16. (*a*) Draw a neat diagram of nuclear reactor and explain the function of its various components.

(*b*) Explain with a neat sketch the principle of working of magneto-hydrodynamic system of power generation. State the difficulties encountered in its design.

17. (*a*) What do you understand by a close cycle gas turbine power plant ? List out its advantages over open cycle plant. What difficulties are there in development of close cycle plants ?

(*b*) Following observations were made during a test on an open cycle constant pressure gas turbine plant :

Inlet temperature = 27°C
Maximum temperature in the cycle = 800°C
Pressure ratio = 6
Isentropic efficiency of compressor = 85%
Isentropic efficiency of turbine = 90%
Combustion efficiency = 95%
Mass flow of air = 100 kg/sec
Specific heat of air = 0.24
Specific heat of gases = 0.26
Specific heat ratio for air and gases = 1.4
Calorific value of fuel = 10,500 kcal/kg

Find : (*i*) Thermal efficiency of the plant : (*ii*) Power developed ; (*iii*) Air fuel ratio ; (*iv*) Specific fuel consumption.

18. (*a*) Describe the functions of the major components used in gas turbine plant.

(*b*) What are the factors to be considered in designing steam piping in thermal plant ? What are the materials used for (*i*) steam piping, and (*ii*) its thermal insulation ?

19. (*a*) What are the advantages of gas turbine plant over other thermal power plants ?

(*b*) Describe briefly the working of closed cycle gas turbine plant with the help of *T-s* diagram.

(*c*) In a closed cycle gas turbine the following data were applied :

Working substance is air with $c_p = 0.24$ and $\gamma = 1.4$
Ambient temperature = 27°C
Maximum temperature = 823°C
Pressure at compressor inlet = 1 kgf/cm^2
Pressure ratio = 4
Compressor efficiency = 80%
Gas turbine efficiency = 85%

Determine the thermal efficiency of gas turbine.

20. In a 5 MW gas turbine generating set, HP turbine is used to drive the compressor unit and LP turbine, mounted on separate shaft, drives the alternator. After two-stage compression having overall pressure ratio of 9 with perfect intercooling, the compressed air is supplied to the combustion chamber *via* a regenerator which receives the exhaust from the LP turbine. The temperature of the gases at entry to the HP turbine is 727°C and the gases are reheated to 727°C again before entering the LP turbine. Draw the schematic diagram of the plant and *T-s* diagram. Considering open cycle, calculate (*i*) overall thermal efficiency of the plant and (*ii*) the mass flow rate of air in kg/sec.

Assume the following :

Air inlet pressure and temperature 1 kg/cm^2 and 27°C respectively
Isentropic efficiency of compressor in each stage = 0.8
Isentropic efficiency of expansion in each unit = 0.85
Mechanical efficiency of both the turbines = 0.98
Thermal ratio of the regenerator = 0.75
Combustion efficiency = 0.97
$c_{p\,\text{air}} = 0.24$: $c_{p\,\text{gas}} = 0.25$; $\gamma_{\text{air}} = 1.4$; $\gamma_{\text{gas}} = 1.33$.

Neglect mass of fuel and consider the specific heat values to be constant over the pressure and temperature range.

6

Hydro-Electric Power Plant

6.1. Introduction. 6.2. Application of hydro-electric plants. 6.3. Advantages and disadvantages of hydro-electric plants. 6.4. Selection of site for a hydro-electric plant. 6.5. Essential features/elements of hydro-electric power plant—Catchment area—Reservoir—Dam—Spillways—Conduits—Surge tanks—Primemovers—Draft tubes—Power house and equipment. 6.6. Classification of hydro-electric power plants—High head power plants—Medium head power plants—Low head power plants—Base load plants—Peak load plants—Run-of-river plants without pondage—Run-of-river plant with pondage—Storage type plants—Pumped storage plants—Mini and microhydel plants. 6.7. Hydraulic turbines—Classification of hydraulic turbines— Description of various types of turbines—Specific speed of a turbine—Efficiencies of a turbine—Cavitation—Performance of hydraulic turbines—Governing of hydraulic turbines—Selection of turbines. 6.8. Plant layout. 6.9. Hydro-plant auxiliaries. 6.10. Cost of hydro-plant. 6.11. Average life of hydro-plant-components. 6.12. Hydro-plant controls. 6.13. Electrical and mechanical equipment in a hydro-plant. 6.14. Combined hydro and steam power plants. 6.15. Comparison of hydro-power stations with thermal power stations. 6.16. Underground hydro-plants. 6.17. Automatic and remote control of hydro-station. 6.18. Safety measures in hydro-electric power plants. 6.19. Preventive maintenance of hydro-plant. 6.20. Calculation of available hydro-power. 6.21. Cost of hydro-power. 6.22. Hydrology—Introduction—The hydrologic cycle—Measurement of run off—Hydrograph—Flow duration curve—Mass curve—6.23. Hydro power development in India. Worked Examples—Highlights—Theoretical Questions—Unsolved Examples—Competitive Examinations Questions.

6.1. INTRODUCTION

In hydro-electric plants energy of water is utilised to move the turbines which in turn run the electric generators. The energy of water utilised for power generation may be kinetic or potential. The *kinetic energy* of water is its energy in motion and is a function of mass and velocity, while the *potential energy* is a function of the difference in level/head of water between two points. In either case continuous availability of a water is a basic necessity ; to ensure this, water collected in natural lakes and reservoirs at high altitudes may be utilised or water may be artificially stored by constructing dams across flowing streams. The ideal site is one in which a good system of natural lakes with substantial catchment area, exists at a high altitude. *Rainfall is the primary source of water* and depends upon such factors as temperature, humidity, cloudiness, wind etc. The usefulness of rainfall for power purposes further depends upon several complex factors which include its intensity, time distribution, topography of land etc. However it has been observed that only a small part of the rainfall can actually be utilised for power generation. A significant part is accounted for by *direct evaporation,* while another similar quantity *seeps* into the soil and forms the underground storage. Some water is also absorbed by vegetation. Thus, only a part of water falling as rain actually flows over the ground surface as direct run off and forms the streams which can be utilised for hydro-schemes.

First hydro-electric station was probably started in America in 1882 and thereafter development took place very rapidly. In India the first major hydro-electric development of 4.5 MW capacity named as Sivasamudram Scheme in Mysore was commissioned in 1902. In 1914 a hydro-power plant named Khopoli project of 50 MW capacity was commissioned in Maharashtra. The hydro-power capacity, upto 1947, was nearly 500 MW.

Hydro (water) power is a conventional renewable source of energy which is clean, free from pollution and generally has a good environmental effect. However the following factors are major obstacles in the utilisation of hydro-power resources :

(*i*) Large investments (*ii*) Long gestation period

(*iii*) Increased cost of power transmission.

Next to thermal power, hydro-power is important in regard to power generation. The hydro-electric power plants provide 30 per cent of the total power of the world. The total hydro-potential of the world is about 5000 GW. In some countries (like Norway) almost total power generation is hydrobased.

6.2. APPLICATION OF HYDRO-ELECTRIC PLANTS

Earlier hydro-electric plants have been used as exclusive source of power, but the trend is towards use of hydropower in an *inter connected system with thermal stations.* As a self-contained and independent power source, a hydro-plant is most effective with adequate storage capacity otherwise the maximum load capacity of the station has to be based on minimum flow of stream and there is a great wastage of water over the dam for greater part of the year. This increases the per unit cost of installation. By inter connecting hydro-power with steam, a great deal of saving in cost can be effected due to :

(*i*) reduction in necessary reserve capacity,

(*ii*) diversity in construction programmes,

(*iii*) higher utilisation factors on hydroplants, and

(*iv*) higher capacity factors on efficient steam plants.

In an inter connected system the base load is supplied by hydropower when the maximum flow demand is less than the stream flow while steam supplies the peak. When stream flow is lower than the maximum demand the hydroplant supplies the peak load and steam plant the base load.

6.3. ADVANTAGES AND DISADVANTAGES OF HYDRO-ELECTRIC PLANTS

Advantages of hydro-electric plant :

1. No fuel charges.
2. An hydro-electric plant is highly reliable.
3. Maintenance and operation charges are very low.
4. Running cost of the plant is low.
5. The plant has no stand by losses.
6. The plant efficiency does not change with age.
7. It takes a few minutes to run and synchronise the plant.
8. Less supervising staff is required.
9. No fuel transportation problem.
10. No ash problem and atmosphere is not polluted since no smoke is produced in the plant.
11. In addition to power generation these plants are also used for flood control and irrigation purposes.
12. Such a plant has comparatively a long life (100-125 years as against 20-45 years of a thermal plant).
13. The number of operations required is considerably small compared with thermal power plants.
14. The machines used in hydro-electric plants are more robust and generally run at low speeds at 300 to 400 r.p.m. where the machines used in thermal plants run at a speed 3000 to 4000 r.p.m. Therefore, there are no specialised mechanical problems or special alloys required for construction.

