure losses in the combustion chamber should be low and the combustion chamber should provide sufficient volume and length for complete combustion of the fuel.

Initially the temperature developed in combustion chamber is too high. The difficulty is avoided by adding a satisfactory amount of air to maintain stable combustion conditions and then the products of combustion are cooled to a temperature suitable for use in gas turbine by introducing secondary air. The sum of primary and secondary air supplied is total air needed for combustion. Fig. 7.2 shows the combustion chamber. In combustion chamber used for aircraft engines a large quantity of air is used to keep the temperature of combustion chamber to about 650°C. The air fuel ratio may be of the order of 60 : 1 in this case.

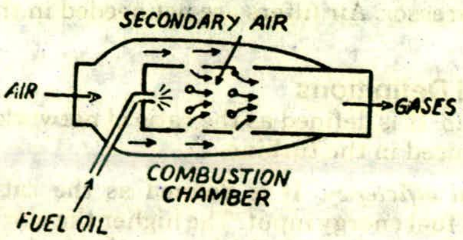


Fig. 7.2

The requirements of a combustion chamber are as follows :

(*i*) Low pressure loss

(*ii*) High combustion efficiency

(*iii*) Good flame stability

(*iv*) Low weight

(*v*) Thorough mixing of cold air and hot products of combustion to generate uniform temperature

(*vi*) Reliability

(*vii*) Low carbon deposit in turbine, and combustion chamber.

Compressor. The various compressors used are reciprocating compressors, centrifugal compressors and axial flow compressor. The reciprocating compressors are not preferred due to the friction in sliding parts, more weight, less speed and inability to handle large volumes of air. For a gas turbine power plant of high output and efficiency generally pressure ratios of 10 : 1 or more is used. It is observed that when a single compressor with a pressure ratio not more than 4 : 1 is required the centrifugal compressor is the most suitable. It is quite rugged in construction, can operate more efficiently over a wide range of mass rate of flow of air than a comparable axial flow compressor. Centrifugal compressor is mainly used in super chargers and in jet aircraft plants, where lowe pressure ratios and small volumes of air is needed.

For higher pressure ratios multi-stage centrifugal compres does not prove to be as useful as an equivalent axial flow compressor. Therefore, when high pressure ratios are needed, axial compressor is advantageous and is always used for industrial gas turbine installations. Further it is desirable that more than one compressor should be used when the pressure ratio exceeds 6 : 1. Although the axial flow compressor is heavier than the centrifugal compressor but it has higher efficiency than the centrifugal compressor.

It is important that air entering the compressor should be free from dust. Therefore, air should be passed through a filter before it enters the compressor. Air filters are not needed in the closed cycle system.

7.2 Terms and Definitions

(*i*) *Work ratio.* It is defined as the ratio of network output to the total work produced in the turbine.

(*ii*) *Thermal efficiency.* It is defined as the ratio of network output the total fuel energy input. The higher the working temperature of the working medium the higher the thermal efficiency of the turbine.

(*iii*) *Air ratio.* It is defined as the amount of air (in pounds or kg) entering the compressor inlet per unit of network output of the turbine.

The size of gas turbine plant is dependent on rate of flow of air in relation to the useful horse power output. Lower the air rate smaller will be the size of plant. Inter cooling and re-heating reduces the air rate. An increase in the compressor and turbine efficiencies will decrease the air rate. An increase in compressor inlet temperature will decrease the net output of the turbine and hence will increase the air rate.

(*iv*) *Pressure ratio.* It is defined as the ratio of absolute pressure at the compressor outlet to the absolute atmospheric pressure at compressor inlet.

(*v*) *Compression efficiency or machine efficiency.* This term is related to the compressor, and is defined as the work required for ideal compression to the actually required by the compressor for a given pressure ratio.

Actual work required by the compressor is always more than the ideal work.

Air rate or Air ratio is a criterion of the size of the plant, *i.e.* the lower the air rate the smaller the plant. From the mechanical and metallurgical point of view the lowering of the air rate results in turbines of smaller physical dimensions with a more a nearly uniform temperature distribution. The work ratio acts as a guide in the determination of the size of gas turbine. If the work ratio is high the variations in the compressor and turbine efficiencies will have less effect on the thermal efficiency of the cycle than if the work ratio is low. A plant with a high work ratio will have higher part load performance efficiency than a plant with a low work ratio.

7.3 Engine Efficiency or Turbine Efficiency

It is defined as the ratio of net output of the turbine to the power that should be ideally produced by the turbine. Network output of the turbine is always less than ideal output.

Ideal conditions mean : (1) that compression and expansion processes are isentropic ; (2) that no losses occur in combustion chambers, heat exchangers, inter-coolers, and pipes connecting the different components ; (3) that heat transfer in heat exchangers is complete, that working fluid behave as perfect gas with constants specific heats ; and (4) rise in temperature on cold side is equal to drop in temperature on hot side.

7.4 Starting of Gas Turbine Power Plant

This plant is not self-starting and for its initial starting the various devices used are as follows :

Electric motor energrised by the batteries for an isolated plant whereas stationary plants may be started by the electric energy supplied by the plant bus bars. Smaller reciprocating internal combustion engines are also used for starting purposes. First of all the internal combustion engine is started by hand cranking and then it is used to start the gas turbine plant.

7.5 Fuels

Various fuels used by gas turbine power plants are liquid fuels gaseous fuels such as natural gas, blast furnace gas, producer gas, coal gas and solid fuels such as pulverised coal. Care should be taken that the oil fuel used should not contain moisture and suspended impurities.

The different types of oils used may be distillate oils and residual oils. The various paraffins used in gas turbine are Methane, Ethane, Propane, Octane (gasoline) and Dodecane (kerosene oil). Out of these gasoline and kerosene or blend of the two are commonly used.

7.5.1 Qualities of Fuel

Some of the important properties to be considered while selecting the fuel for gas turbine are as follows :

1. **Volatility.** The properties has a major effect on starting and combustion efficiency of the engine particularly at low temperature and other adverse conditions. The volatility of the fuel should be such that it is conductive to a quick and successful restart blowout of flame. Highly volative fuels are also not desirable as they have the following disadvantages :

   (*i*) They are more susceptible to fire (although they have less tendency to explode).

   (*ii*) They are conductive to vapour lock and to excessive loss of fuel during flight because of evaporation of certain lighter hydrocarbons. Therefore, in case of aircraft gas turbines in which the quantity of fuel used is sufficiently high, the fuel wastage will also be more if the fuel is highly volatile.

2. **Combustion products.** The products of combustion should not be in the form of solids because they tend to deposit on the combustion chambers, turbine blades and vanes and cause a loss in efficiency.

3. **Energy contents.** Fuel should have greater heating value so that fuel consumption may be less.

4. **Lubricating properties.** The fuel should provide a certain amount of lubrication of friction surfaces of fuel pumps.

5. **Availability.** The fuel selected should be available in large quantities so that it is cheaper.

7.6 Comparison of Kerosene Oil and Gasoline

Kerosene is quite commonly used in aircraft gas turbines. It is not as volatile as gasoline and, therefore, there is less possibility of vapour lock and fuel loss. But its combustion efficiency is low compared to gasoline. The lubrication properties of gasoline are poorer. About 5 to 20% of a barrel of crude may be refined kerosene whereas 40 to 50% of a barrel of crude oil may be refined into gasoline which shows that gasoline can be available in large quantities.

7.7 Air Fuel Ratio

Air fuel ratio in the gas turbines is nearly 60 : 1.

7.8 Gas-Turbine Cycles

The working of gas turbine power plant is mainly based on the two cycles mentioned below :

1. Open Cycle.
2. Closed Cycle.

7.8.1 Open Cycle

A simple open cycle plant is shown in Fig. 7.3. In this case fresh atmospheric air is drawn into by the compressor (*c*) continuously and heat is added by combustion of fuel in the working fluid (air) itself. The products of combustion are expanded through the turbine (*T*) and exhausted to atmosphere. For a given flow of working fluid there is a limit to the amount of fuel which can be burnt in the combustion chamber and the maximum amount of fuel which can be added to combustion chamber is governed by the working temperature of highly stressed turbine blades which should not be allowed to exceed to certain limit. This limiting value of temperature is dependent upon two factors namely creep strength of the material used in the construction of the turbine blades and the working life of the system.

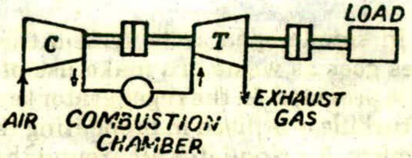


Fig. 7.3

Combustion of fuel takes place either at constant volume or at constant pressure. Theoretically the thermal efficiency of the constant volume cycle is more than the constant pressure cycle. But there are some practical difficulties in the case of constant volume cycle such as valves are necessary to isolate the combustion chambers from the compressor and the turbine. Thus combustion is intermittent and does not allow the smooth running of machine. Due to these defects this cycle has not been widely accepted. In case of constant pressure cycle, combustion is a continuous process and valves are not necessary. This system has proved to be quite satisfactory.

7.8.2 Refinement of Simple Open Cycle

Refinement of open cycle is done by providing regenerator intercooler and reheating combustion chamber (Fig. 7.5 (*a*)).

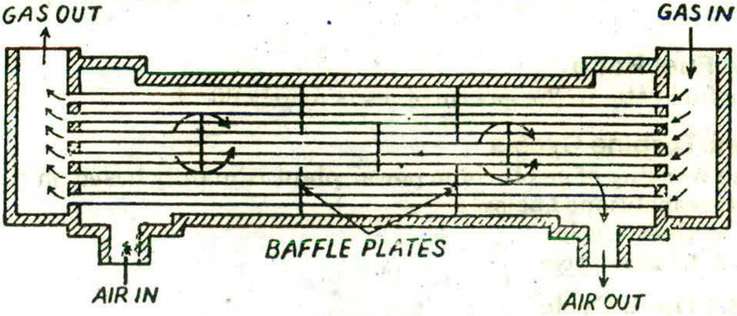


Fig. 7.4

In simple open cycle system the heat of the turbine exhaust gases goes as waste. To make use of this heat a regenerator [Fig. 7.4] is provided. In the regenerator the heat of hot gases coming from the turbine is utilized in preheating the air entering the combustion chamber. Air circulates all around the tubes of regenerator and the exhaust gases pass through the tubes. This arrangement saves some amount of fuel because less heat will be required in combustion chamber (C.C.) and consequently thermal efficiency is improved. However, there will be small reduction in power output because of pressure losses in this working fluid (air) while passing through the regenerator but it is negligible against the improvement in thermal efficiency. For further improvement of the cycle, an intercooler is placed between low pressure compressor and high pressure compressor. In this case the compressor will have to do less work to compress the air (because of reduction in volume). Fig. 7.5 (*b*) shows an intercooler. In the inter-cooler water is passed through the tubes and air circulated all round the tubes. The output can be further improved by providing a reheating combustion chamber between high pressure turbine and low pressure turbine. In reheating combustion chamber fuel is added to reheat the exhaust gases of high pressure turbine to upper temperature limit.

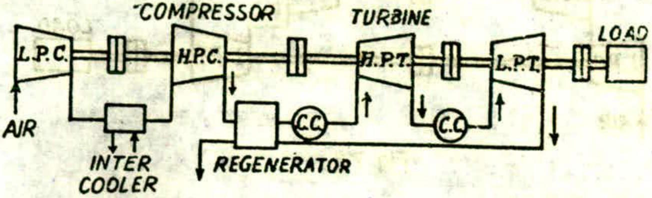


Fig. 7.5 (*a*)

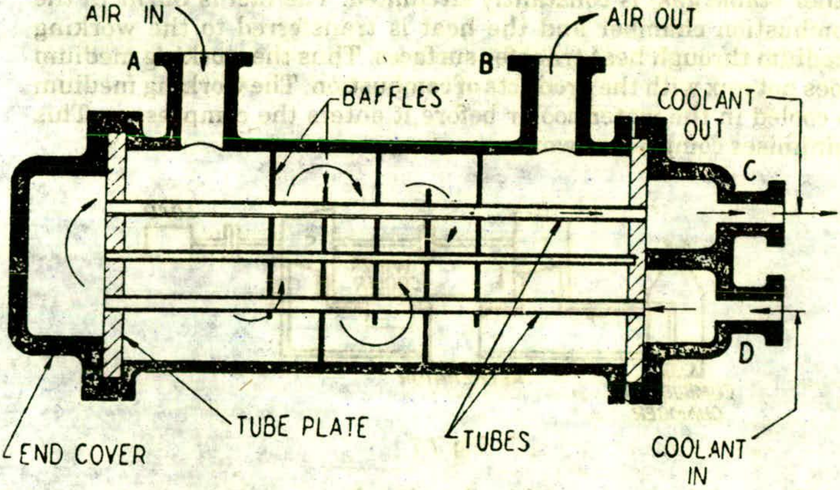


Fig. 7.5 (*b*)

By adding the above refinement equipment, *i.e.* inter-cooler reheating combustion chamber and regenerator, the efficiency of the plant is improved but at the same time the apparatus becomes bulky; and somewhat complicated. These additions raise the efficiency of gas turbine plant to over 30%. The other arrangements used are straight compound units and cross compounded units. In straight compound units (Fig. 7.6) the high pressure compressor (H.P.C.) is driven by the H.P. turbine and low pressure compressor (L.P.C.) is driven by low pressure turbine (L.P.T.). In this system compressors are mechanically independent as, they are driven by separate turbine. In this arrangement the two shafts are capable of adjusting their rotational speeds independent. The turbo-compressor unit may operate at variable speeds while turbo-generator unit can be maintained at constant speed.

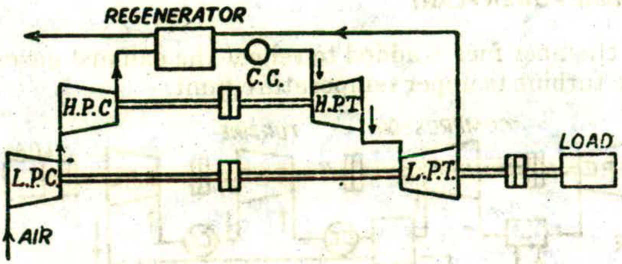


Fig. 7.6

7.8.3 Closed Cycle

In the closed cycle (Fig. 7.7) the same working fluid (air or some other stable gas) is constantly circulated. The fuel is burnt in the combustion chamber and the heat is transferred to the working medium through heat transfer surfaces. Thus the working medium does not mix with the products of combustion. The working medium is cooled in the water cooler before it enters the compressor. This minimises compressor work.

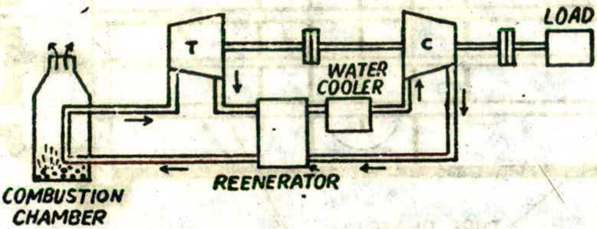


Fig. 7.7

Some of the gases used in closed cycle gas turbine plant are as follows :

(*i*) Helium (He)
(*ii*) Krypton (Kr)
(*iii*) Hydrogen (H_2)
(*iv*) Oxygen (O_2)
(*v*) Nitrogen (N_2)
(*vi*) Carbon-dioxide (CO_2)
(*vii*) Ammonia (NH_3)
(*viii*) Methane (CH_4)
(*ix*) Ethylene (C_2H_4)

7.9 Some Other Possible Arrangements

Some other arrangements of open cycle system are as follows :

(*i*) **Simple Open Cycle—Twin Shaft.** In this arrangement air enters the compressor (*C*) and after being compressed it flows to combustion chamber. The gases then expand in the turbines (*T*). The exhaust of burnt gases takes place in the atmosphere (See Fig. 7.8).

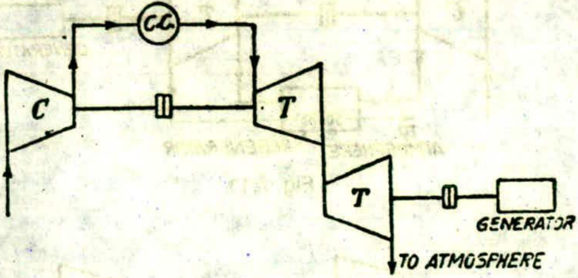


Fig. 7.8

(*ii*) **Inter Single Shaft Open Cycle.** The air from low pressure compressor (L.P.C.) flows to inter-cooler and then to high pressure compressor (H.P.C.). The high pressure compressor delivers the air to combustion chamber (C.C.). The gases then expand in the turbine (Fig. 7.10).

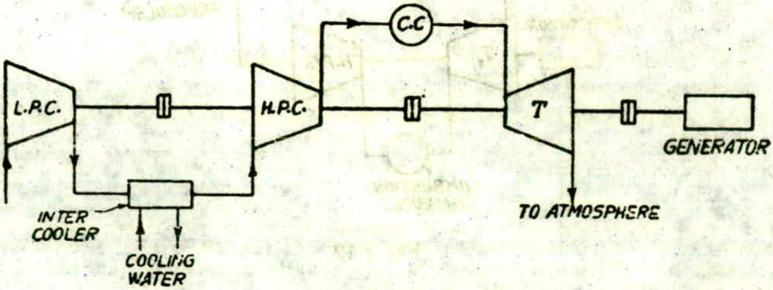


Fig. 7.9

(*iii*) **Reheat Single Shaft Open Cycle.** In this arrangement reheating is achieved by providing a combustion chamber between the two turbines (Fig. 7.10).

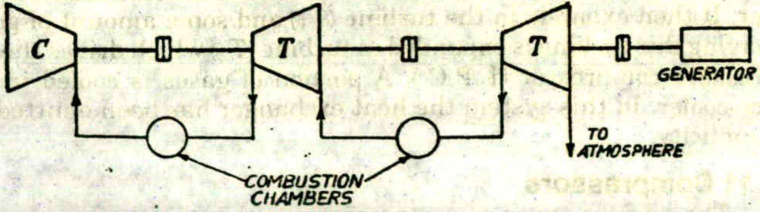


Fig. 7.10

(*iv*) **Regenerative Single Shaft Open Cycle.** In this system the heat of exhaust gases from turbine (*T*) is utilized in heating the compressed air (Fig. 7.11).

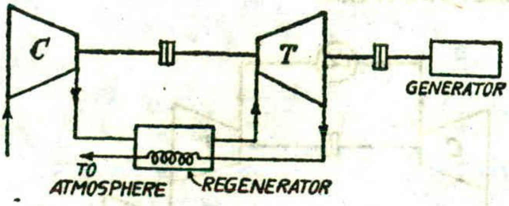


Fig. 7.11

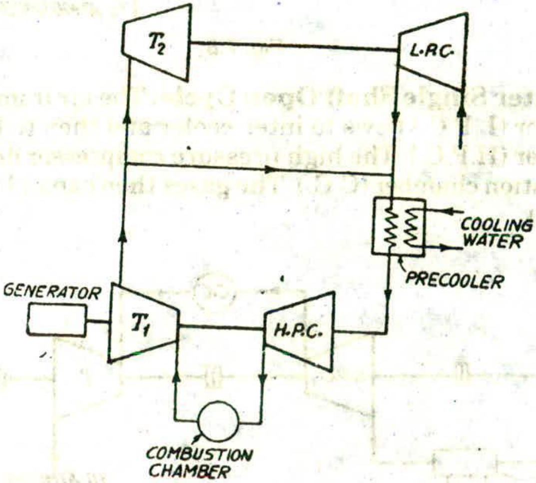


Fig. 7.12

7.10 Semi-closed Cycle Gas Turbine

The system is shown in Fig. 7.12. This system is combination of open cycle and closed cycle. The air enters the low pressure compressor (L.P.C.) and then flows through pre-cooler where its temperature is lowered. Then it is compressed in high pressure compressor (H.P.C.) and after that it is heated in combustion chamber. It then expands in the turbine (T_1) and some amount of gases leaving this turbine is expanded in turbine (T_2) which drives the low pressure compressor (L.P.C.). A portion of gases is cooled in the pre-cooler. In this system the heat exchanger has been omitted for simplicity.

7.11 Compressors

The various tvpes of compressors used in gas turbine are as follows :

1. Centrifugal Compressor. 2. Axial Compressor.

Centrifugal Compressor. It consists of stationary casing and rotating impeller. Impeller is provided with blades. When the impeller rotates the air enters axially and leaves radially. When the impeller rotates the pressure in the region *R* falls and, therefore, the air enter through the eye. The air then flows radially outward through the impeller blades. After that the air flows through the converged passages of diffuser blades and finally the air flows to compressor outlet (Fig. 7.13).

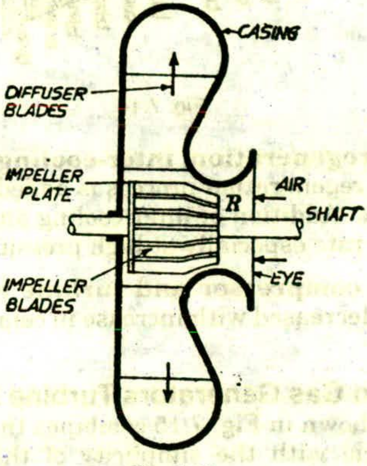


Fig. 7.13

Axial Compressor. This compressor (Fig. 7.14) is quite commonly used in gas turbines. It consists of stator which encloses rotor (*R*). Both stator and rotor are fitted with rings of blades (*RB*—Rotor Blades, *SB*—Stator Blades). In this compressor the air flows in an axial direction from inlet to outlet. Air entering at one end as shown flows through the alternatively arranged rings and gets compressed successively.

7.12 Air Rate

Air rate is the amount of air in kg needed per horse power hour.

7.12.1 Factors affecting air-rate

1. **Effect of turbine inlet temperature and pressure ratio on the air rate.** With increase of turbine inlet temperature the air rate is decreased. As the pressure ratio is increased the air rate firstly decreases to a minimum value and then starts increasing.

2. **Effect of compressor inlet temperature on air rate.** With the increase of compressor inlet temperature the compressor work is increased and the net turbine output is decreased and therefore, air rate is increased.

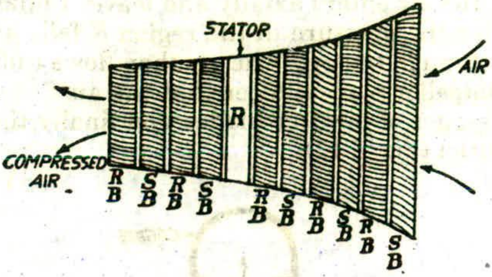


Fig. 7.14

3. **Effect of regeneration, inter-cooling and reheating on air rate.** If only regeneration process is added it increases the air rate to small rate. Addition of inter-cooling and reheating in open cycle reduces air rate especially at high pressure ratios.

4. **Effect of compressor and turbine efficiencies on air rate.** Air rate is decreased with increase in compressor and turbine efficiencies.

7.13 Free Piston Gas Generators Turbine System

The system shown in Fig. 7.15 combines the thermal efficiency of the diesel cycle with the simplicity of the turbine in which expansion of hot gases takes place. The fuel is injected in the centre of diesel cylinder where the combustion of fuel takes place. The expansion of combustion gases forces the pistons and causes out-

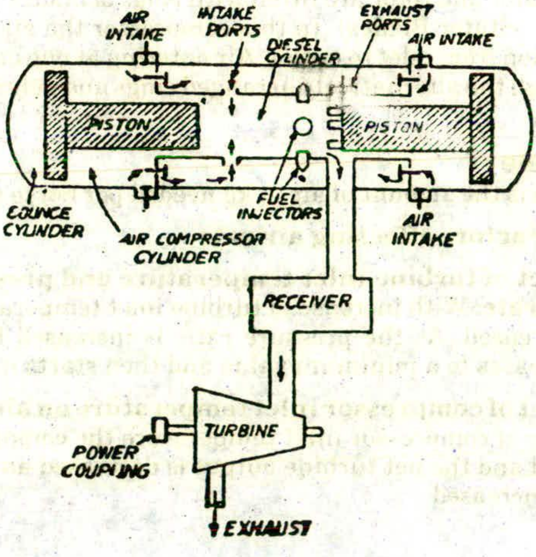


Fig. 7.15

ward moment of pistons. Each piston acts as a single stage air compressor on its inner face and as an air bounce cushion on its outer face. During outward movement of pistons some energy is stored in bounce cylinder. The energy is utilised for causing inward movement of pistons which compress the air in air cylinder and diesel cylinder. Air at a pressure of about 75 to 100 p.s.i., flows from compressor cylinder into central air space and then it enters the diesel cylinder through intake ports. The mixture of air and combustion gases at about a temperature of 1000°F leave through exhaust ports to the turbine where these gases are expanded to atmospheric pressure.

The advantages of the system are :

(*i*) As there are no unbalanced forces and no side forces on cylinder wall, the engine is vibration free.

(*ii*) The system is smaller and lighter than a diesel engine of the same output. Thermal efficiency higher than that of diesel engine and nearly 40% is obtained in this system.

(*iii*) As compared to open cycle gas turbine system the size of this system is about one third the size of open cycle plant.

(*iv*) Air rate is lower in this system.

The main disadvantages of the system are being its difficult starting and control.

7.14 Advantages of Closed Cycle Gas Turbines

The various advantages of closed cycle gas turbines are as follows :

1. As the working fluid does not mix with the products of combustion, therefore, it is possible to use a gas of higher density and higher specific heat than air such as krypton, argon, xenon etc. This will reduce the size of various components. Helium has been successfully used as working medium in closed cycle gas turbines. The specific heat of helium at constant pressure being nearly five times that of the air so heat drop and hence energy dealt per kg of mass flow is about five times in turbines using helium as working medium, as compared to gas turbine using air. Heat exchanger used in gas turbines using helium as working medium has a surface area of about $\frac{1}{3}$ that of heat exchanger used in gas turbines using air as working medium. Therefore, the size of helium unit is comparatively smaller.
2. As the working medium does not mix with the product of combustion so there is no accumulation of carbon deposits on blades and nozzles of the turbine. The compressor remains free of dust as the working medium may be

cleaned. Therefore, the periodic cleaning of components is not needed.

3. The system has improved part load efficiency as the output can be varied by withdrawing or admitting more working medium.
4. External heating can be done by inexpensive solid fuel such as coal.

Disadvantages

1. As the system is under an initial high pressure with a working medium other than air, therefore, the system should be gastight. This increase the cost of the system.
2. A large air heater is needed and this air heater is not as efficient as the combustion chamber used in open cycle.
3. As the system needs cooling water so the system cannot be used in aeronautical engines.

7.15 Advantages of Open Cycle

The advantages of open cycle are as follows :

1. **Simplicity.** The combustion chamber is lighter in weight and smaller in size with a high rate of heat release. Secondly the ignition system is simple only a spark is required for a short period to start the burning after which the combustion continues. The combustion chamber may be designed to burn almost any of the hydrocarbon fuels ranging from gasoline to heavy diesel oil including solid fuels.

2. **Vibrationless.** In this system the moving or rotating parts being the rotor (consisting of turbine and compressor connected by a shaft) and the gear trains that drive the other auxiliaries. There being no unbalanced forces and therefore the engine is vibrationless.

3. **Cooling Water.** Cooling water is not needed except in those turbines using inter-cooler.

4. **Low Weight and Size.** In this cycle the turbine has a lower specific weight and requires lesser space per horse power output (Specific weight is the weight of engine per H.P. output). This property of producing more power output in a small space and low weight is quite useful in aviation engines.

5. **Warm up period.** The warm up period of the engine is negligible because after the engine has been brought up to the speed by starting motor and fuel ignited the engine then can accelerate from a cold start to a full load without warm up time. This property is quite advantageous in marine, aviation etc.

Disadvantages

1. Part load performance is low. This can be improved by using inter-cooler and reheater.
2. Reduction in component efficiencies lowers the thermal efficiency of the cycle.
3. The gas turbine in open cycle requires a large quantity of air.

7.16 Relative Thermal Efficiency at Part Load

The relative thermal efficiency at part loads for various cycles assuming full load thermal efficiency of each cycle is 100% as shown in Fig. 7.16.

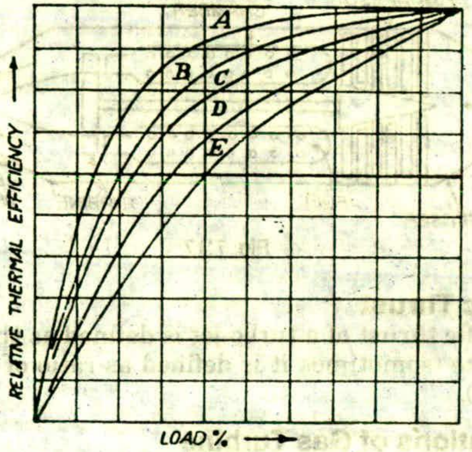


Fig. 7.16

A—closed cycle with regenerator, inter cooler and reheater.

B—open cycle with regenerator, inter-cooler and reheater.

C—open cycle with regenerator (twin shaft system).

D—simple one cycle—twin shaft.

E—simple one cycle—single shaft.

7.17 Jet Propulsion

Gas turbines are quite commonly used for the propulsion of aircrafts. The aircraft units are classified as follows :

1. Turbo-jet unit.
2. Turbo-propeller unit.

Turbo-jet Engine. Its principle is based on open cycle gas turbine. It consists of a diffuser, compressor, combustion chamber, turbine and exit nozzle. The air enters the diffuser at a velocity equal to that of aircraft. The pressure of air rises above atmospheric pressure in the diffuser. The air is then compressed in the compressor to a pressure of about 3.5 kg/cm^2. The compressor used is generally radial or axial type. The air is then supplied to the combustion chamber. The liquid fuel is injected into the combustion chamber where its combustion takes place. The hot gases expand in the turbine. The turbine extracts enough energy to drive the compressor and the necessary auxiliary equipment. The hot gases are then expanded through exit nozzle and they leave the nozzle at high velocity and cause a momentum due to which the engine exerts a forward thrust (Fig. 7.17.).

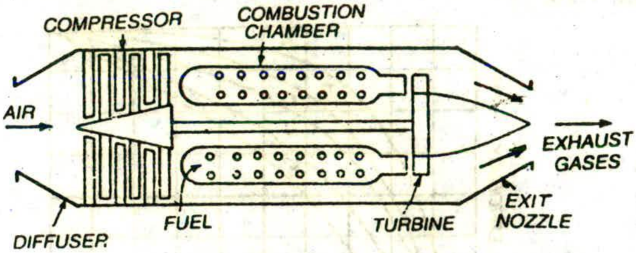


Fig. 7.17

7.18 Specific Thrust

The specific thrust of a turbo-jet is defined as the ratio of force to air flow-rate (sometimes it is defined as ratio of thrust force to fuel flow-rate).