15. The cost of land is not a major problem since the hydro-electric stations are situated away from the developed areas.

Disadvantages :

1. The initial cost of the plant is very high.
2. It takes considerable long time for the erection of such plants.
3. Such plants are usually located in hilly areas far away from the load centre and as such they require long transmission lines to deliver power, subsequently the cost of transmission lines and losses in them will be more.
4. Power generation by the hydro-electric plant is only dependent on the quantity of water available which in turn depends on the natural phenomenon of rain. So if the rainfall is in time and proper and the required amount of can be collected, the plant will function satisfactorily otherwise not.

6.4. SELECTION OF SITE FOR A HYDRO-ELECTRIC PLANT

The following factors should be considered while selecting the site for a hydro-electric plant :

1. Availability of water
2. Water storage
3. Water head
4. Accessibility of the site
5. Distance from load centre
6. Type of the land of site.

1. Availability of water :

The most important aspect of hydro-electric plant is the availability of water at the site since all other designs are based on it. Therefore the run-off data at the proposed site must be available before hand. It may not be possible to have run-off data at the proposed site but data concerning the rainfall over the large catchment area is always available. Estimate should be made about the average quantity of water available throughout the year and also about maximum and minimum quantity of water available during the year. These details are necessary to :

(*i*) decide the capacity of the hydro-electric plant,

(*ii*) setting up of peak load plant such as steam, diesel or gas turbine plant and to,

(*iii*) provide adequate spillways or gate relief during the flood period.

2. Water storage :

Since there is a wide variation in rainfall during the year, therefore, it is always necessary to store the water for continuous generation of power. The storage capacity can be calculated with the help of mass curve. Maximum storage should justify the expenditure on the project.

The two types of storages in use are :

(*i*) The storage is so constructed that it can make water available for power generation of one year only. In this case storage becomes full in the beginning of the year and becomes empty at the end of each year.

(*ii*) The storage is so constructed that water is available in sufficient quantity even during the worst dry periods.

3. Water head :

In order to generate a requisite quantity of power it is necessary that a large quantity of water at a *sufficient head* should be available. An increase in effective head, for a given output, reduces the quantity of water required to be supplied to the turbines.

4. Accessibility of the site :

The site where hydro-electric plant is to be constructed should be easily accessible. This is important if the electric power generated is to be utilised at or near the plant site. The site selected should have transportation facilities of rail and road.

5. Distance from the load centre :

It is of paramount importance that the power plant should be set up *near the load centre* ; this will *reduce the cost of erection and maintenance of transmission line.*

6. Type of the land of the site :

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

The necessary requirements of the foundation rocks for a masonry dam are as follows :

(*i*) The rock should be strong enough to withstand the stresses transmitted from the dam structure as well as the thrust of the water when the reservoir is full.

(*ii*) The rock in the foundation of the dam should be reasonably impervious.

(*iii*) The rock should remain stable under all conditions.

6.5. ESSENTIAL FEATURES/ELEMENTS OF HYDRO-ELECTRIC POWER PLANT

The following are the *essential elements of hydro-electric power plant* :

1. Catchment area
2. Reservoir
3. Dam
4. Spillways
5. Conduits
6. Surge tanks
7. Primemovers
8. Draft tubes
9. Powerhouse and equipment.

Fig. 6.1 shows the flow sheet of hydro-electric power plant.

The description of various elements of hydro-electric plants is as follows :

6.5.1. Catchment Area

The whole area behind the dam draining into a stream or river across which the dam has been built at a suitable place, is called *catchment area.*

6.5.2. Reservoir

The water reservoir is the primary requirement of hydro-electric plant. A reservoir is employed to store water which is further utilised to generate power by running the hydraulic turbines.

A reservoir may be of the following two types :

1. Natural
2. Artificial

A *natural reservoir* is a lake in high mountains.

An artificial reservoir is built by erecting a dam across the river.

Water held in upstream reservoir is called *storage* whereas water behind the dam at the plant is called *pondage.*

6.5.3. Dam

A dam is a barrier to confine or raise water for storage or diversion to create a hydraulic head. An hydro-electric dam diverts the flow from the river to the turbines and usually increases the head. A reservoir dam stores water by raising its level.

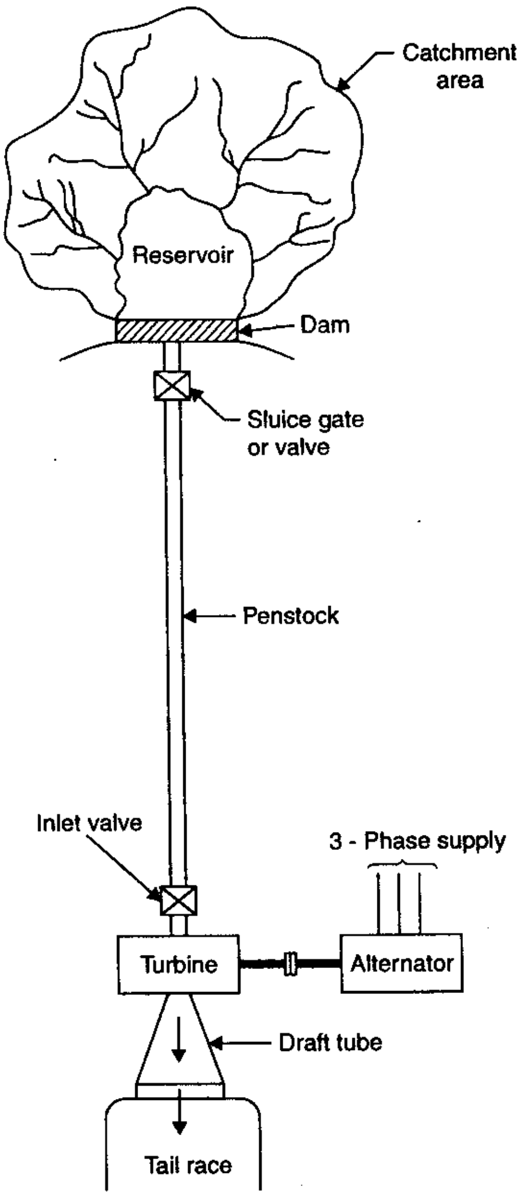


Fig. 6.1. Flow sheet of hydro-electric power plant.

Dams are built of *concrete* or *stone masonry, earth* or *rock fill,* or *timber.* Masonry dams may be the solid-gravity, buttress or arch type. A *barrage* is a diversion dam, especially at a tidal power project. A *weir* is a low overflow dam across a stream for measuring flow or maintain water level, as at a lake outlet. A *dike* is an embankment to confine water ; a *levee* is a dike near the bank of a river to keep low land from being overflowed.

6.5.3.1. Types of dams

The different types of dams are as follows :

A. Fill dams

1. Earth dams
2. Rock-fill dams.

B. Masonry dams

1. Solid gravity dams
2. Buttress dams
3. Arch dams.

C. Timber dams

Selection of site for dams

The following points should be taken into consideration while selecting the site for a dam.

1. For achieving economy the water storage should be largest for the minimum possible height and length. Naturally site should be located in a narrow valley.

2. For safe and cheap construction good foundation should be available at moderate depth.

3. Good and suitable basin should be available.

4. Material for construction should be available at a dam site or near by. As huge quantities of construction materials are required for construction of the dam, the distance at which the material is available affects the total cost of the project.

5. For passing the surplus water, after the reservoir has been filled upto its maximum capacity, a spillway is to be provided. There should be good and suitable site available for spillway construction. It may be in dam itself or near the dam on the periphery of the basin.

6. The value of the property and the land likely to be submerged by the proposed dam should be sufficiently low in comparison with the benefits expected from the project.

7. The site of the dam should be easily accessible in all the seasons. It should be feasible to connect the site with good lines of communication.

8. There should be a good catchment on the upstream side of the site, that is the catchment should contribute good and sufficient water to the basin. The catchment area should not be easily erodable otherwise excessive silt will come in the reservoir basin.

9. There should be suitable site available for providing living accommodation to the labourers and engineering staff. It is very essential to see that the climate of the site is healthy.

10. Overall cost of construction and maintenance of the dam should be taken into consideration.

Selection of type of a dam

The selection of a type of dam is affected by the following topographical and geological factors :

1. Nature of foundation

Sound rock formation in the foundation	Any type of dam can be adopted
Poor rock and earth foundation	Earth dam

2. Nature of valley

Narrow valleys (with good rock abutments)	Arch dam
If george with rocky bed available	Solid gravity dam

If valley is wide and foundation is weak	Buttress dam
For any width of valley with good foundations	Steel dam
For any width of valley with any foundation and low height of water to be stored	Timber dam
For wide valley with gentle side slopes	Earth dam or rock fill dam.
3. Permeability of foundation material	
When uplift pressure exerted on the base of the dam is excessive	Arch dam
When the foundations are pervious	Earth dam

In addition to these factors the following points should also be given consideration.