7.19 Applications of Gas Turbine

1. Gas turbine plants are used as standby plants for the hydro-electric power plants.
2. Gas turbine power plants may be used as peak loads plant and standby plants for smaller power units.
3. Gas turbines are used in jet aircrafts and ships. Pulverised fuel fired plants are used in locomotive.

7.20 Advantages of Gas Turbine Power Plant

The economics of power generation by gas turbines is proving to be more attractive, due to low capital cost, and high reliability and flexibility in operation. Quick starting and capability of using wide variety of fuels from natural gas to residual oil or powdered coal are other outstanding features of gas turbine power plants. Major progress has been made in three directions namely increase in unit capacities of gas turbine units (50—100 MW), increase in their efficiency and drop in capital cost (about Rs. 700 per kW installed). Primary application of gas turbine plant is to supply peak load. However gas turbine plants now-a-days are universally used as peak load, base load as well as standby plants.

1. It is smaller in size and weight as compared to an equivalent steam power plant. For smaller capacities the size of the gas turbine power plant is appreciably greater than a high speed diesel engine plant but for larger capacities it is smaller in size than a comparable diesel engine plant. If size and weight are the main consideration such as in ships, aircraft engines and locomotives, gas turbines are more suitable.
2. The initial cost and operating cost of the plant is lower than an equivalent steam power plant. A thermal plant of 250 MW capacity cost about Rs. 250 crores. Presently whereas a gas turbine plant of that same-size cost nearly 70 crores.
3. The plant requires less water as compared to a condensing steam power plant.
4. The plant can be started quickly, and can be put on load in a very short time.
5. There is no standby losses in the gas turbine power plant whereas in steam power plant these losses occur because boiler is kept in operation even when the turbine is not supplying any load.
6. The maintenance of the plant is easier and maintenance cost is low.
7. The lubrication of the plant is easy. In this plant lubrication is needed mainly in compressor, turbine main bearing and bearings of auxiliary equipment.
8. The plant does not require heavy foundations and building.
9. There is great simplification of the plant over a steam plant due to the absence of boilers with their feed water evaporator and condensing system.

Disadvantages

1. Major part of the work developed in the turbine is used to derive the compressor. Therefore, network output of the plant is low.
2. Since the temperature of the products of combustion becomes too high so service conditions become complicated even at moderate pressures.

7.21 Layout

Fig. 7.18 shows the layout of gas turbine power plant. The air filter is used to clean the air. The air leaving the air filter flows to the low pressure compressor. The compressed air then flows through the inter-cooler and then it enters the high pressure compressor. The air leaving the high pressure compressor flows through the heat exchanger and the hot air flows to the combustion chamber. Products of combustion are expanded in the high pressure turbine and then in low pressure turbine.

7.22 Advantages of Gas Turbine Over Steam Turbine

The various advantages of a gas turbine over a steam turbine are as follows :

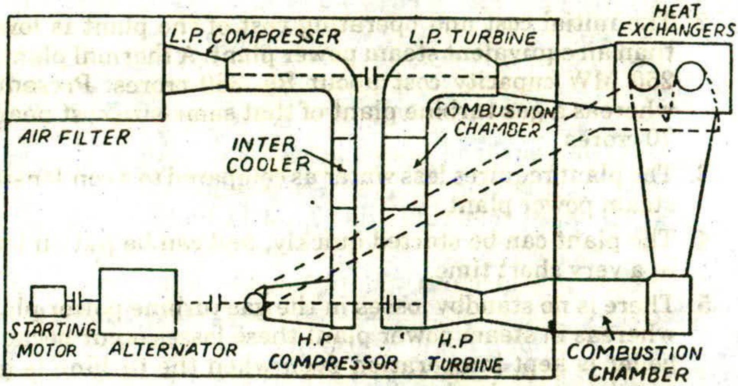


Fig. 7.18

(*i*) Its operation is simple and it can be quickly started

(*ii*) Its initial and maintenance costs are low.

(*iii*) It requires few parts and their design is simple.

(*iv*) It has low weight-power ratio.

(*v*) Its lubrication cost is low.

(*vi*) Maximum operating pressure is about 6 kg/cm^2, therefore the material is not subjected to heavy stresses. However due to high temperature of gases (nearly 900°C) the material used should be able to withstand it.

(*vii*) In gas turbine the inlet temperature is about 800°C whereas it is about 500°C in case of steam turbine. Therefore, thermal efficiency of gas turbine is more than steam turbine other things being equal in both cases.

7.23 Gas Turbine Cycle Efficiency

Gas turbines may operate either on a closed or on an open cycle. The majority of gas turbines currently in use operate on the open cycle in which the working fluid, after completing the cycle is exhausted to the atmosphere. The air fuel ratio used in these gas turbines is approximately 60 : 1.

The ideal cycle for gas turbine is Brayton Cycle or Joule Cycle. This cycle is of the closed type using a perfect gas with constant specific heats as a working fluid. This cycle is a constant pressure cycle and is shown in Fig. 7.19. On *P-V* diagram and in Fig. 7.20 on $T - \phi$ diagram. This cycle consists of the following processes :

The cold air at 3 is fed to the inlet of the compressor where it is compressed along 3—4 and then fed to the combustion chamber where it is heated at constant pressure along 4—1. The hot air enters the turbine at 1 and expands adiabatically along 1—2 and is then cooled at constant pressure along 2—3.

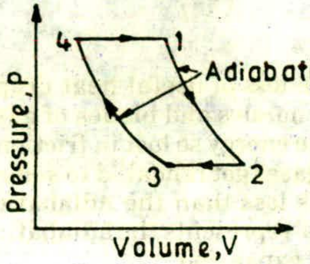


Fig. 7.19

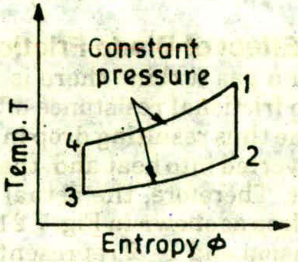


Fig. 7.20

Heat supplied to the system $= K_P (T_1 - T_4)$

Heat rejected from the system $= K_P (T_2 - T_3)$

where K_P = Specific heat at constant pressure,

Work done = Heat supplied – Heat rejected

$$= K_p (T_1 - T_4) - K_p (T_2 - T_3)$$

Thermal efficiency (η) of Brayton Cycle

$$\eta = \frac{\text{Work done}}{\text{Heat Supplied}} = \frac{K_1 \, [(T_1 - T_4) - (T_2 - T_3)]}{K_p (T_1 - T_4)}$$

$$\eta = 1 - \frac{T_2 - T_3}{T_1 - T_4} \qquad \text{...(1)}$$

For expansion 1—2

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{(\gamma - 1)/\gamma}$$

$$T_1 = T_2 \left(\frac{P_1}{P_2}\right)^{(\gamma - 1)/\gamma}$$

For compression 3—4

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{(\gamma - 1)/\gamma} = \left(\frac{P_1}{P_2}\right)^{(\gamma - 1)/\gamma}$$

$$T_4 = T_3 \left(\frac{P_1}{P_2}\right)^{(\gamma - 1)/\gamma}$$

Substituting the values of T_1 and T_4 in equation (1), we get

$$\eta = 1 - \frac{T_2 - T_3}{T_2\left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma} - T_3\left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}}$$

$$= 1 - \frac{T_2 - T_3}{\left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}(T_2 - T_3)} = 1 - \frac{1}{\left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}}$$

7.24 Effect of Blade Friction

In a gas turbine there is always some loss of useful heat drop due to frictional resistance offered by the nozzles and blades of gas turbine thus resulting drop in velocity. The energy so lost in friction is converted into heat and, therefore, the gases get reheated to some extent. Therefore, the actual heat drop is less than the adiabatic heat drop as shown in Fig. 7.21, where 1—2′ represents the adiabatic expansion and 1—2 represents the actual expansion.

Actual heat drop $= K_p\,(T_1 - T_2)$

Adiabatic heat drop $= K_p\,(T_1 - T_2')$

Adiabatic efficiency of turbine

$$= \frac{\text{Actual heat drop}}{\text{Adiabatic heat drop}}$$

$$= \frac{K_p\,(T_1 - T_2)}{K_p\,(T_1 - T'_2)} = \frac{T_1 - T_2}{T_1 - T_2'}$$

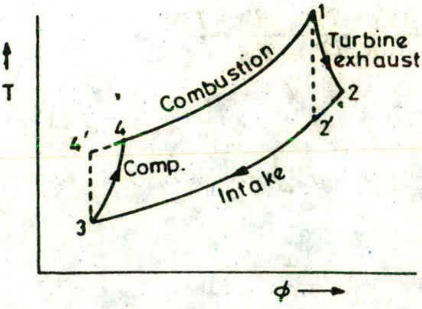


Fig. 7.21

For adiabatic process 1—2′.

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

In the compressor also reheating takes place which causes actual heat increase to be more than adiabatic heat increase. The process 3—4 represents the actual compression while 3—4′ represents adiabatic compression.

Adiabatic heat drop $= K_p\,(T'_4 - T_3)$

Actual heat drop $= K_p\,(T_4 - T_3)$

Adiabatic efficiency of compressor

$$= \frac{K_p (T'_4 - T_3)}{K'_p (T_4 - T_3)} = \frac{T_4 - T_3}{T_4 - T_3}.$$

7.25 Improvement in Open Cycle

The open cycle for gas turbine is shown in Fig. 7.21. The fresh atmospheric is taken in at the point 3 and exhaust of the gases after expansion in turbine takes place at the point 2. An improvement in open cycle performance can be effected by the addition of a heat exchanger which raises the temperature of the compressed air entering the turbine by lowering exhaust gas temperature which is a waste otherwise. Less fuel is now required in the combustion chamber to attain a specified turbine inlet temperature. This is called a regenerative cycle (Fig. 7.22).

This regenerative cycle is shown on $T = \phi$ diagram in Fig. 7.23. where ϕ = entropy.

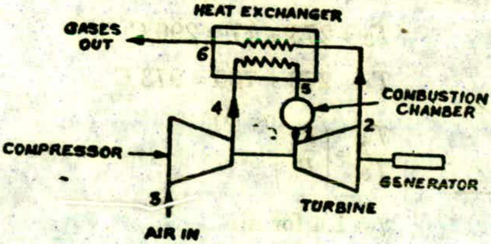


Fig. 7.22

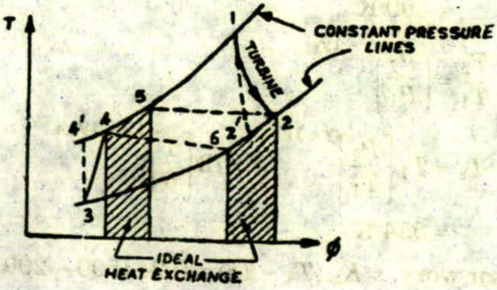


Fig. 7.23

Heat supplied $= K_p (T_1 - T_3) = K_p (T_1 - T_2)$

Heat rejected $= K_p (T_5 - T_3) = K_p (T_4 - T_3)$

(η) Thermal efficiency of theoretical regenerative cycle

$$(\eta) = \frac{K_p\,(T_1 - T_2) - K_p\,(T_4 - T_3)}{K_p\,(T_1 - T_5)}$$

For isentropic compression and isentropic expansion thermal efficiency is given by

$$\eta = \frac{K_p\,(T_2 - T'_2) - K_p\,(T_4 - T_3)}{K_p\,(T_1 - T_5)}$$

Example 7.1. *In a gas turbine power plant working on Joule cycle, air is compressed from 1 kg/cm² and 17°C through a pressure ratio of 6. It is then heated in the combustion chamber to 700°C and expanded back to a pressure of 1 kg/cm². Calculate the following :*

(*a*) *Cycle efficiency*
(*b*) *Work ratio*
(*c*) *Specific work output of the plant.*

Solution. The cycle is shown in Fig. 7.24 on $T = \phi$ diagram

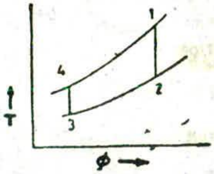


Fig. 7.24

$$T_3 = 273 + 17 = 290^\circ\text{C}$$

$$T_1 = 273 + 700 = 973^\circ\text{C}$$

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{(\gamma - 1)/\gamma}$$

$$\gamma = 1.4 \text{ for air}$$

$$T_4 = T_3\left[\frac{6}{1}\right] = 290\left[\frac{6}{1}\right]^{(14 - 1)/1.4}$$

$$= 500^\circ\text{K}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma - 1)/\gamma}$$

$$T_2 = T_1\left[\frac{P_2}{T_1}\right]^{(\gamma - 1)/1} = 973\left[\frac{1}{6}\right]^{(1.4 - 1)/1.4}$$

$$= 554^\circ\text{K}$$

Compressor work $= K_p\,(T_4 - T_3) = 0.24\,(500 - 290)$

$= 50.4$ kcal

(Assuming $K_p = 0.24$)

Work done by turbine $= K_p\,(T_1 - T_2)$

$= 0.24\,(973 - 554) = 100.56$ kcal

Net work done $= 100.56 - 50.4 = 50.16$ kcal

$$\text{Heat supplied} = K_p (T_1 - T_4) = 0.24\,(973 - 500)$$

$$= 0.24 \times 473 = 113.5 \text{ kcal.}$$

$$\text{Cycle efficiency } (\eta) = \frac{\text{Net work done}}{\text{Heat supplied}} = \frac{0.16}{113.5}$$

$$= 0.44 = 44\%$$

$$\text{Work ratio} = \frac{\text{Net work done}}{\text{Work done by turbine}} = \frac{50.16}{100.56} = 0.49$$

$$\text{Specific work output} = 50.16 \text{ kcal}$$

$$= 50.16 \times 426.94 = 21{,}415 \text{ kgfm/kg.}$$

$$\text{as } (1 \text{ kcal} = 426.94 \text{ kgfm})$$

7.26 Combined Working of Gas Turbine Plant and Steam Power Plant

When a load is to be supplied by both steam power plant and gas turbine power plant then the base load is supplied by steam power plant and peak load is supplied by gas turbine power plant. The size of gas turbine plants used in a large system varies normally from 10 to 25 MW and largest size used is about 50 MW. A gas turbine plant can be started quickly and has a short starting time as compared to steam power plant. Gas turbine plants are particularly useful and economical where cost of gas is not excessive. The capital cost of gas turbine power plants is less as compared to steam power plant of equal size. The fixed charges of gas turbine power plants are also lower than those of steam power plant of same size.

7.27 Gas Turbine Power Plants in India

Gas turbine power plants are quite helpful in meeting the growing power demand of the country with the minimum capital cost.

Some of the gas turbine power plants in our country are as follows :

(*a*) **Gas turbine power plant in Namrup.** This power plant is located at Namrup in Assam. It is of 70 MW capacity.

(*b*) **Uran gas turbine power plant.** This power plant is of 240 MW (60 × 4) capacity and is located at Uran in Maharashtra.

(*c*) **Auraiya Gas power plant.** This is India's largest combined cycle module having 652 MW capacity. It supplies power to the northern grid. It is situated in Uttar Pradesh. It has been constructed by N.T.P.C. India's largest public sector power utility in the field of power generation and transmission. Th Mitshubishi Heavy

Industry of Japan had collaborated with N.T.P.C. in the construction of this prestigious project.

PROBLEMS

7.1. What are the essential components of a simple open cycle gas of turbine plants ? How intercooling and regeneration help in improving thermal efficiency of the plant ?