(*i*) Suitable site for locating spillways sometimes affects the selection of the type of a dam.

(*ii*) The availability of construction material may sometimes dictate the choice.

It may be mentioned that in general the most permanent and safe dam will be found to be most economical one.

Description of dams

A. *Fill dams :*

1. Earth dams. For small projects, in particular, dam constructed of earth fill or embankment are commonly used. Because of the great volume of material required, it is imperative that the fill be obtainable in the vicinity of dam site.

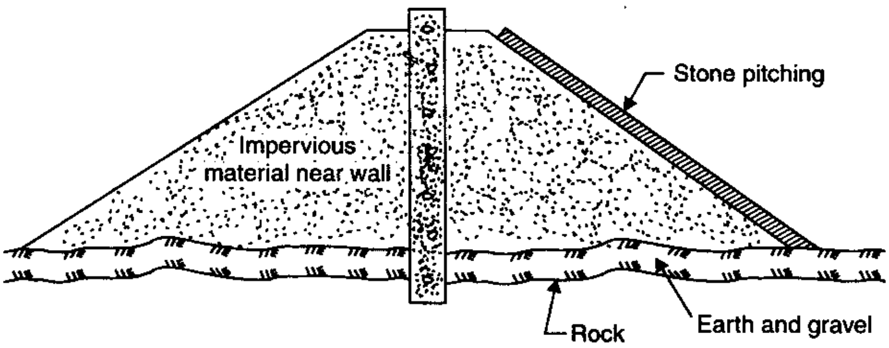


Fig. 6.2. Earth dam.

The earth dams have the following **advantages** :

(*i*) It is usually cheaper than a masonry dam.

(*ii*) It is suitable for relatively previous foundation.

(*iii*) It blends best with the natural surroundings.

(*iv*) It is the most permanent type of construction if protected from corrosion.

Disadvantages of the earth dam are :

(*i*) It has greater seepage losses than most other types of dams.

(*ii*) Since this type of dam is not suitable for a spillway structure, therefore it requires a supplementary spillway.

(*iii*) It is subject to possible destruction or serious damage from erosion by water either overtopping the dam or seeping through it.

Following are the *causes of failure* of earth dams :

1. Overtopping caused by insufficient spillway capacity.
2. Seepage along conduits through the dam.
3. Piping through the dam or its foundation.

2. Rock-fill dams. A rock-fill dam consists of loose rock of all sizes and has a trapezoidal shape with a wide base, with a watertight section to reduce seepage. It is *used in mountaneous locations* where rock rather than earth is available. A rock-fill dam may be destroyed if overtopped to any great extent, and so it needs a supplementary spillway of adequate capacity.

B. *Masonry dams :*

1. Solid gravity dams. This type of dam is more massive and bulky than the other types since it depends on its weight for stability. Because of its weight it requires a sound rock foundation. It may be used as a spillway section for a dam of another type on sand or gravel foundations if the stresses are limited and a suitable cut-off is provided. On a rock foundation the base of a solid gravity dam which is 0.7 of the head usually results in a satisfactory and economical section for either a bulkhead or spillway section. On an earth foundation the base generally equals the head.

2. Buttress dam. A buttress dam has an inclined upstream face, so that water pressure creates a large downward force which provides stability against overturning or sliding. The forces on the upstream face are transmitted to a row of buttresses or piers. This type of dam requires only about *one-third* the concrete needed for a solid gravity dam, but extra cost of reinforcing steel and framework and the skilled labour needed for the thinner sections may largely offset the saving in concrete. The relatively thin sections of concrete in a buttress dam are susceptible to damage from frost and temperature and may require protection or precautionary measures.

Fig. 6.3 and Fig. 6.4 show typical buttress dams.

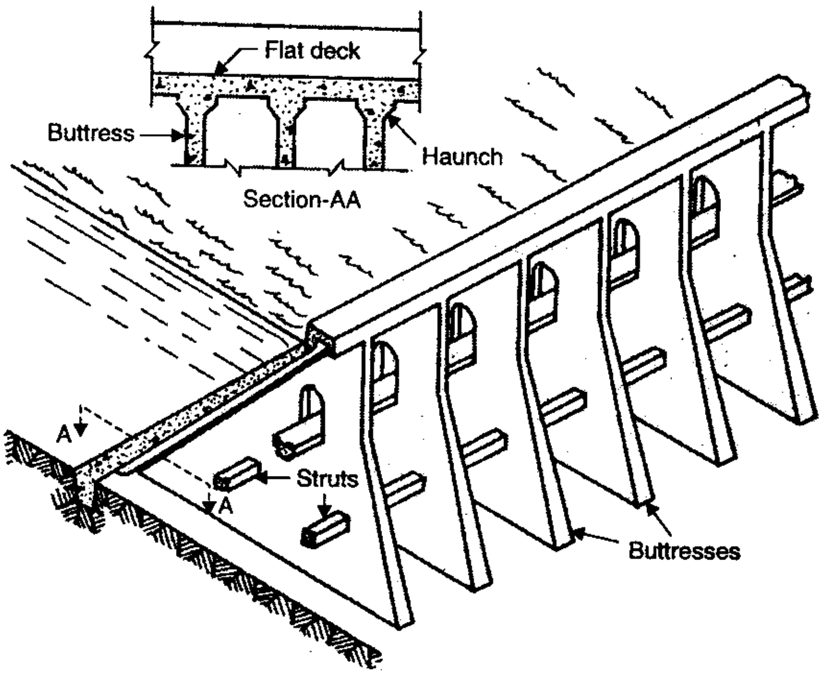


Fig. 6.3. Slab-and-buttress type.

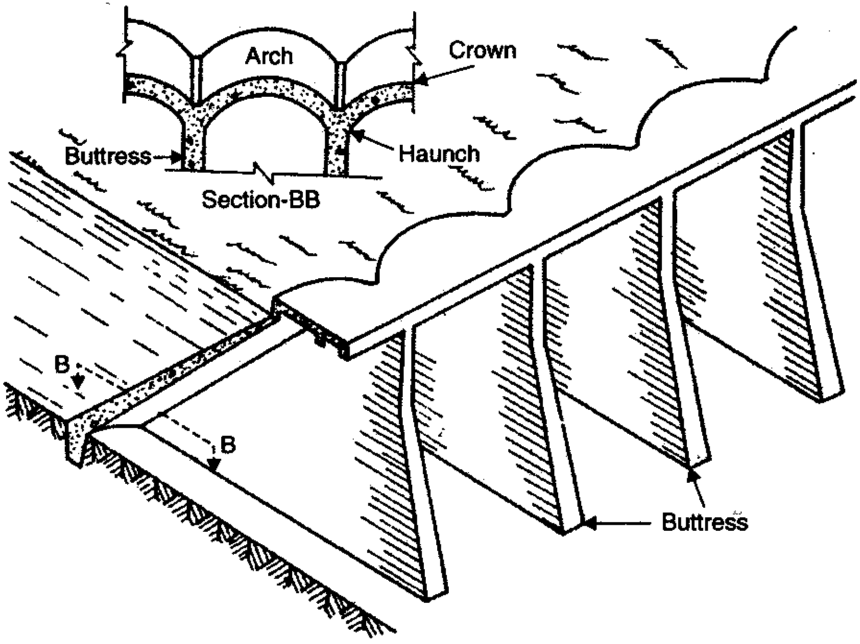
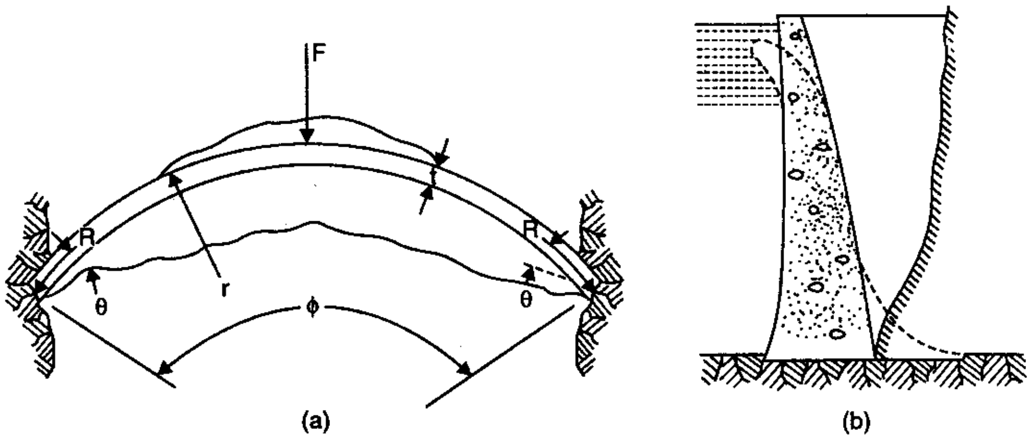


Fig. 6.4. Multiple-arch type.

3. Arch dam. Refer Fig. 6.5. This type of dam resists the water force by being braced against the canyon sides because of its curved shape. Few sites are suitable for the this type of dam, which requires a fairly narrow valley with steep slopes of solid rock to support the outward thrust of the structure. An arch dam is not ordinarily used for a spillway as the downstream face is too steep for the over- flowing water except for low discharges. It is generally necessary to provide a separate spillway for an arch dam, either a tunnel or conduit type, a side-channel wasteway at the end of the dam, or a spillway in another location.



(a)
Plan

(b)
Section

Fig. 6.5. Typical arch dam : (*a*) Plan (*b*) Section.

C. *Timber dams :*

When wood is plentiful and more durable materials are not accessible timber is sometimes used for low dams upto 12 m. In the early days, timber could be had for the cutting, but most of the original timber dams have been superseded by masonry or fill dams. Now-a-days wooden dams are uncommon.

6.5.4. Spillways

When the water enters the reservoir basin, the level of water in basin rises. This rise is arranged to be of temporary nature because excess accumulation of water endangers the stability of dam structure. To relieve reservoir of this excess water contribution, a structure is provided in the body of a dam or near the dam or on the periphery of a basin. This *safeguarding structure is called a spillway*.

A spillway should fulfill the following requirements :

1. It should provide structural stability to the dam under all conditions of floods.
2. It should be able to pass the designed flood without raising reservoir level above H.F.L. (high flood level).
3. It should have an efficient operation.
4. It should have an economical section.

Types of spillways

Following are some types of spillways :

(*i*) Overfall spillway or solid gravity spillway

(*ii*) Chute or trough spillway (*iii*) Side channel spillway

(*iv*) Saddle spillway (*v*) Emergency spillway

(*vi*) Shaft or glory hole spillway (*vii*) Siphon spillway.

In the types from (*i*) to (*v*) *water spills and flows over the body of the spillway whereas* in the types (*vi*) and (*vii*) *water spills over the crest and then flows through the body of the spillway.*

The *selection* of type of spillway is generally based *on the type of the dam and the quantity of flood water to be discharged below* ; it also depends on the *site conditions.*

6.5.4.1. Overfall spillway or solid gravity spillway

Refer Fig. 6.6. This type of spillway is provided in case of concrete and masonry dams. It is situated in the body of the dam, generally in the centre. As it is provided in the dam itself the length of dam should be sufficient to accommodate the designed spillway crest.

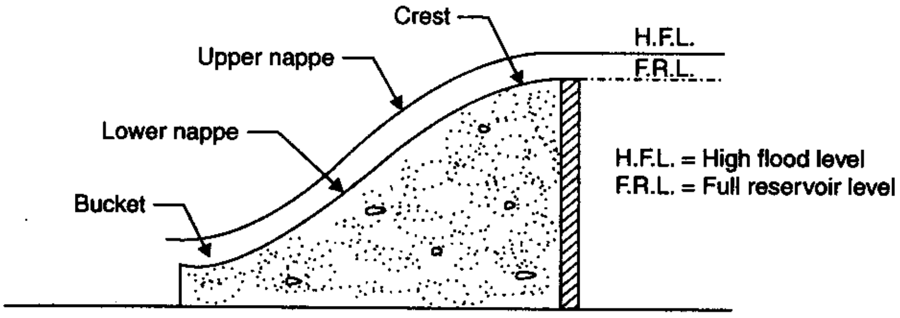


Fig. 6.6. Overfall spillway.

This spillway consists of an *ogee crest* and a *bucket.* Water spills and flows over the crest in the form of a rolling sheet of water. The bucket provided at the lower end of the spillway *changes the* *direction of the fast moving water.* In this process the excess energy of fast moving water is *destroyed.* The portion between the front vertical face and the lower nappe of sheet of water is filled with concrete to conform the profile of the spillway to the lower nappe. This type of construction practically avoids the development of *negative pressures.* The section is always designed for maximum head of water over the crest of spillway.

6.5.4.2. Chute or trough spillway

This type of spillway is most suited under the situation when the *valley is too narrow* to accommodate the solid gravity spillway in the body of the dam or when the non-rigid type of dam is adopted. It is called chute spillway because after crossing over the crest of the spillway the water flow *shoots down a channel or a trough* to meet the river channel downstream of the dam.

In this type the crest of the spillway is at right angles to the centre line of the trough or the chute. The crest is isolated from the dam axis. The trough is taken straight from the crest to the river and it is generally lined with concrete.

6.5.4.3. Side channel spillway

A side channel spillway is employed when the *valley is too narrow in case of a solid gravity dams and when non-rigid dams are adopted.* In non-rigid dams it is undesirable to pass the flood water over the dam. When there is no room for the provision of chute spillway this type is adopted as it requires comparatively limited space. Thus the situations where chute and side channel spillways are required are mostly the same. *The side channel spillway differs from the chute spillway in the sense that after crossing over the spillway crest, water flows parallel to the crest length in former, whereas the flow is normal to the crest in the latter* (Fig. 6.7).

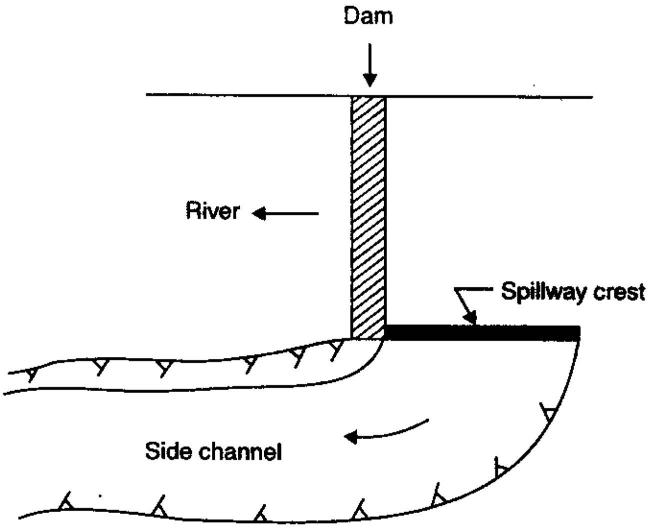


Fig. 6.7. Side channel spillway.

To maintain satisfactory flow conditions a sufficient longitudinal slope is given to the side channel.

6.5.4.4. Saddle spillway

A saddle spillway may be constructed when conditions are not favourable for any of the types mentioned above. There may be some natural depression or saddle on the periphery of the reservoir basin away from the dam as shown in Fig. 6.8. The depression may be used as a spillway. It is essential that *the bottom of the depression should be at full reservoir level*. For ideal conditions there should be good rock formation at the site of a spillway.

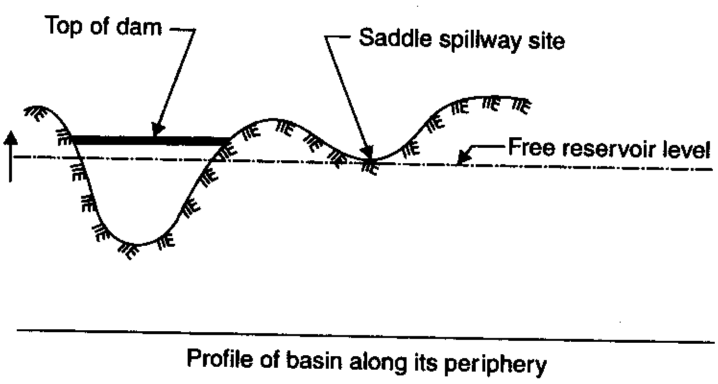


Fig. 6.8. Saddle spillway.

6.5.4.5. Emergency spillway

As the name suggests this type of spillway is very rarely put into action. Naturally it is not necessary to protect the structure, its foundation or its discharge channel from serious damage.

An emergency spillway comes into action when the occurring flood discharge *exceeds* the designed flood discharge.

6.5.4.6. Shaft or glory hole spillway

The shape of shaft spillway is just like a funnel. The lower end of the funnel is turned at right angles and then taken out below the dam horizontally. Water spills over the crest, which is circular, and then enters the vertical shaft and is taken out below the dam through a horizontal tunnel. Sometimes the flow is guided by means of radial piers on the crest of the spillway. It avoids creation of spiral flow in the shaft. The piers may be used to support a bridge around the crest. The bridge may be used to connect the spillway to the dam.