7.2. Describe a closed cycle gas turbine plant. What are the advantages of closed cycle ?

7.3. What are the advantages and disadvantages of gas turbine power plant ? Discuss the applications of such plant.

7.4. What are the various factors to be considered while selecting the site for gas turbine power plant ?

7.5. Give the layout plan of gas turbine power plant.

7.6. What methods are used to improve the efficiency of gas turbine?

7.7. What are the various compressors used in gas turbine ? State their relative advantages and disadvantages ?

7.8. Explain free piston gas generator turbine system ?

7.9. What are the requirements (Qualities) of fuel used in gas turbines ? Compare kerosene and gasoline as fuels.

7.10. State the principle of jet propulsion. Describe a turbojet engine.

7.11. Write short notes on the following :

(*a*) Pressure ratio
(*b*) Semi-closed cycle
(*c*) Specific thrust of turbo-jet engine.
(*d*) Relative thermal efficiency at part loads of various gas turbine cycles.

7.12. (*a*) Define work ratio.
(*b*) Which is better, a high or low work ratio ? Why ?

7.13. Compare a gas turbine with a steam turbine ?

7.14. Define air rate. Does a low air rate increase or decrease the size of an engine ?

7.15. List the five operating variables that strongly effect the thermal efficiency of an open cycle gas turbine.

Solution. The thermal efficiency of an open cycle gas turbine is heavily dependent upon the following operating variables :

(*i*) Pressure ratio
(*ii*) Turbine efficiency
(*iii*) Turbine inlet temperature
(*iv*) Compressor efficiency
(*v*) Atmospheric or compressor inlet air temperature.

7.16. Discuss combined working of gas turbine plant and steam power plant.

7.17. Describe any two gas turbine power plants in India.

7.18. State the requirements of a combustion chamber for a gas turbine.

7.19. Discuss the factors affecting air-rate in gas turbine.

8

Instrumentation

8.0 Introduction

In every power station different types of instruments are used. They measure pressure, temperature and flow etc. in the plant. The various functions of such instruments can be summarised as follows:

(*i*) They provide guidance to operate the power plant efficiently and economically.

(*ii*) They can be used to check the internal conditions of the equipment and thus provide maintenance guidance.

(*iii*) They enable economical supervision.

(*iv*) They help in plant performance calculations.

(*v*) They help in costs accounting and cost allocations.

8.1 Classification of Instruments

The various type of instruments can be divided into two categories as follows :

(*i*) Electrical Instruments.

(*ii*) Mechanical Instruments.

Electrical Instruments. Electrical instruments include ammeters, voltmeters, wattmeters power factor meters, ground detector and reactive voltampere meters.

Mechanical Instruments. Mechanical instruments used for various purposes are of the following types.

8.2 Measurement of Pressure

Instruments known as gauges are used to measure pressures. The various gauges used are as follows :

(*i*) Barometers

(*ii*) Manometer gauges

(*iii*) Vacuum gauges

(*iv*) Pressure gauges.

A barometer is a device for measuring atmospheric pressure. Manometers are used to measure pressure below or above atmospheric pressure. U-tube manometers used for measuring pressure

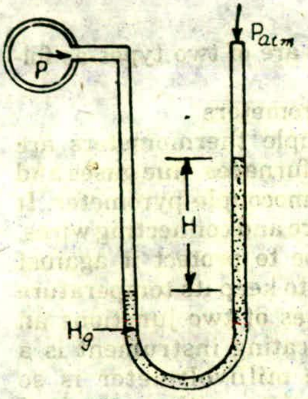


Fig.8.1

above atmospheric pressure are known as manometer gauges. Gauges used to measure pressure less than atmospheric are known as vacuum gauges. Such gauges are used to measure condenser vacuums. Manometers contain fluid such as mercury, water etc. and read pressure in centimeters of mercury and water respectively.

Fig. 8.1 shows a U-tube manometer used for measuring pressure below atmospheric (vacuum). One leg of U-tube is connected to the vessel in which pressure is less than atmospheric, the other leg of the tube is open to atmospheric. In this manometer,

$$H = P_{atm} - P$$

where P_{atm} = atmospheric pressure

p = pressure of gas inside the vessel.

Fig. 8.2 shows a U-tube manometer used to measure pressure above atmospheric pressure. Here

$$H = P - P_{atm}$$

Gauges used for measuring pressure greater than atmospheric pressure are called pressure gauges. Pressure indicated by such gauges is called gauges pressure. Fig. 8.3 shows a Bourdon pressure gauge. The pressure of steam in the boiler is generally measured by this gauge.

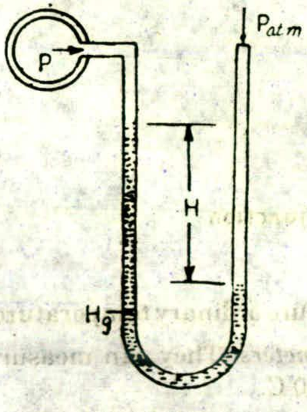


Fig. 8.2

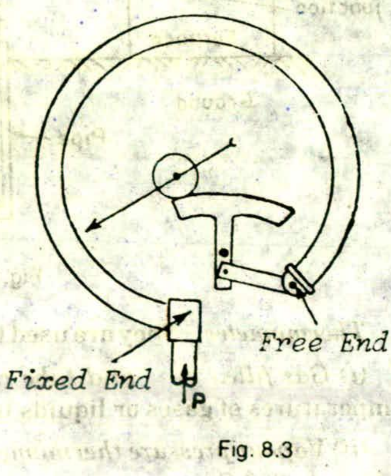


Fig. 8.3

8.3 Temperature Measurements

Temperature measuring instruments are of two types as follows :

(*i*) Thermometers. (*ii*) Pyrometers.

Pyrometers. Pyrometers or thermocouple thermometers are used to measure very high temperatures of furnaces, flue gases and super heated steam. Fig. 8.4 shows a thermocouple pyrometer. It consists of thermocouple, an indicating device and connecting wires. The hot junction is placed in an iron tube to protect it against damage and cold end is buried in ground so to keep its temperature constant. Due to difference in temperatures of two junctions an electromotive force is generated. The indicating instrument is a potentiometer or a millivoltmeter. The millivoltmeter is so calibrated as to read in degrees by comparison with a standard thermometer. This pyrometer can measure temperatures from 300 to 3000°F.

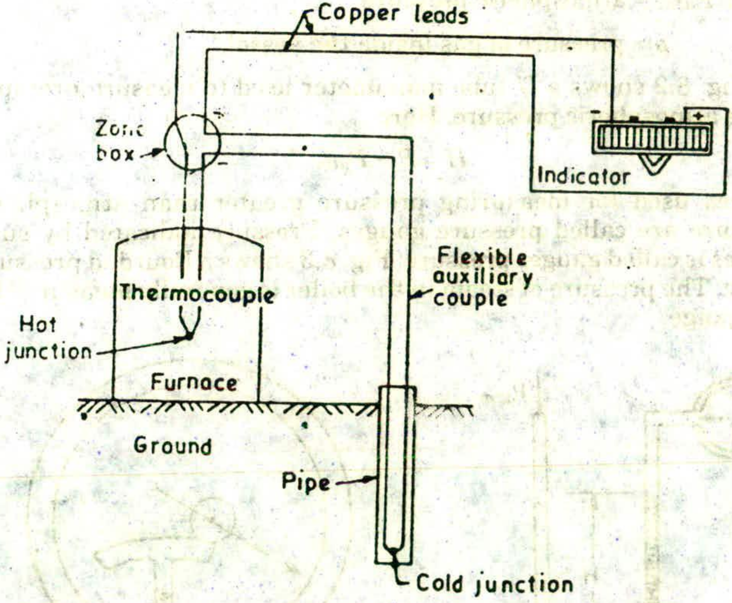


Fig. 8.4

Thermometers. They are used to measure ordinary temperature.

(*i*) *Gas filled [illegible] and tube thermometers.* They can measure temperatures of gases or liquids up to 500°C.

(*ii*) *Vapour pressure thermometers.* They can measure temperature up to 250°C.

(iii) Glass tube mercury thermometers. They are used to measure temperature of feedwater, condensate, circulating water and bearing oil etc.

8.4 Flow Measurement

The various flow meters used measured flow rate are as follows:

(i) Steam flow meters. They are used to measure steam output of boilers and turbine supply etc.

(ii) Water flow meters. These are used to measure feed water condensate and pump discharge.

(iii) Air flow meters. Rate of flow of water is generally measured by a venturi meter. Fig. 8.5 shows a venturi meter, a simple device operating on the Bernoulli's principle. It consists of two tapering lengths of pipe A and B interconected by a cylindrical part C. The diameter of the wide ends is equal to that of the pipe in which the rate of discharge is being measured. On the cylindrical parts piezometric tubes T_1 and T_2 are fixed. As the water flow from end 1 to end 2 a difference between water level (h) in the piezometers is obtained.

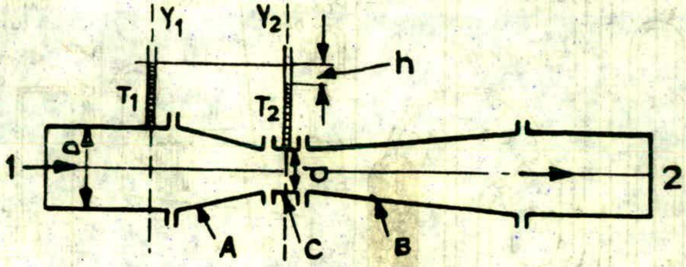


Fig. 8.5 Venturimeter.

The rate of water discharge in the pipe is given by

$$Q = \text{Rate of discharge}$$

$$= C_d A_1 \sqrt{\frac{2gh}{\left(\frac{A_1}{A_2}\right)^2 - 1}} \text{ metre per sec}$$

where C_d = Discharge coefficient

A_1 = Area at section $Y_1Y_2 = \frac{\pi}{4} D^2$

A_2 = Area at section $Y_2Y_2 = \frac{\pi}{4} d^2$

h = Difference between water levels in the piezometers.

8.5 Fuel Measurement

The various instruments needed to measure the quantity of coal, gas and fuel oil consist of belt conveyor, weighers, or coal volume measuring meters, gas meters and oil meters respectively.

8.6 Speed Measurement

Vibrating reed tachometer, stroboscope, clock type tachometer and revolutions counter are various instruments used for measuring speed.

8.7 Level Indicators

They are used to record the level in boilers, tanks etc.

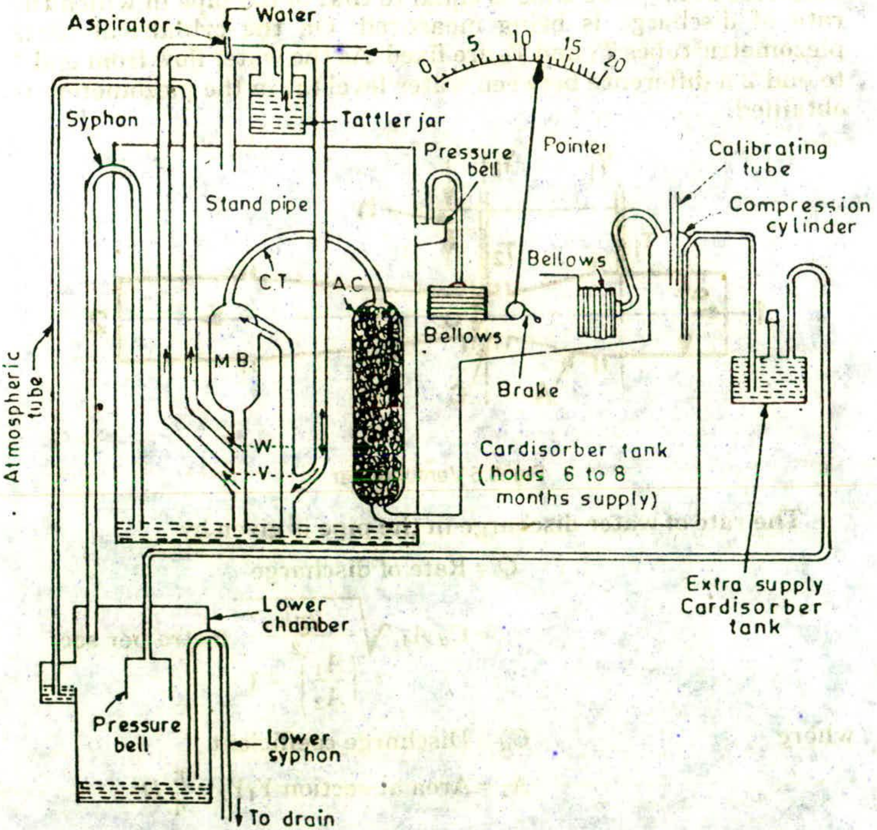


Fig. 8.6

8.8 Gas Analysis

The equipment used for the gas analysis may be Orsat apparatus or CO_2 meters, oxygen meters. Orsat apparatus is used to determine the volumetric analysis of products of combustion.

Fig. 8.6 shows Hay's CO_2 recorder which is used to record only CO_2 in flue gas. Flue gas enters, at regular intervals and CO_2 gets absorbed and its percentage is indicated by the pointer moving across the chart. Water falling from aspirator draws the flue gases from the measuring burette (M.B.) and enters the stand pipe. When the level of water reaches *V*, a sample of gas is trapped. Rising water sends the extra gas to the atmospheric tube. When the water level rises to the point W burette contains an accurate sample of gas at atmospheric pressure. Rising water pushes the gases from burette through the capillary tube (C.T.) into the absorption chamber (A.C.) where it comes in contact with liquid cardisorber. Some of the cardisorber is pushed by the gas which seals the compression chamber of the caustic tank and simultaneously the bellows are operated to move the pointer. Water in stand pipe reaches the top of machine at the end of cycles. The water than starts a syphon which empties the machine of water and a fresh sample of gas is drawn.

8.9 Calorimeters Fuel and Steam Meters

8.9. (*a*) Gong alarms give warning about the higher temperatures of generator or transformer coil of high water in hot well or of low water in boiler feed tank and lubricating oil temperature.

8.9. (*b*) Other instruments used are : indicating, and recording. Indicating instruments provide operating guidance whereas recording instruments help in performing calculations.

8.10 Selection of Instruments

The instruments used should be accessible, accurate and easy to handle. Although size and importance of a power station are the deciding factors in selecting the instruments but it is desirable to use as far as possible minimum number of instruments. This saves money and avoids unnecessary complication of the power stations. As compared to hydro power station and diesel power station, steam power station requires more number of mechanical instruments. The electrical instruments are about the same for all plants of comparable capacity. Some of the essential instruments for a steam power station include pressure gauge, boiler water gauge, a thermometer on the feed water main and on steam line, feed water meter, a vacuum gauge on condenser, lubricating oil thermometer, a feed water meter, a steam flow meter, fuel meter, flue gas thermometer, switch board voltmeter, ammeter and watt hour meter.

8.11 Electrical Instruments

The electrical instruments are used to measure current voltage electric resistance, power and energy.

(*i*) Electric current is measured by ammeters and voltage is measured by voltmeters.

(*ii*) Electrical bridges are used to measure electric resistance.

(*iii*) Wattmeters are used to measure power.

(*iv*) Energy is measured by means of watthour meter.

8.12 Instrumentation and Controls in Steam Power Stations

In a steam power station the major controls provided are as follows :

(*a*) *Boiler Instrumentation* :

(*i*) Combustion control

(*ii*) Feed water control

(*iii*) Steam flow control

(*iv*) Main steam temperature system

(*v*) Furnace safe guard supervisory system

(*vi*) Typical measurement of flue gas analysis, chemical and physical analysis of feed water.

Combustion control regulates the flow of fuel and air so as to generate the required amount of heat in accordance with the steam load. Fuel feeds is controlled by varying the speed of coal feeder and air flow is controlled by positioning the damper in the primary air inlet ducts and inlet vanes of forced draft fans.

Feed water control is used to regulate the flow of feed water to the boiler. The quantity of feed water flowing to the boiler will depend upon the steam requirements. The feed water flow is measured by a nozzle fitted in the feed water discharge pipe.

Flow of the steam through a stationary turbine is usually regulated so as to produce constant rotative speed in the presence of variable load demand. Control is exercised by varying the quantity and pressure of steam flowing through the turbine. The main steam temperature at the super heater outlet is controlled.

(*b*) *Turbine instrumentation* :

(*i*) Turbine supervisory instrumentation

(*ii*) Typical measurement and controls in turbine like condensate level controls. Condensate re-circulation controls, vacuum controls etc.

Modern thermal power stations are becoming of higher capacity and require coordinated master control hand manual facility, surveillance of the control system, redundancy in critical areas, and more exact turning of control loops. In fact there is a trend towards greater automation. Reliability of instrumentation and control in thermal power plants is of vital importance. To ensure that the sophisticated electronic equipment control and instrumentation system works with maximum efficiency it is essential to provide the specified environment such as air conditioning and dust free atmosphere in control room.

Fig. 8.6 (*a*) shows a typical central control room layout. The positioning of the instruments depends on their shape, size and number. It is desirable to group together the various controls in order to have easier regulation and adjustment either automatic or manual.

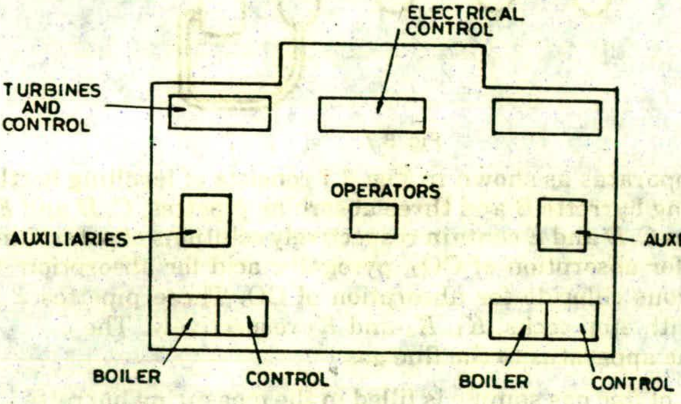


Fig. 8.6 (*a*)

8.13 Instruments and Controls Arrangement

In steam power stations a grouped arrangement of instruments and controls is used. Two systems generally used are as follows :

(*i*) Area system

(*ii*) Centralised system.

In area system all the controls and instrument for boiler and its auxiliaries are placed in one room or area in the boiler room. Similarly all the controls and instruments for the turbine and its auxiliaries are arranged in one room or area in the turbine room and all the controls and instruments for generator and its auxiliaries are arranged one room are area in the switch house. In centralised control system the instruments and controls for all equipment of power station are placed in the same room.

8.14 Orsat Apparatus

This apparatus is used to carry out the analysis of flue gas from boiler. The amount of CO_2, O_2, CO and N_2 present in flue gases can be determined.

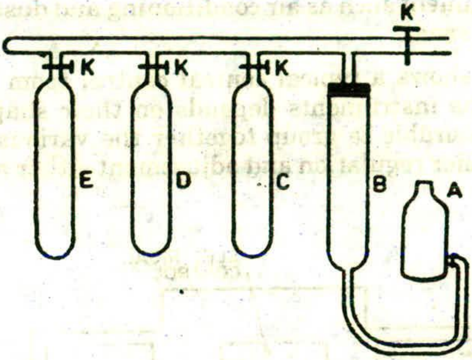


Fig. 8.7

This apparatus as shown in Fig. 8.7 consists of levelling bottle *A*, measuring burrette *B* and three absorbing pipettes, *C*, *D* and *E*. The pipettes *C*, *D* and *E* contain respectively solutions of potassium hydroxide for absorption of CO_2, pyrogallic acid for absorption of O_2 and curous chloride for absorption of CO. These pipettes a provided with stop cocks, K_1, K_2 and K_3 respectively. The c connects the apparatus to the flue gas.

100 c.c. of flue gas sample is filled in the measuring burrette lowering the levelling bottle *A*. The stop cock K_1 is opened and by adjusting the bottle *A* the flue gas sample is transferred to pipette *C* where CO_2 is absorbed. The remaining gas is brought back to measuring burette *B* and volume measured. The difference between original volume (100 c.c.) and this volume is the volume of CO_2. Again flue gas is transferred to pipette *D* where O_2 is absorbed. The remaining gas is brought back to *B* and volume measured. Difference of two volumes is the volume of O_2. Finally gas is transferred to pipette *E* where CO is absorbed. The gas is brought back to measuring burette *B* and volume measured. Difference in volumes is the volume of CO, when percentage of CO_2, O_2 and CO are known, the remainder of the gas is assumed to the nitrogen.

During a test of boiler performance flue gas samples are analysed periodically to find the contents of CO_2, O_2, CO and N_2.

8.15 Oxygen Meter

The presence of dissolved oxygen in feed water for boiler is responsible for the corrosion of boiler tubes and impairs the performance of condenser. The deaerating system is included in the plant to reduce the concentration of oxygen. It is desirable that the value of oxygen should be kept below 0.1 c.c. per litre or a value of 0.007 ppm is considered the limit for a plant operating in the pressure range of 100 to 170 kg/cm^2.

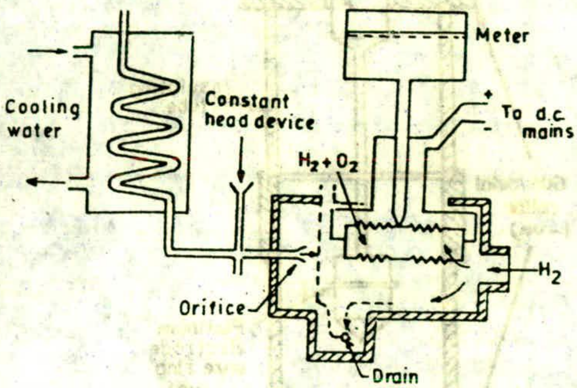


Fig. 8.8

Fig. 8.8 shows a dissolved oxygen meter. In this meter the difference in thermal conductivity of pure hydrogen gas is compared with that of a mixture of hydrogen and oxygen. Hydrogen enters from the right chamber and displaces some of the oxygen in the sampled water. Consequently the required conditions for instrument based on the principle mentioned above are fulfilled.

8.16 Impurity Measuring Instruments

The feed water used in a boiler to generate steam may consist of the following impurities :

(*i*) Calcium sulphate ($CaSO_4$) and other sulphates
(*ii*) Sodium chloride and other chlorides
(*iii*) CO_2 from evaporators
(*iv*) Metallic pieces picked up by steam while passing through pipes
(*v*) Silica from dust etc.
(*vi*) Oxygen from air in condensers etc.

These impurities should be kept to the minimum.

Fig. 8.9 shows dionic water purity meter. The principle used in the meter is that the electrical conductivity of an electrolyte dissolved in water depends on the amount of salt in solution *i.e.* the extent of impurity. The resistance between the opposite faces of a cube of standard water in the instrument is compared with the resistance when the water contains more impurities.

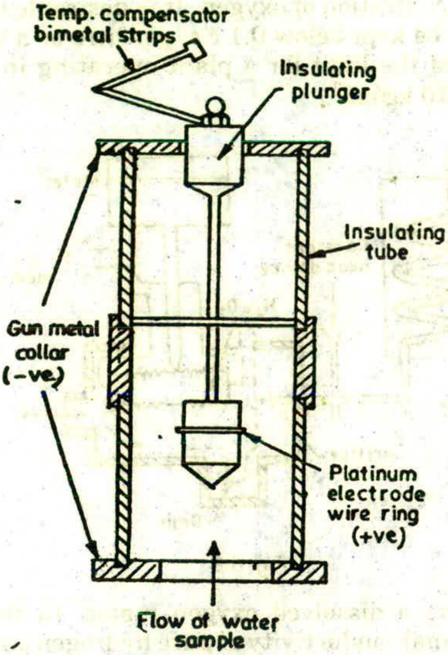


Fig. 8.9

In this meter a sample of water is allowed to flow through it. The automatic correction for temperature variation is effected by the plunger. The insulating plunger varies water cross section automatically by temperature compensator to give correction to 20°C. Conductivity is measured of two water columns in between rings and G.M. coilars. The conductivity per cm^3 indicated is the reciprocal of the resistance measured. The standard of reference is the resistance of one meg-ohm between the opposite face of a cm^3 of solution. The conductivity being the reciprocal of resistance equals one micro mho per cm^3.

Dionic readings of condensate and feed water at various points of flow are brought to one control point, connections to the meter being provided by special piping. This arrangement enables to locate the source of contamination speedily.

8.17 Measurement of Smoke and Dust

The amount of smoke and dust present in the flue gases going out of chimney should not exceed a predetermined level in order to avoid pollution of atmosphere. The main pollutants from the thermal power plants are dust and gases like CO, CO_2, SO_2, NO_2 etc.

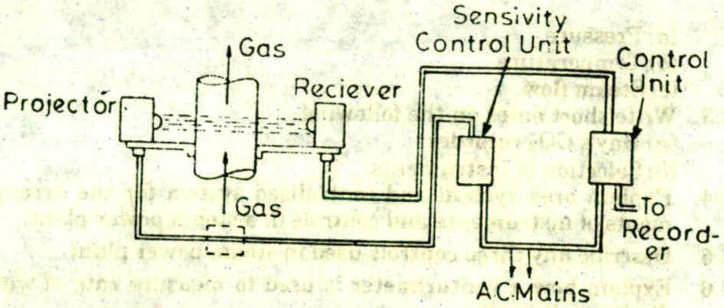


Fig. 8.10

8.17.1 Photo cell-type smoke meters

Fig. 8.10 shows photo cell principle for the smoke density measurement. In this arrangement a focused light beam through the chimney is passed on a photo cell and the variations in the signal of the photo cell circuit are measured. The variation of the obscuration of light source due to the smoke and dust in the gases is measured.

8.17.2 Reflected light dust recorder

In this dust meter shown in Fig. 8.11, the reflected light from he dust particles is measured. Light from the lamp is beamed into ne dust through a suitable opening. Some of this light is reflected ck on the photo cell. The light reflected varies with variation of ıst quantity in the flue gas.

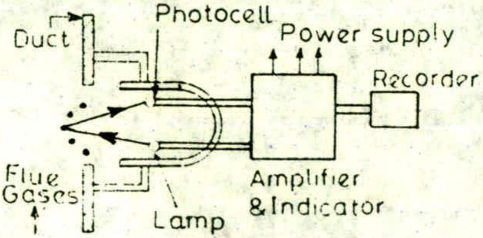


Fig. 8.11

PROBLEMS

8.1. (*a*) What are the functions of instruments in a power station ?

(*b*) Name any five electrical and any five mechanical instruments used in a power station.

8.2. State and explain the instruments used to measure the following:

(*a*) Pressure
(*b*) Temperature
(*c*) Steam flow.

8.3. Write short notes on the following :
(*a*) Hay's CO_2 recorder
(*b*) Selection of instruments.

8.4. Explain area system and centralised system for the arrangements of instruments and controls in a steam power plant.

8.5. Describe any three controls used in steam power plant.

8.6. Explain how a venturimeter is used to measure rate of water discharge in a pipe.

8.7. Describe Orsat apparatus used for flue gas analysis.

8.8. Describe oxygen meter.

8.9. Sketch and describe the feed water impurity measuring instrument.

8.10. Sketch and describe the photo-cell type smoke meter.

8.11. Sketch and describe the reflected light dust recorder.

9

Miscellaneous Problems

9.1 Magneto-hydro Dynamic (MHD) Generator

Principle. The principle of a magneto hydro dynamic (MHD) generator is based on Faraday's law of electromagnetic induction which states that a changing magnetic field induced an electric field in any conductor located in it. This electric field while acting on the free charges in the conductor causes a current to flow. As in case of conventional electric generator conductor crosses the line of the magnetic field and a voltage is induced. Similarly in a magneto hydrodynamic generator when an ionised gas flows across the lines of magnetic field a voltage is induced. The ionised gas acts like an electrical conductor. The gas used may have a temperature between 2000°–3000°K.

M.H.D. generator is a highly efficient heat engine which directly converts thermal energy into electricity. It is the latest technique of advanced method of power generation where efficiency as high as 60% can be achieved as compared to about 35% efficiency of conventional thermal power stations. A M.H.D. generator requires a suitable working fluid which is electrical conducting. The working fluid is a partially ionised gas. The concepts of M.H.D. generation depends much more on the conductivity of the gas. The conductivity of the gas is a function of temperature. Gases become conducting when their atoms of molecules are stripped of one or more electrons thermally, electrically or by using radiations. However to achieve thermal ionization of the products of combustion of fossil fuel or inert gases extremely high temperatures are necessary. Reasonable ionisation and hence reasonable value of electrical conductivity is obtained at temperature around 2000 to 3000°K when the gases are seeded with additives of easily ionising materials (alkali metals). This method of power generation will reduce environmental pollution considerably.

The initial cost of setting up of an M.H.D. power plant is anticipated to be slightly higher than that of conventional thermal power station but this would be offset by factors like higher efficiency and improved cycle of operation.

Working. The various components of MHD generator are shown in Fig. 9.1. The hot ionized gas passes between the poles of an electro-magnet and induces a potential difference between a pair of electrodes which are at right angles of magnetic field and a current starts flowing in the resistive load connected between electrodes. The ionised gas has high temperature and pressure and after passing through MHD generator it is passed through a generator where energy is added to it and it is then recirculated in the MHD generator. This system is simpler and has large power and temperature handling capacity. Having no moving parts it has high-reliability, MHD power plants can operate as base load, peaking or semi peaking units and along with a large load variations without significant loss in efficiency.

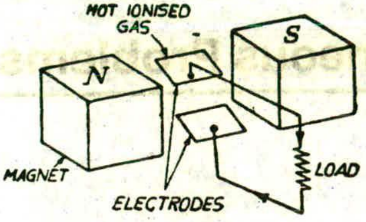


Fig. 9.1

The technology of MHD power generation is poised for a big leap and as a major contender for future power plant schemes. In India the department of science and the technology has sponsored a research and development programme in the field of coal based MHD generator. The programme aims at studying various aspects of MHD with a plasma obtained from coal as fuel. The programme is being carried out by Bhabha Atomic Research Centre in collaboration with Bharat Heavy Electricals Limited.

The Indian MHD programme emphasis on the following :

(*i*) Developing the necessary competence in areas of associated technology which will form the basis of sophisticated and commercially viable equipment for MHD power generation.

(*ii*) Creation of a suitable base of R and D work in the field of MHD power generation, setting up a 5 MW–MHD experimental plant with a provision to increase the thermal rating to 15 MW with suitable modifications and developing scientific data.

(*iii*) Considering the abundance resources of coal and compared to natural gas and oil, the MHD research programme will be based on coal technology. Initial effort in the development of technology will be through coal gasification route, specially because of the considerable experience available in clean fuel MHD generators.

In our country an MHD power plant of thermal capacity 5 MW is being set-up at Tiruchirapally. Later this capacity will be increased to 15 MW. This power plant is expected to be commissioned in 1983.

9.2 Fuel Cell

It is an electrochemical device which converts chemical energy directly in electrical energy. Fig. 9.2 shows hydrogen oxygen fuel cell. This fuel cell uses hydrogen (or hydro-carbon) as a fuel and oxygen (or air) as an oxidiser. There are two chambers. In one chamber hydrogen in introduced and in other chamber oxygen is introduced. The gases are at high pressure.