6.5.4.7. Siphon spillway

A siphon spillway, as the name suggests, is designed on the *principle of a siphon*.

Fig. 6.9 shows a saddle siphon spillway. The crest is fixed at full reservoir level (F.R.L.). When the water level in the reservoir rises above F.R.L. water starts spilling over the crest. The step or a joggle deflects the sheet of water and consequently the lower end is sealed. As the lower end is sealed the air gets entrapped in the lower limb. This air is driven out by incoming water completely. This process of evacuating and filling the lower limb by water is known as *priming*. Once the siphon is primed water starts flowing out till the level of the water in the reservoir falls below the level of the upper limb. Usually the lower end of the upper limb is kept below full reservoir level. It prevents blocking of the entrance due to the floating matter such as ice etc. Naturally if the water is emptied till the lower end of the upper limb emerges out the useful live storage is lost. To break the siphon action at proper time, that is when the water level falls to F.R.L., an air vent is provided on the crown as shown in Fig. 6.9. Thus when the water level falls to F.R.L. air enters in the lower limb through air vent and siphonic action is broken or stopped.

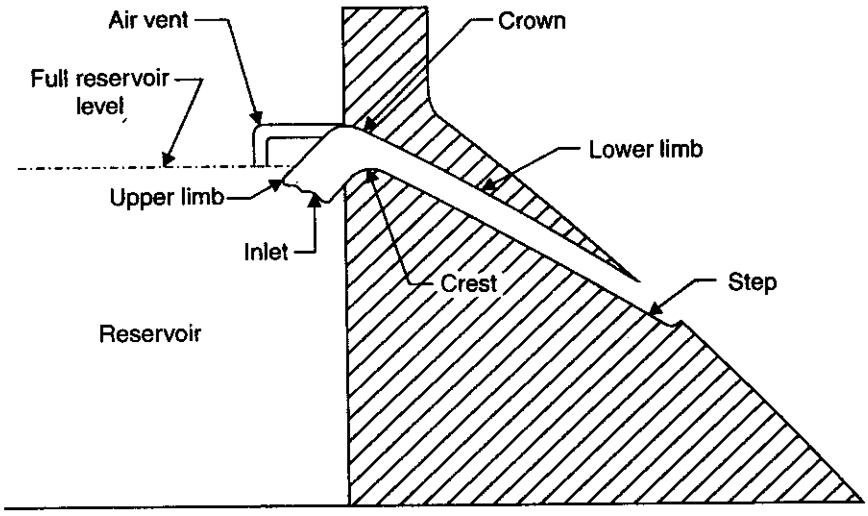


Fig. 6.9. Saddle siphon spillway.

6.5.5. Conduits

A headrace is a channel which leads water to a turbine and a tailrace is a channel which conducts water from the wheels. The conduit may be open or close.

Open conduits ...... Canals and flumes

Close conduits ...... Tunnels, pipelines and penstocks

Canal. A canal is an open waterway excavated in natural ground. It has to follow the contour of the ground, with perhaps a slight gradient corresponding to the head loss.

Flume. A flume is an open channel erected on the surface of supported above ground on a trestle. A flume might be used with a canal to cross a ravine or where the slope of the ground is greater than the hydraulic gradient.

Tunnel. It is a closed channel excavated through a natural obstruction such as a ridge of higher land between the dam and the powerhouse. A tunnel across a bend in the river might be cheaper than a conduit that goes around. Tunnels are also commonly used in diverting water from one drainage area to another, where the divide between watersheds is higher than the reservoir.

Pipeline. A pipeline is a closed conduit usually supported on or above the surface of the land. When a pipeline is laid on the hydraulic gradient, it is called a *flow line.*

Penstock. It is a closed conduit for supplying *water under pressure* to a turbine.

Advantages and limitations of different types of conduits :

Open channels are generally the *least expensive,* but the cost of a flume increases with the height of the trestle.

Where the land is fairly level at head water elevation between the dam and powerhouse sites, a *canal* would be feasible, but not many sites fit this requirement.

Tunnels are generally the *most costly type* of conduit for a given length but are justified if their use results in considerable saving in distance. While ordinarily tailraces are open channels, tunnels are used for the discharge from an underground hydro-station.

Penstocks are used where the *slope is too great for a canal,* especially for the final stretch of the diversion system where the land pitches steeply to the powerhouse. Surge tanks or other measures are necessary to prevent damage in closed conduits due to abnormal pressures.

Fig. 6.9 (*a*) shows the combination of tunnel, flume, and penstocks at a high-head development. The tunnel intake regulates the flow between the reservoirs, while the sluice gates at the entrance to the flume control the discharge to that needed by the turbines. The regulating forebay has a small storage capacity to care for minor flow fluctuations. It has an automatic spillway to discharge overflow when turbines shut down suddenly.

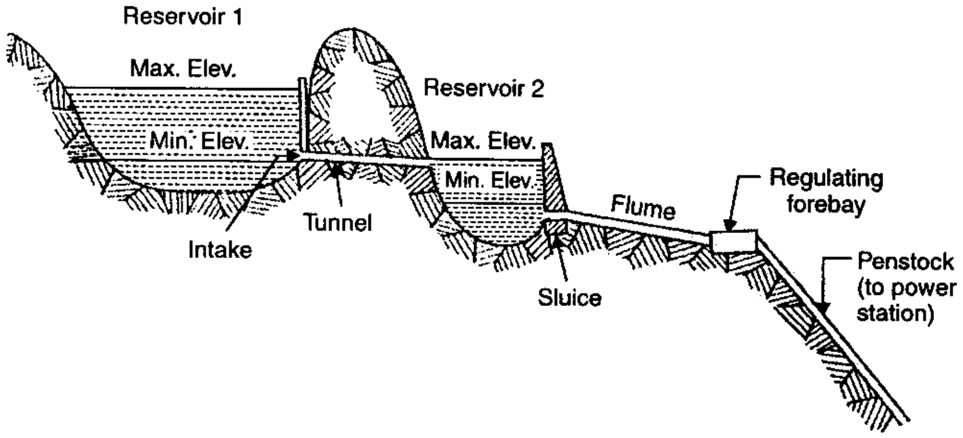


Fig. 6.9. (*a*) Combination of tunnel, flume and penstocks at a high-head development.

Penstocks :

(*i*) *How to calculate penstock thickness ?*

The thickness of steel penstock which depends on the water head hoop/circumferential stress allowed in the material can be calculated by using the following relation :

$$t = \frac{pd}{2f\eta}$$

where t = Thickness of the penstock,

p = Pressure due to water including water hammer = wH, w and H being specific weight of water and head of water respectively,

d = Diameter (internal) of the penstock,

f = Permissible hoop/circumferential stress, and

η = Joint efficiency.

(*ii*) *Number of penstocks to be used :*

To supply water to a number of turbines penstocks needed may be decided from the *following alternatives* :

1. To provide *one penstock for each turbine* separately. In such a case water is supplied independently to each turbine from a separate penstock.

2. To use a *single penstock* for the entire plant. In this case the penstock should have as *many branches* as the number of hydraulic turbines.

3. To provide *multiple penstocks* but each penstock should supply water to atleast two hydraulic turbines.

While selecting the number of penstocks to be used for supplying water to the turbines, the following points need be considered :

(*a*) **Operational safety.** As far as possible a single penstock should not be used for supplying to different turbines for generating power because any damage to this penstock would mean shut down of the entire set of turbines.

(*b*) **Economy.** From view point of economy, if the length of penstock required is short then one penstock each may be provided to the turbines, however for longer penstocks a single penstock or as few penstocks as possible may be used.

(*c*) **Transportation facilities.** The penstock size should be so selected that it is easily transported from one place to another.

(*iii*) *Penstock materials and their suitability :*

— *Reinforced concrete penstocks* are suitable upto 18 m head as greater pressures cause rapid deterioration of concrete exposed to frost action.

— *Wood-stave penstocks* are used for heads upto about 75 m and consist of treated timbers laid side by side to form a cylinder held together by the steel hoops. The size and spacing of the hoops on a wood-stave pipe and the reinforcing steel in concrete increase with the head.

— *Steel penstocks* can be designed for any head, with the thickness varying with the pressure and diameter. The minimum thickness of steel plate is used for heads upto 45 m ; for lower heads it may be more economical to use wood or concrete pipe rather than steel.

The strength of a penstock can be expressed as the horse power it can carry. Since the size of a pipe depends on the flow, the product of head and flow determines both maximum stresses and power.

— *High pressure penstocks* are fabricated in 6 to 8 m lengths for mountaneous regions where transportation is difficult. The manholes give access to the interior of the penstocks for inspection and maintenance. *Welded joints are preferable to riveted ones because of the higher friction losses in the latter. Steel penstocks* are usually given protective coatings in the shop and after erection.