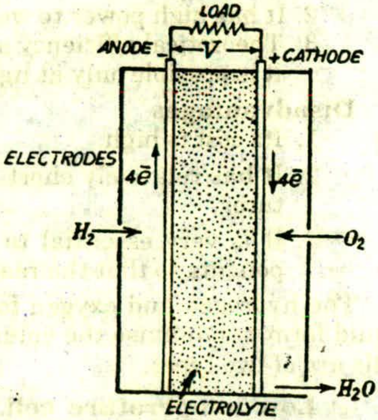


Fig. 9.2

The two chambers are separated by an electrolyte, which may be solid or liquid. The various electrolytes used are Potassium hydroxide. Zirconia oxide porous ceramic and solid Polymers. When the temperature is high the electrolyte material acts as sieve and the hydrogen ions can migrate through the material. The electrical load is connected between anode and cathode. Hydrogen ions are produced by the dissociation of hydrogen molecules at the anode electrolyte interface. The reaction being as follows :

$$2H_2 \rightarrow 4H^+ + 4e^-$$

The electrons so formed return to fuel cell at cathode leaving a positive charge at anode. The hydrogen ions diffuse through electrolyte and when they reach cathode they combine with electrons and oxygen molecules and form water. The reaction being as follows :

$$4H^+ + 4e^- + O_2 \rightarrow 2H_2O$$

In this chemical reaction the energy representing the enthalpy of combustion of fuel is released and a part of it is available for conversion into electrical energy.

At the present time the fuel used in fuel cells is usually either hydrogen or a mixture of gaseous hydrocarbons and hydrogen. The oxidizer is usually oxygen. However, current development is directed toward the production of fuel cells that use hydrocarbon fuels and air. Although the conventional (or nuclear) steam power plant is still used in large-scale power-generating systems, and conventional piston engines and gas turbines are still used in most transportation power systems, the fuel cell may eventually become a serious competitor. The fuel cell is already being used to produce power for space and other special applications.

Advantages -

1. It is simple.
2. It has high power to weight ratio.
3. Theoretical efficiency as high as 90% can be expected but it is possible only at light loads.

Disadvantages

1. Its cost is high.
2. It has relatively short life particularly at high temperatures.
3. It is very essential to select proper materials for components so that the reaction cannot attack them.

The hydrogen and oxygen for operating the cell are stored in liquid form to minimise the volume occupied. The Hydrox (H_2, O_2) cells are of two types.

(*i*) **Low temperature cell.** In this cell the temperature of electrolyte is 90°C. The electrolyte may be pressurised up to four atmospheres.

(*ii*) **High pressure cell.** In this cell the temperature of electrolyte is about 300°C and it is pressurised up to 45 atmospheres.

Depending upon the type of fuel used the fuel cells are classified as follows : (*a*) Hydrogen (H_2) fuel cell ; (*b*) Hydrozine ($N_2 H_4$) fuel cell ; (*c*) Hydrocarbon fuel cell ; (*d*) Alcohol (Methanol) fuel cell.

Fuel cells are particularly suited for low voltage and high current applications.

9.3 The Indian Electricity Act 1910

Some extracts of the Indian Electricity Act are as follows :

Definitions

(*i*) **Area of supply.** It means the area within which alone a licensee is for the time being taken authorised by this licence to supply energy.

(*ii*) **Consumer.** Consumers means any person who is supplied with energy by a licensee or the government or by any other person engaged in the business of supplying energy to the public under this Act or any other law for the time being in force and includes any person whose premises are for the time being connected for the purpose of receiving energy with the works of a licensee, the government or such other person as the case may be.

(*iii*) **Distributing main.** It means the portion of any main with which a service line is or is intended to be immediately connected.

(*iv*) **Electric supply line.** It means a wire, conductor or other means used for conveying, transmitting or distributing energy.

(*v*) **Energy.** Energy means electrical energy : (*a*) generated transmitted, or supplied for any purpose or (*b*) used for any purpose except the transmission of message.

(*vi*) **Licensee.** Licensee means person licensed to supply energy (explained under the heading 'Supply Energy').

(*vii*) **Main.** It is an electric supply line through which energy is or is intended to be supplied to the public.

(*viii*) **Service line.** Service line means any electric supply line through which energy is intended to be supplied.

(*a*) to a single consumer either from a distributing main or immediately from the supplier's premises, or

(*b*) from a distributing main to a group of consumers on the same point of the distributing main.

(*ix*) **Works.** Works include energy supply line and any building plant, machinery, apparatus and any other thing of whatever description required to supply energy to the public and to carry into effect the object of licence or sanction granted under this Act or other law for the time being in force.

Supply of Energy

1. **Grant of Licence.** This State Government may on application made in the prescribed form and on payment of the prescribed fee (if any) grant after consulting the State Electricity Board a licence to any person to supply energy in any specified area and also to lay down or place electric supply lines for the conveyance and transmission of energy :

(*a*) where the energy to be supplied is to be generated outside such area from a generating station situated outside such area to the boundary of such area or

(*b*) where energy is to be conveyed or transmitted from any place in such area to any other place therein across intervening area not included therein across such area.

2. **Revocation or Amendment of Licences.** The State Government may, if in its opinion the public interest so requires, revoke a licence in any of the following cases :

(*i*) where the licensee breaks any of the terms or condition of his licence the breach of which is expressly declared by such licence to render it liable or revocation ;

(*ii*) where the licensee in the opinion of the State Government makes willful and unreasonably prolonged default in doing anything required of him by or under this Act ;

(*iii*) where the licensee fails within the period fixed ;

(*a*) to show to the satisfaction of the State Government that is in a position fully and efficiently to discharge the duties and obligations imposed on him by his licence or

(*b*) to make the deposite or furnish the security required by his licence.

Provision as to the opening and breaking up of stress railways and tramways.

The licensee from time to time but subject always to the terms and conditions of his licence may

(*a*) open and break up the soil and payment of any street, railway or tramway ; (*b*) open and break up any sewer, drain or tunnel in or under any street, railway or tramway ; (*c*) lay down and place electric supply lines and other works ; (*d*) repair alter or remove the same.

Criminal Offences

(*a*) **Theft of energy.** Whoever, dishonestly abstracts consumes or uses any energy shall be deemed to have committed theft within the meaning of Indian Penal Code.

(*b*) **Penalty for maliciously wasting energy or injuring works.** Whoever maliciously causes energy to be wasted or diverted or with intent to cut off the supply of energy cuts or injures or attempts to cut or injure any electric supply line or works shall be punishable with imprisonment for a term which may extend to two years or with fine which may extend to one thousand rupees or with both.

(*c*) **Penalty for interference with meters.** Whoever connects any meter, indicator, or apparatus with any electric supply line through which energy is supplied by a licensee or disconnects the same from any such electric supply line, maliciously injures any meter, indicator or apparatus or wilfully alters the index or any such meter shall be punishable with fine which may extend to five hundred rupees and in the case of continuing offence with a daily fine which may extend to fifty rupees.

(*d*) **Penalty for extinguishing public lamps.** Whoever maliciously extinguishes any public lamp shall be punishable with imprisonment for a term which may extend to six months or with fine which may extend to three hundred rupees or both.

9.4 Indian Electricity Rules, 1956

Some extracts of Indian Electricity Rules are as follows :

Some Important Definitions

(*i*) **Conductor.** Conductor means any wire, cable, bar tube, rail or plate used for conducting energy and so arranged as to be electrically connected to a system.

(*ii*) **Voltage.** Voltage means the difference of electrical potential measured in volts between any two conductors or between any part of either conductor and the earth as measured by a suitable voltmeter.

(*iii*) **Low Voltage.** It means the voltage which does not exceed 250 volts under normal conditions.

(*iv*) **Medium Voltage.** It means the voltage which does not exceed 650 volts under normal conditions.

(*v*) **High voltage.** It means the voltage which does not exceed 33,000 volts under normal conditions.

(*vi*) **Extra-high Voltage.** It means the voltage which exceeds 33,000 volts under normal conditions.

Inspector

Qualifications of Inspector. No person shall be appointed as an inspector unless

(*a*) he possesses a degree or diploma in electrical engineering from a recognised university or college.

(*b*) he has been regularly engaged for a period of at least eight years in the practice of electrical engineering of which not less than two years have been spent in an electrical or mechanical engineering workshop or in generation transmission or distribution of electricity or the administration of the Act and the Rules made thereunder in a position of responsibility.

Inspection

(*i*) Any inspector or any officer appointed to assist an inspector may enter, inspect and examine any place and carry out tests.

(*ii*) Every supplier, consumer, owner and occupier shall afford at all times all reasonable facilities to any such inspector or officer to make such examinations and tests.

(*iii*) An inspector may serve an order upon any supplier, consumer, owner or occupier calling upon him to comply with any specified rule and person so served shall thereupon comply with the order within the period named therein and shall report in writing to the inspector when the order is complied with.

General Safety Precautions

(*i*) All electric supply lines and apparatus shall be sufficient in power and size and shall be of sufficient mechanical strength and shall be constructed, installed, protected worked and maintained in such a manner as to prevent danger.

(*ii*) The consumer shall take precautions for the safe custody of the equipment in his premises belonging to the supplier.

(*iii*) The consumer ensure that the installation under his control is maintained in a safe conditions.

(*iv*) The supplier shall provide suitable cut-out in each conductor of every service line other than an earthed or earthed neutral conductor.

(*v*) Where more than one consumer is supplied through a common service line each consumer shall be provided with an independent cut-out at the point of junction to the common service.

Accessibility of Bare Conductors. Where bare conductors are used in a building the owner of such conductors shall

(*i*) ensure that they are inaccessible ;

(*ii*) provide, in readily accessible position, switches for rendering them dead wherever necessary.

Caution Notice

The owner of every medium, high and extra-high voltage installation shall affix permanently a caution notice on :

(*a*) every motor, generator, transformer and other electrical plant and equipment together with apparatus used for regulating the same ;

(*b*) all supports of high and extra-high voltage overhead lines.

Provision applicable to protective equipment

(*a*) Fire buckets filled with clean, dry sand and ready for immediate-use for extinguishing fire shall be kept in all generating stations, enclosed switch station in convenient situations.

(*b*) First-aid boxes or cupboards shall be provided in every generating station, enclosed sub-section and enclosed switch station so as to be readily accessible.

Sealing of Meter and Cut-outs

(*a*) The supplier may affix one or more seals to any cut-out and any meter and no person other than the supplier shall break any such seal.

(*b*) The consumer shall ensure that no such seals is broken otherwise than by the supplier.

Overhead Lines

(*a*) **Materials and strength.** (*i*) All conductors of overhead lines shall have a breaking strength of not less than 317.5 kg.

(*ii*) Where the voltage is low and span is of less than 15.24 metres and is on the consumer's or owner's permises a conductor having an actual breaking strength of not less than 126.08 kg may be used.

(*b*) **Joints.** Joints between conductors of overhead lines shall be mechanically and electrically secured under the conditions of operation.

(*c*) **Clearance above ground.** No conductor of an over-head lines shall be erected across a steel at a height less tha·

(*i*) for low and medium voltage–5.791 metres ;

(*ii*) for high voltage line–6.096 metres.

Overhead line should not be erected along any street at a height less than.

(*i*) for low medium and high voltage line upto and including 11,000 volts if bare–4.6 metres,

if insulated–4 metres ;

(*ii*) for high voltage lines above 11,000 volts–5.182 metres.

For extra-high voltage lines the clearance above ground shall not be less than 5.182 metres plus 0.305 metres for every 33,000 volts or part thereof by which the voltage of the lines exceeds 33,000 volts.

Penalty for Breaking Seal. The persons breaking the seal shall be punishable with fine which may extend to two hundred rupees.

Payment of Bills

(*i*) Bills should be paid at the licencee's local office within 15 days from the date of their presentation.

(*ii*) Any complaints with regard to the accuracy of the bills shall be made in writing to the licensee and the amounts of such bills shall be paid under protest within the same period of 15 days.

9.5 Energy Cycles

Thermodynamic cycles which are generally used are of two types :

(*i*) Gas power cycles.

These may be classified as follows :

(*a*) Spark ignition (S.I.) cycle.

(*b*) Compression ignition (C.I.) cycle.

(*c*) Gas turbine cycle.

(*ii*) Vapour power cycles.

Various power cycles are as follows :

1. Carnot cycle
2. Rankine cycle
3. Regenerative cycle
4. Reheat cycle
5. Regenerative Reheat cycle
6. Binary Vapour cycle.

9.5.1 Carnot Cycle

This cycle is of great value to heat power theory although it has not been possible to construct a practical plant on this cycle. It has high thermodynamic efficiency.

It is a standard of comparison for all other cycles. The thermal efficiency (η) of Carnot cycle is as follows :

$$\eta = \frac{T_1 - T_2}{T_1}$$

where T_1 = Temperature of heat source

T_2 = Temperature of receiver.

9.5.2 Rankine Cycle

Steam engine and steam turbines in which steam is used as working medium follow Rankine cycle. This cycle can be carried out in four pieces of equipment joint by pipes for conveying working medium as shown in Fig. 9.3. The cycle is represented on Pressure Volume *P-V* and *S-T* diagram as shown in Figs. 9.4 and 9.5 respectively.

Efficiency of Rankine cycle

$$= \frac{H_1 - H_2}{H_1 - H_{w2}}$$

where H_1 = Total heat of steam at entry pressure

H_2 = Total heat of steam at condenser pressure (exhaust pressure)

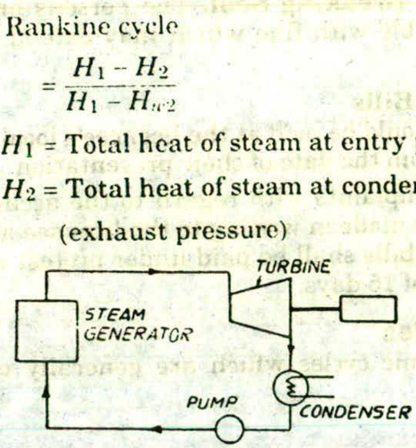


Fig. 9.3

H_{w2} = Total heat of water at exhaust pressure.

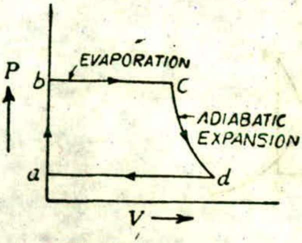


Fig. 9.4

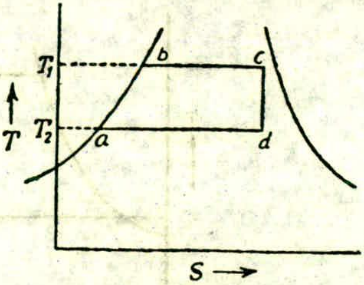


Fig. 9.5

9.5.3 Reheat Cycle

In this cycle steam is extracted from a suitable point in the turbine and reheated generally to the original temperature by flue gases. Reheating is generally used when the pressure is high say above 100 kg/cm^2. The various advantages of reheating are as follows :

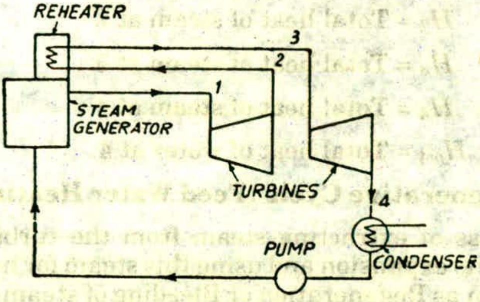


Fig. 9.6

(*i*) It increases dryness fraction of steam at exhaust so that blade erosion due to impact of water particles is reduced.