— Penstocks are generally supported by *concrete piers* or *cadles,* although they may be laid on or in the ground. A bridge or trestle is used to carry a penstock across a narrow defile. *Anchors* on steep grades support the weight of the fill penstock and also take the thrusts from water pressure acting at angles in the pipe. It may be cheaper to bury small pipes, while penstocks are sometimes covered to protect them from rock or snow slides, prevent freezing, or eliminate expansion joints. *Buried penstocks* are subject to corrosion, which can be eliminated or atleast greatly reduced by *cathodic protection* which prevents electrolysis from attacking the metal. *Exposed penstocks last longer and are more accessible for inspection and maintenance.*

6.5.6. Surge Tanks

*A **surge tank** is a small reservoir or tank in which the water level rises or falls to reduce the pressure swings so that they are not transmitted in full to a closed circuit.* In general a surge tank serves the following purposes :

1. To reduce the distance between the free water surface and turbine thereby reducing the water-hammer effect (the *water hammer* is defined as the change in pressure rapidly above or below normal pressure caused by sudden changes in the rate of water flow through the pipe according to the demand of prime mover) on penstock and also protect upstream tunnel from high pressure rises.

2. To serve as a *supply tank* to the turbine when the water in the pipe is accelerating during increased load conditions and as a *storage tank* when the water is decelerating during reduced load conditions.

Types of surge tanks

The different types of surge tanks in use are :

1. Simple surge tank
2. Inclined surge tank
3. The expansion chamber and gallery type surge tank
4. Restricted orifice surge tank
5. Differential surge tank.

1. Simple surge tank. A simple surge tank is a vertical stand pipe connected to the penstock as shown in Fig. 6.10. In the surge tank if the overflow is allowed, the rise in pressure can be eliminated but *overflow surge tank is seldom satisfactory and usually uneconomical.* Surge tanks are built high enough so that water cannot overflow even with a full load change on the turbine. It is always desirable to place the surge tank on grond surface, above the penstock line, at the point where the latter drops rapidly to the power house as shown in Fig. 6.10. Under the circumstances when suitable site for its location is not available the height of the tank should be increased with the help of a support.

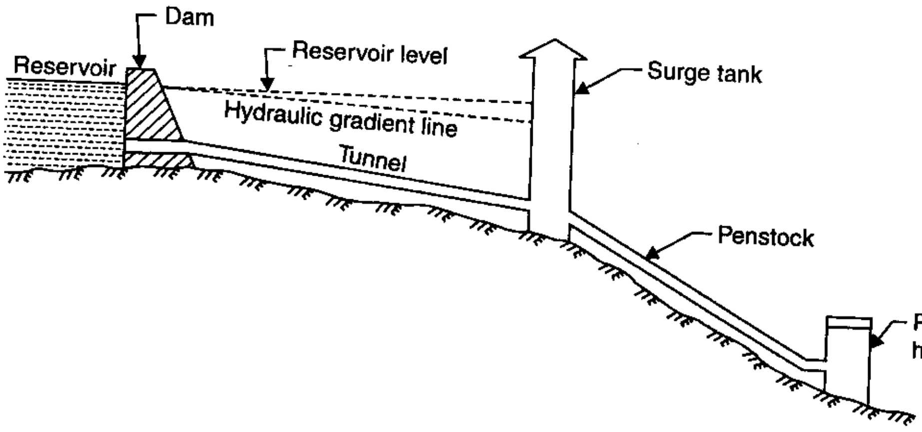


Fig. 6.10. Surge tank on ground level.

2. Inclined surge tank. When a surge tank is inclined (Fig. 6.11) to the horizontal its effective water surface increases and therefore, lesser height surge tank is required of the same diameter if it is inclined or lesser diameter tank is required for the same height. But this type of surge tank is *more costlier than ordinary type as construction is* difficult and is rarely used unless the topographical conditions are in favour.

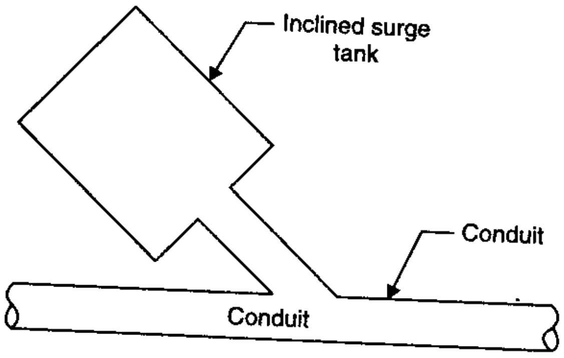


Fig. 6.11. Inclined surge tank.

3. Expansion chamber surge tank. Refer Fig. 6.12. This type of a surge tank has an expansion tank at top and expansion gallery at the bottom ; these expansions *limit the extreme surges*. The 'upper expansion chamber' must be *above the maximum reservoir level* and 'bottom gallery' must be *below the lowest steady running level in the surge tank*. Besides this the intermediate shaft should have a stable minimum diameter.

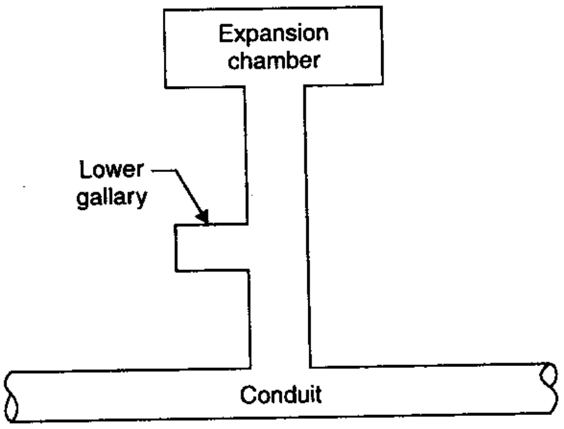


Fig. 6.12. The expansion chamber surge tank.

4. Restricted orifice surge tank. Refer Fig. 6.13. It is also called *throttled surge tank*. The main object of providing a throttle or restricted orifice is *to create an appreciable friction loss when the water is flowing to or from the tank*. When the load on the turbine is reduced, the surplus water passes through the throttle and a retarding head equal to the loss due to throttle is built up in the conduit. The size of the throttle can be designed for any designed retarding head. *The size of the throttle adopted is usually such as the initial retarding head is equal to the rise of water surface in the tank when the full load is rejected by the turbine* (a case when there is closure of the gate valve).

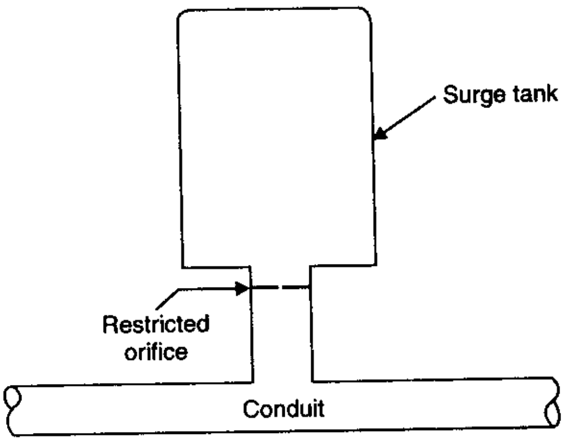


Fig. 6.13. Restricted orifice surge tank.

Advantage. Storage function of the tank can be separated from accelerating and retarding functions.

Disadvantage. Considerable portion of water hammer pressure is transmitted directly into the low pressure conduit.

In comparison to other types of surge tanks these are *less popular*.

5. Differential surge tank. Refer Fig. 6.14. A differential surge tank has a riser with a small hole at its lower end through which water enters in it. The function of the surge tank depends upon the area of hole.

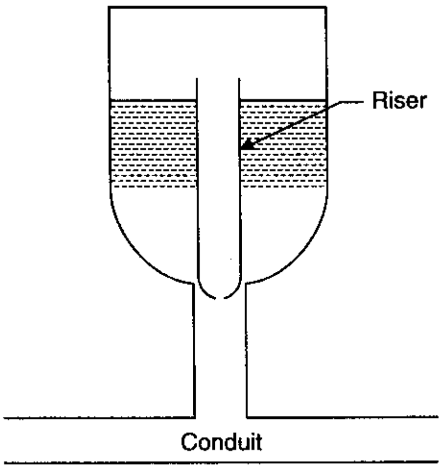


Fig. 6.14. Differential surge tank.

6.5.7. Primemovers

In an hydraulic power plant the primemover converts the energy of water into mechanical energy and further into electrical energy. These machines are classified on the basis of the action of water on moving blades. As per action of water on the primemover, they are classified as :

1. Impulse turbine. Here the *pressure energy of water is converted into kinetic energy* when passed through the nozzle and forms the high velocity jet of water. The formed water jet is used for driving the wheel.