(*ii*) It increases thermal efficiency.

(*iii*) It increases the work done per kg of steam and this results in reduced size of boiler.

The disadvantages of reheating are as follows :

(*i*) Cost of plant is increased due to the reheater and its long connections.

(*ii*) It increases condenser capacity due to increased dryness fraction.

Fig. 9.6 shows flow diagram of reheat cycle. First turbine is high pressure turbine and second turbine is low pressure (L.P.) turbine.

This cycle is shown on *T-S* (Temperature entropy) diagram (Fig. 9.7).

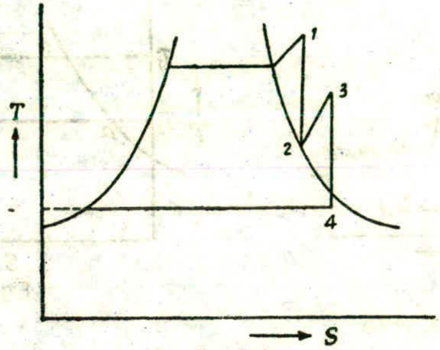


Fig. 9.7

$$\text{Efficiency} = \frac{(H_1 - H_2) + (H_3 - H_4)}{H_1 + (H_3 - H_2) - H_{w4}}$$

where H_1 = Total heat of steam at 1

H_2 = Total heat of steam at 2

H_3 = Total heat of steam at 3

H_4 = Total heat of steam at 4

H_{w4} = Total heat of water at 4.

9.5.4 Regenerative Cycle (Feed Water Heating)

The process of extracting steam from the turbine at certa points during its expansion and using this steam for heating for feed water is known as Regeneration or Bleeding of steam. The arrangement of bleeding the steam at two stages is shown in Fig. 9.8.

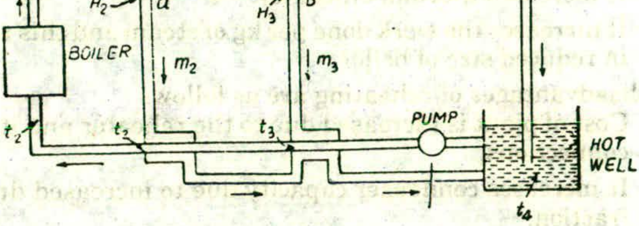


Fig. 9.8

Let m_2 = Weight of bled steam at *a* per kg of feed water heated

m_3 = Weight of bled steam at *b* per kg of feed water heated

H_1, H_{w1} = Enthalpies of steam and water in boiler

H_2, H_3 = Enthalpies of steam at points a and b

t_2, t_3 = Temperatures of steam at points a and b

H_4, H_{w4} = Enthalpy of steam and water exhausted to hot well.

Work done in turbine per kg of feed water between entrance and a

$$= H_1 - H_2$$

Work done between a and b = $(1 - m_2)(H_2 - H_3)$

Work done between b and exhaust

$$= (1 - m_2 - m_3)(H_3 - H_4)$$

Total heat supplied per kg of feed water = $H_1 - H_{w2}$

$\therefore$ Efficiency n

$$= \frac{(H_1 - H_2) + (1 - m_2)(H_2 - H_3) + (1 - m_2 - m_3)(H_3 - H_4)}{(H_1 - H_{w2})}$$

9.5.5 Binary Vapour Cycle

In this cycle two working fluids are used. Fig. 9.9 shows Elements of Binary vapour power plant. The mercury boiler heats the mercury into mercury vapours in a dry and saturated state. These mercury vapours expand in the mercury turbine and then flow through heat exchanger where they transfer the heat to the feed water, convert it into steam. The steam is passed through the steam superheater where the steam is super-heated by the hot flue gases. The steam then expands in the steam turbine.

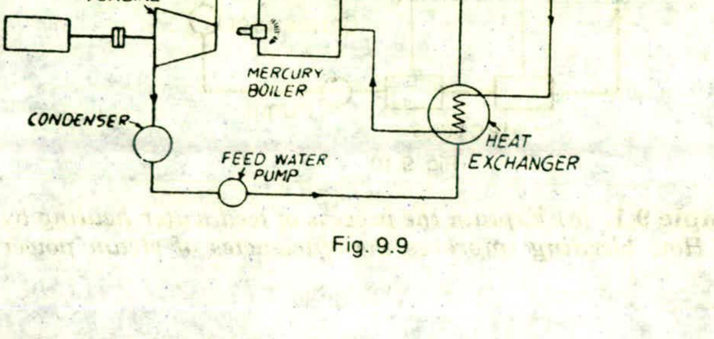


Fig. 9.9

Advantages of Mercury as a vapour cycle fluid

1. It has high density and, therefore, it is easier to separate vapour from liquid in the boiler.
2. It is an element and hence stable.
3. At higher fluid temperature it has moderate vapour pressure.
4. The efficiency of binary vapour plant using mercury is more than steam power plant of same capacity.

Disadvantages

1. In mercury vapour plant there is danger due to poisonous fumes if any leakage of mercury vapour occurs.
2. The investment cost per kW of a binary vapour cycle power plant is more than a steam power plant. Therefore, it is desirable to use binary vapour cycle plant as base load plant because of its higher thermal efficiency to justify the cost.
3. Cost of mercury is high.
4. Mercury has toxic qualities.

9.5.6 Reheat-regenerative cycle

In steam power plants using high steam pressure reheat regenerative cycle is used. The thermal efficiency of this cycle is higher than only reheat or regenerative cycle. Fig. 9.10 shows the flow diagram of reheat regenerative cycle. This cycle is commonly used to produce high pressure steam (90 kg/cm^2) to increase the cycle efficiency.

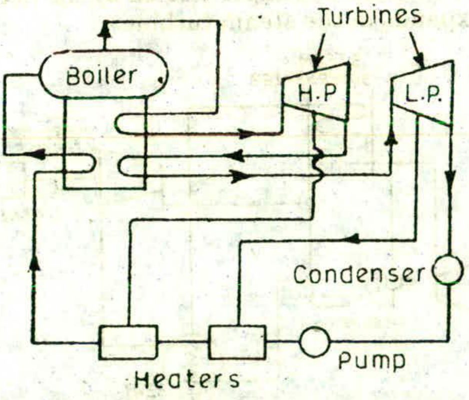


Fig. 9.10

Example 9.1. *(a) Explain the process of feed water heating by bleeding. How bleeding improves the efficiencies of steam power plant ?*

(*b*) *Calculate theoretical thermal efficiency of a plant working between 20 kg/cm^2 (abs.) dry and saturated and 0.08 kg/cm^2.*

(*i*) *Without bleeding.*

(*ii*) *What correct weight of steam is bled at 2.5 kg/cm^2 (abs.)*

Solution. (*i*) From Mollier diagram

Heat drop from 20 kg/cm^2 to 0.08 kg/cm^2

$$H_d = 197 \text{ kcal/kg.}$$

From steam tables

Heat at 20 kg/cm^2, H_1 = 668.7 kcal/kg

Total heat of water at 0.08 kg/cm^2.

$$H_{w3} = 41.1 \text{ kcal/kg.}$$

Therefore, theoretical thermal efficiency

$$= \frac{197}{668.7 - 41.1} = 0.293 \textbf{ Ans.}$$

(*ii*) When steam is bled at 2.5 kg/cm^2
From Mollier diagram

Heat drop from 20 to 2.5 kg/cm^2 = 88 kcal/kg = H_{d1}

Heat drop from 2.5 to 0.08 kg/cm^2

$$H_{d2} = 109 \text{ kcal/kg}$$

Dryness fraction $q_2 = 0.87$

Let m = Weight of bled steam per kg of feed water

$$m\,(H_2 - H_{w3}) = H_{w2} - H_{w3}$$

$$m = \frac{H_{w2} - H_{w3}}{H_2 - H_{w3}}$$

where H_{w2} = Total heat of water at 2.5 kg/cm^2

$= 127.2$ kcal/kg

$H_2 = q_2L_2 + H_{w2}$

(L_2 = Latent heat of steam at 2.5 kg/cm^2)

$= (0.87 \times 522.3 + 127.2)$ kcal/kg

$$m = \frac{127 - 41.1}{0.87 \times 522.3 + 127.2 - 41.1} = 0.16 \text{ kg.}$$

Therefore, weight of steam left in the turbine to expand from 2.5 kg/cm^2 to 0.08 kg/cm^2 is 1 – 0.16 – 0.84 kg.

Work done per kg of feed water

$$= Hd_1 \times 1 + Hd_2 \times 0.84$$

$$= 88 \times 1 + 109 \times 0.84 = 179.56 \text{ kcal.}$$

Heat supplied by fuel

$$= H_1 - H_{w2} = 668.7 - 127.2 = 541.5 \text{ kcal.}$$

∴ Theoretical thermal efficiency

$$= \frac{179.56}{541.5} = 0.351$$

Hence there is an increase in theoretical thermal efficiency due to bleeding.

Example 9.2. *Steam at a pressure of 15 kg/cm² (abs.) and temperature of 250°C is expanded through a turbine to a pressure of 5 kg/cm² (abs.). It is then reheated at constant pressure to a temperature of 200°C after which it completes its expansion through the turbine to an exhaust pressure of 0.1 kg/cm² (abs). Calculate theoretical efficiency.*

(a) *Taking reheating into account.*

(b) *If the steam was expanded direct to exhaust pressure without reheating.*

Solution. (*a*) From Mollier diagram

H_1 = Total heat of steam at 15 kg/cm² and 250°C

$$= 698 \text{ kcal/kg}$$

H_2 = Total heat of stream at 5 kg/cm²

$$= 646 \text{ kcal/kg}$$

Now steam is reheated to 200 C at constant pressure

H_3 = Heat in this stage = 682 kcal/kg

Then steam is expanded to 0.1 kg/cm²

H_4 = Heat at this stage = 553 kcal/kg

H_{w4} = Total heat of water at 0.1 kg/cm²

$$= 45.4 \text{ kcal/kg}$$

Theoretical efficiency

$$= \frac{(H_1 - H_2) + (H_3 - H_4)}{H_1 + (H_3 - H_2) - H_{w4}}$$

$$= \frac{(698 - 646) + (682 - 533)}{698 + (642 - 646) - 45.4}$$

$$= \frac{201}{688.6} = 0.293 \text{ or } 29.3\%. \quad \textbf{Ans.}$$

(*b*) Without reheating

$$\text{Theoretical efficiency} = \frac{H_1 - H_5}{H_1 - H_{w5}}$$

H_5 = Heat of steam at 0.1 kg/cm^2 (From Mollier diagram) if steam was expanded from 25 kg/cm^2 to 0.1 kg/cm^2 (abs)

$= 510$ kcal/kg

H_{w5} = Total heat of water at 0.1 kg/cm^2

$= 45.4$ kcal/kg

Theoretical efficiency

$$= \frac{698 - 510}{698 - 45.4} = 0.282 = 28.2\%. \quad \textbf{Ans.}$$

9.6 Installation of Power Plant

Some of the factors to be considered while installing a power plant are as follows :

(*a*) Selection of plant system,
(*b*) Location of plant,
(*c*) Building layout,
(*d*) Selection of prime mover,
(*e*) Selection of operating conditions
(*f*) Cost,
(*g*) Selection of units.

1. **Selection of Power System.** The type of power plant to be installed depends upon the source of energy. A hydropower plant should be installed where sufficient head of water is available whereas a steam power station is suitable near coal mines. A nuclear plant should be installed near a source of water for example lake, river etc. Diesel plant is preferred for smaller loads. Further choice about the number of generating units should be made. For example if a steam power plant of 200 MW capacity is to be installed then it is to be decided whether a single boiler will be supplying steam to a single steam turbine or there will be two units each of 100 MW capacity or four units of 50 MW each or there can be single boiler supplying steam to four turbines each of 50 MW capacity. Unit system in which a single boiler supplies steam to single turbine as preferable.

The points to be considered while choosing the type of generation are as follows :

(*i*) Type of fuel available
(*ii*) Type of load to be supplied
(*iii*) Reliability of operation
(*iv*) Cost of land
(*v*) Cost of fuel transportation
(*vi*) Availability of cooling water
(*vii*) Cost of power transmission.

2. **Location of Power Plant.** It should be installed near the load centre so that the cost for transmitted power is reduced. It should be nearer to source of fuel and sufficient amount of water should be available near the power station. The soil should be such that special and costly foundation is not required. The plant site should be accessible by road or railway line so that the transportation of equipment is easy.

3. **Building for a Power Plant.** The power plant building should be simple, rugged and should have pleasing appearance. The size, arrangement and shape of power plant depends upon the type of power plant. The roofs are made usually flat. The roof deck can be carried on reinforced concrete slabs and beams. The floors may be made up of concrete or tiles. Concrete floors as preferred. The structure should be fire proof. While laying out the various equipment allowances should be made for sufficient clearance and walkways. Some space should be left for future expansion. The rooms of the building should be spacious, uncrowded, well lighted and clean.

4. **Selection of Prime Mover.** Depending on the load and type of power stations, the selection of steam turbine, hydraulic turbines, boilers, diesel engines, gas turbines should be made. The units installed should have capacity more than the peak load and some provisions should be made for future expected load. For example the peak load of one city is 36 MW. Then two units each of 20 MW or four units each of 10 MW could be used keeping in view the future load.

Heat transfer is the primary function of the boiler. It should be capable of utilising the heat of the combustion of fuel to a great extent. In central power stations water tube boilers are preferred. Coal fired boilers have higher efficiency, than boilers using oil or gas as fuel because hydrogen loss is more in gaseous fuels. Pulverised fuel is preferred in case of low ranking fuels such as lignite etc. The cost of boiler depends upon operating pressure, operating temperature, type of firing and efficiency desired. Higher pressure requires forced circulation. For higher temperature superheaters are needed and, therefore, cost becomes high. The system used for coal firing in the boiler also influences the cost of boiler. Stoker firing is cheaper than pulverised fuel firing. The efficiency of boiler is increased by adding heat recovery equipment such as economisers and air adding heat recovery equipment such as economisers and air preheater. Economiser improve the efficiency of boiler by about 4 to 10% whereas preheater further improves the efficiency by about is 6 to 8%. The temperature of exhaust flue gases should be below than 150 C because otherwise the condensation of moisture may take place and in combustion with sulphur dioxide it (moisture) will produce sulphuric acid dilute solution which is harmful for equipment. In selecting a boiler its fixed cost and operating cost should be considered. The working pressure and capacity of modern boilers are quite high. In modern boilers working pressure has reached up to about 360 kg/cm^2 and evaporative capacity of about 2000 tonnes per hour.

5. **Selection of Operating Conditions.** The power plant should supply the varying power demand. To supply varying power the supply of fuel, air, water, etc. should be varied accordingly. In order to keep the power plant efficient, the older and inefficient units should be replaced by new and efficienct units.

6. **Cost.** The cost of power plants consists of fixed cost, operating cost, depreciation charges etc. Cost of the power station should be kept as low as possible. Some of the factors, which affect the cost are as follows :

(*a*) The cost can be kept low by installing the power station near the load centre.

(*b*) The cost can be reduced by selecting prime movers of proper capacity. The cost of the power station is increased if the prime movers installed are of too high capacity as compared to the maximum expected power demand.

(*c*) As considerable area is required for a power station so the cost of land should be reasonable. As far as possible site sub-soil conditions should be such that piling or blasting is not required and a good foundation can be made at reasonable depth

(*d*) Water should be available in large quantity in case of steam power station, nuclear power station and diesel power station.

7. **Selection of Generating Units.** The generating units should fulfill the following requirements.

(*i*) The number of units selected should not be too many but they should not be less than two. In case two units are selected each should be capable of supplying the maximum load.