2. Reaction turbine. In this case the water pressure combined with the velocity works on the runner. The power in this turbine is developed from the *combined action of pressure and velocity of water* that completely fills the runner and water passage.

For more details on hydraulic turbines refer article 6.7.

6.5.8. Draft Tubes

The draft tube serves the following two purposes :

1. *It allows the turbine to be set above tail-water level, without loss of head, to facilitate inspection and maintenance.*

2. *It regains, by diffuser action, the major portion of the kinetic energy delivered to it from the runner.*

At rated load the velocity at the upstream end of the tube for modern units ranges from 7 to 9 m/s, representing from 2.7 to 4.8 m head. As the specific speed (it is the speed of a geometrically similar turbine running under a unit head and producing unit power) is increased and the head reduced, it becomes increasingly important to have an efficient draft tube. Good practice limits the velocity at the discharge end of the tube to 1.5 to 2.1 m/s, representing less than 0.3 m velocity head loss.

Types of draft tubes. The following two types of draft tubes are commonly used :

(*i*) The straight conical or concentric tube (*ii*) The elbow type.

Properly designed, the two types are about equally efficient, over 85%.

(*i*) **Conical type.** The conical type is generally used on low-powered units for all specific speeds and, frequently, on large high-head units. The side angle of flare ranges from 4 to 6°, the length from 3 to 4 times the diameter and the discharge area from four to five times the throat area. Fig. 6.15 shows a straight conical draft tube.

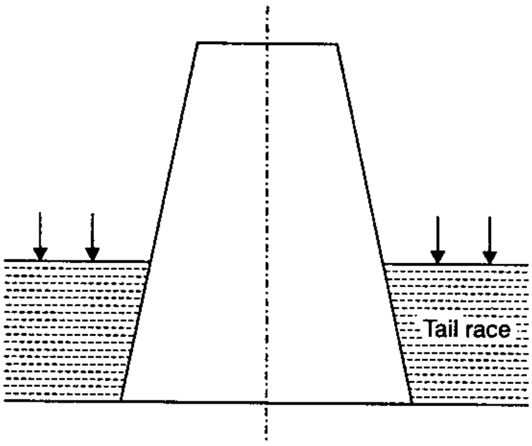


Fig. 6.15. Straight conical draft tube.

(*ii*) **Elbow type.** The elbow type of tube is now used with most turbine installation. With this type the vertical portion begins with a conical section which gradually flattens in the elbow section and then discharges horizontally through substantially regular sections to the tailrace. Most of the regain of energy takes place in the vertical portion, very little in the elbow section, which is shaped to deliver the water to the horizontal portion so that the regain may be efficiently completed. Fig. 6.16 shows an elbow type draft tube. One or two vertical piers are placed in the horizontal portion of the tube, for structural and hydraulic reasons.

Small conical tubes are sometimes made entirely of steel plate. Most tubes are made of concrete with a steel-plate lining extending from the upper end to a point where the velocity has been sufficiently reduced (say 5 m/s) to prevent erosion of the concrete. Sometimes the liner is carried around the elbow. Pier noses are also lined where necessary to prevent erosion for structural reasons.

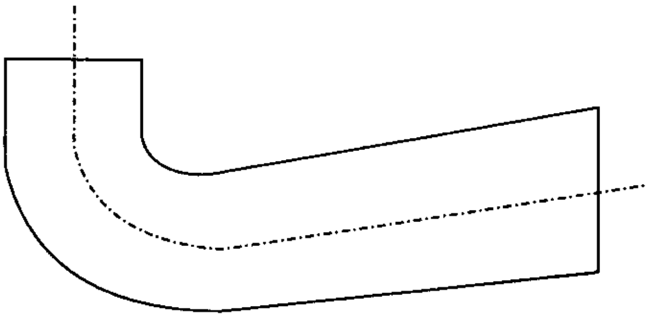


Fig. 6.16. Elbow type draft tube.

6.5.9. Power House and Equipment

A power house should have a stable structure and its layout should be such that adequate space is provided around the equipment (such as turbines, generators, valves, pumps, governors etc.), so that the dismantling and repairing may be easily carried out.

A power house, mostly, comprises of the following sub-divisons :

1. **The substructure.** This part of the powerhouse extends from top of generator to the soil or rock and houses most of the generating equipment. In case of Francis and Kaplan turbines the substructure not only accommodates various equipment but draft tube as well.

2. **Intermediate structure.** It is that part of the structure which extends from the top of the draft tube to top of generator foundation.

3. **The superstructure.** This part of the structure lies above the generator level. It houses mostly the cranes which handle the heavy equipment in the substructures.

Following important equipment may be provided in a power house

(*i*) Hydraulic turbines
(*ii*) Electric generators
(*iii*) Governors
(*iv*) Gate valves
(*v*) Relief valves
(*vi*) Water circulating pumps
(*vii*) Flow measuring equipment
(*viii*) Air duct
(*ix*) Water circulating pumps
(*x*) Switch board equipment and instruments
(*xi*) Oil circuit breakers
(*xii*) Reactors
(*xiii*) Low tension and high tension bar
(*xiv*) Storage batteries
(*xv*) Cranes.

Besides the above important equipment shops and offices are also provided in the power house.

6.6. CLASSIFICATION OF HYDRO-ELECTRIC POWER PLANTS

Hydro-electric power stations may be classified as follows :

A. According to availability of head

1. High head power plants
2. Medium head power plants
3. Low head power plants

B. According to the nature of load

1. Base load plants
2. Peak load plants

C. Accordingly to the quantity of water available

1. Run-of-river plant without pondage
2. Run-of-river plant with pondage
3. Storage type plants
4. Pump storage plants
5. Mini and micro-hydel plants

A. According to availability of head

The following figures give a rough idea of the heads under which the various types of plants work :

(*i*) High head power plants	100 m and above
(*ii*) Medium head power plants	30 to 500 m
(*iii*) Low head power plants	25 to 80 m.

Note. It may be noted that figures given above overlap each other. Therefore it is difficult to classify the plants directly on the basis of head alone. The basis, therefore, technically adopted is the *specific speed* of the turbine used for a particular plant.

6.6.1. High Head Power Plants

These types of plants work under heads 100 m and above. Water is usually stored up in lakes on high mountains during the rainy season or during the reason when the snow melts. The rate of flow should be such that water can last throughout the year.

Fig. 6.17 shows high head power plant layout. Surplus water discharged by the spillway cannot endanger the stability of the main dam by erosion because they are separated. The tunnel through the mountain has a surge chamber excavated near the exit. Flow is controlled by head gates at the tunnel intake, butterfly valves at the top of the penstocks, and gate valves at the turbines. This type of site might also be suitable for an underground station.

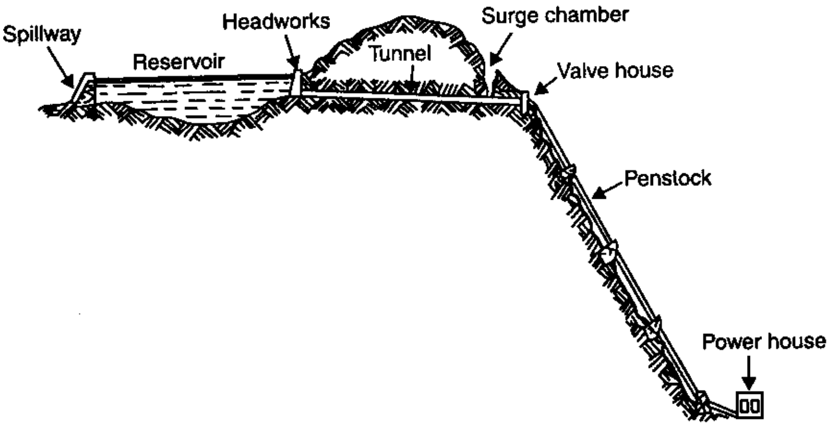


Fig. 6.17. High head power plant layout. The main dam, spillway, and powerhouse stand at widely separated locations. Water flows from the reservoir through a tunnel and penstock to the turbines.

The *Pelton wheel* is the common primemover used in high *head power plants*.