(*ii*) The units selected should be capable to supply the maximum load. The future demand extension should be kept in view while deciding the capacity of the units.

(*iii*) A reserve unit should be installed to supply the load if there is a break down of highest capacity.

(*iv*) The units should operate at high load factors and should have high efficiency and their cost should be below.

9.7 Bio-Gas

The most important sources of organic waste for the production of bio gas in India is cow-dung and agricultural wastes. The cow-dung and agricultural waste are used extensively as direct sources of energy in rural areas. The development of the technology for bio-gas production from organic wastes to preserved their manurial value and at the same time to provide the rural area with a substitute source of energy has been recognised. Indian has about 237million cattle population and if the entire dung field from the cattle population is utilized for the bio gas production in an optimum manner, the annual gas availability would be about 66,000 million m^3. Agricultural wastes have the capacity to produce a lot more gas than cow-dung. A kilogram of paddy straw can produce about six cubic feet of a gas as against a kilogram of cow-dung which can produce about 1.3 cubic feed of gas. In a bio-gas plant apart from the gas that is produced, enriched manure is also obtained.

A number of institutions have played a significant role in the development of technology of bio-gas production. The Khadi and village Industries Commission has played a key role in popularising the installation of Gobar Gas plants in the country.

The programme of bio-gas as being implemented now in India is oriented towards establishing mainly small size plants to serve the needs of individual families. To achieve maximum economy as also for accelerating the development of bio-gas potential it is considered that large size of bio-gas plants should be established for serving the whole village community in a village. Some of the institutions carrying out research on bio-gas technology are as follows :

(*a*) Gobar Gas Research centre of Khadi and Village Industries Commission.

(*b*) Indian Agricultural Research Institute, New Delhi.

(*c*) National Environmental Engg. Institute, Nagpur.

One of the main advantages of street lighting or home lighting with bio-gas is that the entire process will be simple with absolutely no recurring expenditure. Also in case of bio-gas system failure the villagers themselves will be able to rectify the fault. Further the same gas that is used for cooking can after a simple process of conversion be used to light a bulb. The maintenance costs on a community type gobar gas plant are easy to bear as it is run by a group of persons.

Gobar gas plants are cheap, simple easy to handle and can be made locally by using indigenous materials. The plant not only produces enough gas for the kitchen and oil engines but also makes available fertilisers to increase food production. Bio-gas plants have proved to be a boon to the farmer because the manure from bio-gas plants is richer in nitrogen content and more in quantity than that obtained by conventional composing. The gobar gas plants also reduce firewood consumption.

At present about 80,000 bio-gas plants are operating in our country as against an estimated potential of about 18 million family size and half million community size plants. In the sixth five year plan about one million bio-gas plants will be installed.

In the gobar gas plant the cow-dung is fermented to yield a combustible gas which can be used for cooking as well as lighting purposes. The residue becomes available for use as manure.

A gobar gas plant consists of two main parts namely digester and gas holder. The digester is a sort of wall, constructed of masonry work below the surface of ground. The gas holder is built with bricks and cement as dome cover of the well of the digester into which a mixture of various organic wastes mostly cow and buffalo dung and water is fed at regular intervals. When the gas is formed by fermentation of cow-dung in the digester it ascends towards the top of dome and pushes the slurry down.

The displaced level of slurry provides necessary pressure for the release of the gas up to the burners of kitchens or other outlets. The manure obtained from bio-gas plants is richer in nitrogen content and more in quantity than obtained by conventional composting.

Bio-gas, a mixture of methane 55-65%, carbon dioxide (CO_2) 30-40% and other impurities is produced during decomposition. The materials for generation of the gas should possess the following characteristics :

(*a*) Proper carbon to nitrogen (C/N) ratio.

(*b*) Appropriate Volatile-solid concentration.

(*c*) Particle size as small as possible.

Material from which bio-gas is produced retains its nutrient value and can be used as fertilizer.

Bio-gas is produced by digestion or hydrogasification process. Digestion is biological process that occurs in the absence of oxygen and in the presence of anaerobic organisms at ambient pressure and temperature 350 C.

Biogas produced by fermentation of organic wastes essentially contains methane and carbon dioxide in large proportion as indicated below :

Composition	*% Volume*
Methane	50—60
Carbon dioxide	30—45
Hydrogen	5—10
Nitrogen	0.5—0.7
Hydrogen, Sulphide and oxygen	Traces

Methane is the only combustible portion the gas. Biogas is a flammable gas. The main products of the bio-gas plant are fuel gas and organic manure.

The gobar gas plant should be near the kitchen, in an open place and away from any wall or tree so as to be under sunshine as much as possible. This will ensure better fermentation and better gas production. This plant helps to keep the environment clean.

In the face of global energy crisis and depleting forest resources in the country bio-gas energy assumes great importance in strengthening rural economy. Today along with other items like food, shelter and clothing energy also forms part of the basic needs of the rural household.

Fuel from gobar gas plant has a very high thermal efficiency of about 60% whereas efficiency of cow-dung is only 11%.

Bio-gas is a flammable gas. The combustible portion is only methane in the gas. One m^3 gas may be thought of equivalent to 0.7 kg of gasoline for power qutput. A bio-gas lamp of a luminosity of about 60 watts equivalent electrical light can be functioning for six to seven hours if one m^3 gas is available. One horse power engine can work for nearly two hours with a m^3 of gas. The gas has a flame temperature of about 500 C.

The major constraints in the wide spread adoption of bio-gas technology are as follows :

(*i*) The high cost of gas plants with the models now in use.

(*ii*) The constant attention required in operation at these plants.

The target of setting up of over half a million bio-gas plants during the Seventh Plan is expected to be exceeded. The rapid progress in the last few years in this direction has been due to the package of measures taken by the Department of Non-conventional Energy Sources (DNES).

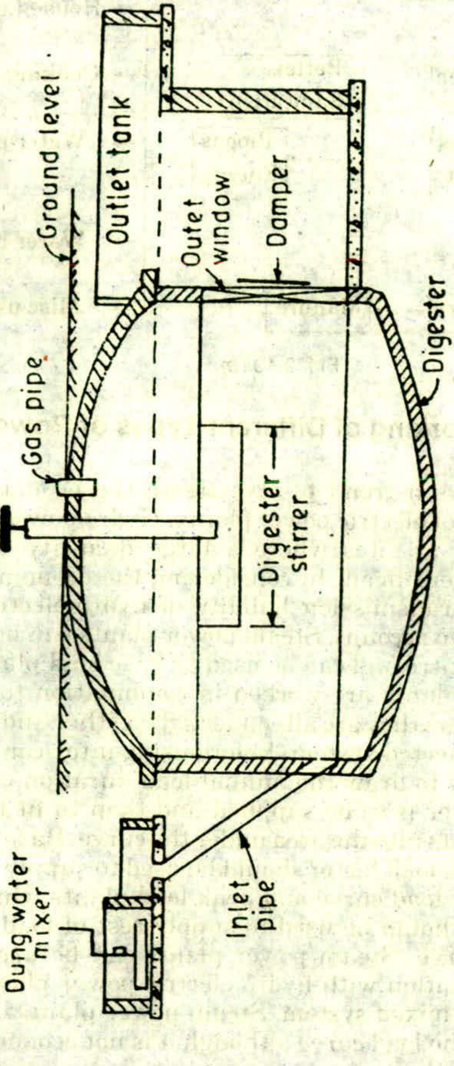


Fig. 9.10 (*a*)

9.7.1 Biogas manure plant

Fig. 9.10 (*a*) shows a precast R.C.C. biogas manure plant. This plant is easy to operate and is simple in construction. The raw material of the material is mixture of dung and water which flows down through the inlet pipe to the bottom of digester. A pipe is provided at the top for flow of gas for usage.

Fig. 9.10 (*b*) shows the flow sheet of a community Bio-gas plant.

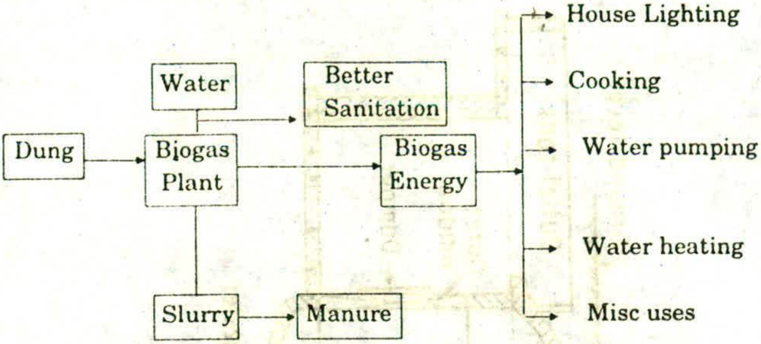


Fig. 9.10 (*b*)

9.8 Combined Working of Different Types of Power Plants

There is always a trend to investigate the economics of the combined working of electric power plants. Hydro power plants can be developed only at sites where a large quantity of water is available at sufficient head. In considering the economy of power development the transmission liability of hydro-electric projects should be taken into account. Steam power plants can be located at or near the load centre and can be used as base load plant. When a number of power plants are worked in combination to supply an electric power system they are all connected together and the system is called inter-connected system. Before using inter-connected system it is necessary to draw the annual load duration curve of the area to which power is to be supplied and then to fit the various types of power plants into the area under the curve. Base load plants which run at a high load factor should be used to supply the load on the base portion of load curve and peak load plants which work at a low load factor should be used to supply rest of load on the top portion of load curve. Steam power plants can be used with advantage in combination with hydro electric power plant to obtain economy from the mixed system. Steam power plants can be used on any portion of the load curve although it is not economical to use them as peak load plants.

In combined working of hydro power plant and nuclear power plant the nuclear power plant should be used as base load plant and hydropower plant can supply the variable load. Gas turbine plants are the cheaper type in some situations when they are used as peak load plants in combination with base load plants.

During combined working of hydro power plant and steam power plant the hydro power plant with ample water storage should be used as base load plant and steam power plant should be used as peak load power plant. If the amount of water available is less at hydro plant then the steam power plant should supply the base load and hydro-plant should act as peak load again. Diesel power plants are generally used as peak load plants.

When pumped storage plant is used in combination with steam power plant then pumped storage plant is used to supply sudden peak loads of short duration. The advantages of pump storage plant in an inter connected system are as follows :

- (*a*) It stores the energy using off peak energy of thermal plant and the same is supplied during demand.
- (*b*) It minimises wastage of off-peak energy of steam power plant.
- (*c*) Use of pumped storage plant helps in loading economically the steam power plant. During coordination of hydro power plant and gas turbine power plant the gas turbine power plant is used peak load plant. The high working cost of gas turbine plant is compensated by lower fixed cost and lower operating and maintenance cost.

Inter connected power system can provide large savings both in capacity and fuel cost at the same time ensuring reliability and continuity of power supply. The main purpose of inter-connection is to distribute the load among the interconnected power plants system in order to achieve the overall economy.

The various advantages of combined working of different types of power plants are as follows :

- (*a*) There is a reliability of power supply to consumers because in the event of power failure at one of the power plants the system can be fed from other powers plant to avoid complete shut down.
- (*b*) The spinning reserve required in a power system is reduced.
- (*c*) Combined working of different types of power plants reduces the amount of generating capacity required to be installed as compared to that which would be required without inter-connection.
- (*d*) The inter-connection of various power plants helps in reducing the amount of generating capacity to be installed.
- (*e*) In an inter-connected system the overall cost of energy is less.

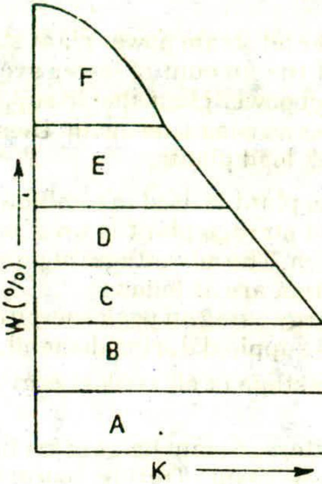


Fig. 9.11

Fig. 9.11 shows a typical annual load duration curve between percentage of year (K) and load (W). The various loads which should be supplied by different power plants are indicated in Table 9.1.

Table 9.1

Load	*Power plant*
A	Run off river plant
B	Nuclear power plant
C	Hydro power plant with sufficient storage
D	Steam power plant
E	Hydro power plant with limited storage
F	Diesel power plant or Gas turbine power plant

Following factors should be considered while deciding the load to be shared among different types of power plants :

(*i*) Capacity of power plant
(*ii*) Degree of reliability
(*iii*) Probable load factor
(*iv*) Cost of fuel and transport facilities
(*v*) Initial cost and operating cost
(*vi*) Load between different power plants should be so decided that overall economy is achieved.
(*vii*) Time required to start the plant from cold condition.

9.9 Economy of Operation

The factors directly affecting the economy of operation of various power plants are as follows :

- (*i*) Cost of generating units
- (*ii*) Normal and emergency equipment ratings
- (*iii*) Fuel cost
- (*iv*) Labour cost
- (*v*) Reserve requirements
- (*vi*) Voltage limitations
- (*vii*) Characteristics of prime movers
- (*viii*) Transmission losses.

9.10 Efficiency of Power Plants

The efficiency of a power plant depends on load and time period. Fig. 9.12 shows the efficiency of various power plants with respect to load. The increase in efficiency of hydro power plants is higher as compared to other power plants at high load.

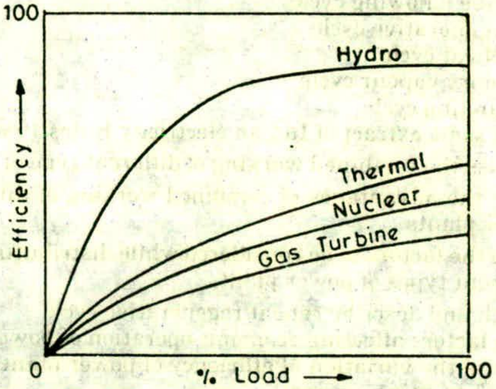


Fig. 9.12

The efficiency of power plants is reduced with increase in time period. Fig. 9.13 shows effect of time period in years on efficiency of power plants.

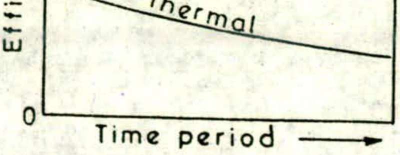


Fig. 9.13

PROBLEMS

9.1. (*a*) What is M.H.D. generator?
(*b*) Discuss the working principle of an M.H.D. generator.
(*c*) State the advantages of M.H.D. power generator.

9.2. Write short notes on the following:
(*a*) Fuel cell
(*b*) Bio-gas
(*c*) Carnot cycle.

9.3. Describe the factors to be considered while installing a power plant.

9.4. A steam power plant uses dry steam at a pressure of 38.7 kg/cm^2 absolute and exhausts it at 0.06 kg/cm^2. If the plant works on perfect regeneration cycle determine work done per kg of steam. Calculate also the ideal efficiency of the cycle.

9.5. Describe following cycle:
(*a*) Regenerative cycle
(*b*) Reheat cycle
(*c*) Binary vapour cycle
(*d*) Ranking cycle.

9.6. State some extract of Indian electricity Rules 1956.

9.7. Discuss the combined working of different type of power plants.

9.8. State the advantages of combined working of different type of power plants.

9.9. State the factors to be considered while distributing load among different types of power plants.

9.10. Sketch and describe reheat regenerative cycle.

9.11. State factors affecting economic operation of power plants

9.12. Discuss the variation of efficiency of power plants with respect to load and time period.