6.6.2. Medium Head Power Plants

Refer Fig. 6.18. When the operating head of water lies between 30 to 100 metres, the power plant is known as medium head power plant. This type of plant commonly uses *Francis turbines*. The

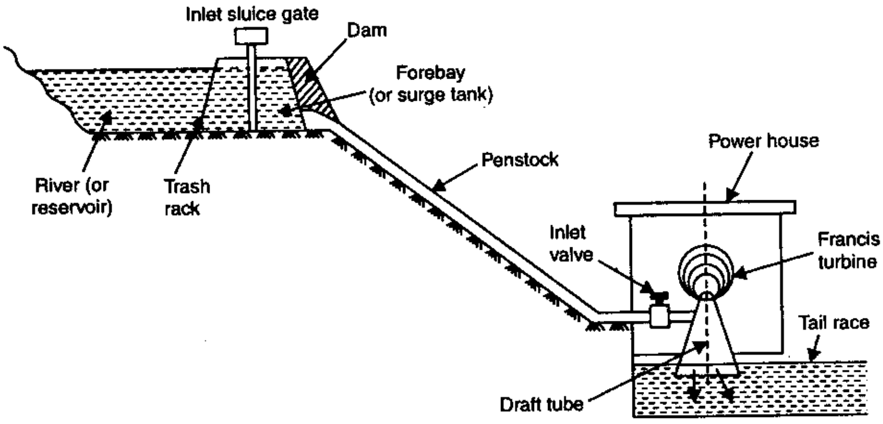


Fig. 6.18. Medium head power plant layout.

forebay provided at the beginning of the penstock serves as water reservoir. In such plants, the water is generally carried in open canals from main reservoir to the forebay and then to the powerhouse through the penstock. The forebay itself works as a surge tank in this plant.

6.6.3. Low Head Power Plants

Refer Fig. 6.19. These plants usually consist of a dam across a river. A sideway stream diverges from the river at the dam. Over this stream the power house is constructed. Later this channel joins the river further downstream. This type of plant uses vertical shaft Francis turbine or Kaplan turbine.

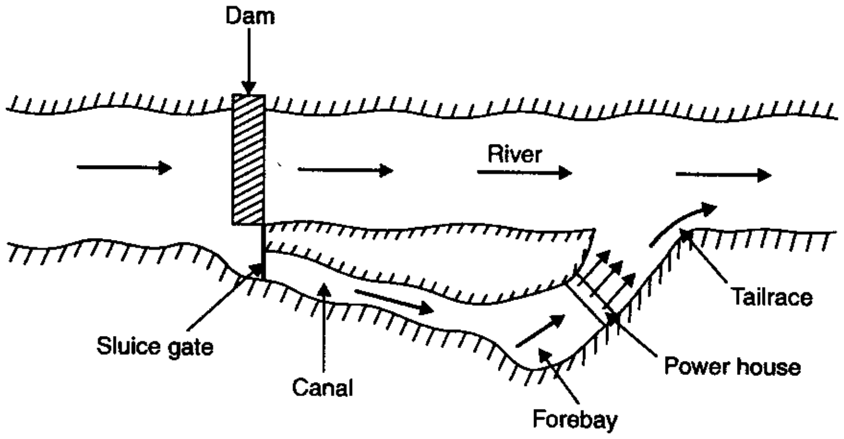


Fig. 6.19. Low head power plant layout.

B. *According to the nature of load*

6.6.4. Base Load Plants

The plants which cater for the base load of the system are called *base load plants*. These plants are required to *supply a constant power when connected to the grid*. Thus they *run without stop* and are often remote-controlled with which *least staff* is *required for such plants*. Run-of-river plants without pondage may sometimes work as baseload plant, but the firm capacity in such cases, will be muchless.

6.6.5. Peak Load Plants

The plants which can supply the power during peak loads are known as *peak load plants*. Some of such plants supply the power during average load but also supply peak load as and when it is there ; whereas other peak load plants are required to work during peak load hours only. The run-of-river plants may be made for the peak load by providing pondage.

C. *According to the quantity of water available*

6.6.6. Run-of-river Plants without Pondage

A run-of-river plant without pondage, as the name indicates, does not store water and uses the water as it comes. There is *no control on flow of water* so that during high floods or low loads water is wasted while during low run-off the plant capacity is considerably reduced. *Due to non-uniformity of supply and lack of assistance from a firm capacity the utility of these plants is much less* than those of other types. The head on which these plants work *varies considerably*. Such a plant can be made a great deal more useful by providing sufficient storage at the plant to take care of the hourly fluctuations in load. This lends some *firm capacity* to the plant. During good flow conditions these plants may cater to base load of the system, when flow reduces they may supply the peak demands. *Head water elevation for plant fluctuates with the flow conditions.* These plants without storage may sometimes be made to supply the base load, but the firm capacity depends on the minimum flow of river. The run-of-river plant may be made for load service with pondage, though storage is usually seasonal.

6.6.7. Run-of-river Plant with Pondage

Pondage usually refers to the collection of water behind a dam at the plant and increases the stream capacity for a short period, say a week. *Storage* means collection of water in up stream reservoirs and this increases the capacity of the stream over an extended period of several months. Storage plants may work satisfactorily as base load and peak load plants.

This type of plant, as compared to that without pondage, is *more reliable* and its generating capacity *is less dependent on the flow rates of water available.*

6.6.8. Storage Type Plants

A storage type plant is one with a reservoir of sufficiently large size to permit carry-over storage from the wet reason to the dry reason, and thus to supply firm flow substantially more than the minimum natural flow. This plant can be used as base load plant as well as peak load plant as water is available with control as required. The majority of hydro-electric plants are of this type.

6.6.9. Pumped Storage Plants

Refer Fig. 6.20.

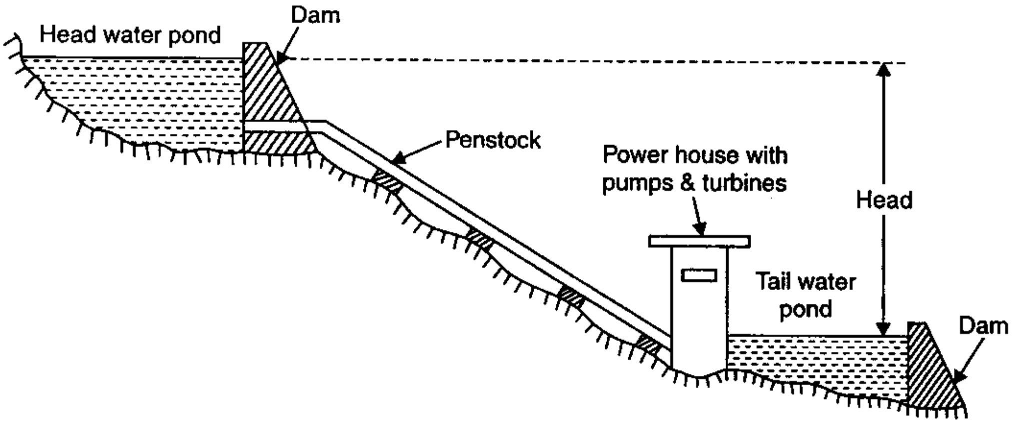


Fig. 6.20. Pumped storage plant.

Pumped storage plants are employed at the places where the quantity of water available for power generation is *inadequate*. Here the water passing through the turbines is stored in *'tail race pond'*. During low load periods this water is pumped back to the head reservoir using the extra energy available. This water can be again used for generating power during peak load periods. Pumping of water may be done seasonally or daily depending upon the conditions of the site and the nature of the load on the plant.

Such plants are *usually interconnected* with steam or diesel engine plants so that off peak capacity of interconnecting stations is used in pumping water and the same is used during peak load periods. Of course, the energy available from the quantity of water pumped by the plant is *less* than the energy input during pumped operation. Again while using pumped water the *power available is reduced* on account of losses occuring in primemovers.

Advantages. The pump storage plants entail the following *advantages* :

1. There is substantial increase in peak load capacity of the plant at comparatively low capital cost.
2. Due to load comparable to rated load on the plant, the operating efficiency of the plant is high.
3. There is an improvement in the load factor of the plant.
4. The energy available during peak load periods is higher than that of during off peak periods so that inspite of losses incurred in pumping there is *over-all gain*.
5. Load on the hydro-electric plant remains uniform.
6. The hydro-electric plant becomes partly independent of the stream flow conditions.

Under pump storage projects almost 70 percent power used in pumping the water can be recovered. In this field the use of "*Reversible Turbine Pump*" units is also worth noting. These units can be used as turbine while generating power and as pump while pumping water to storage. The generator in this case works as motor during reverse operation. The efficiency in such case is high and almost the same in both the operations. With the use of reversible turbine pump sets, additional capital investment on pump and its motor can be saved and the scheme can be worked more economically.

6.6.10. Mini and Microhydel Plants

In order to meet with the present energy crisis partly, a solution is to develop *mini* (5 m to 20 m head) and *micro* (less than 5 m head) hydel potential in our country. The low head hydro-potential is scattered in this country and estimated potential from such sites could be as much as 20,000 MW.

By proper planning and implementation, it is possible to commission a small hydro-generating set up of 5 MW with a period of one and half year against the period of a decade or two for large capacity power plants. Several such sets upto 1000 kW each have been already installed in Himachal Pradesh, U.P., Arunachal Pradesh, West Bengal and Bhutan.

To reduce the cost of micro-hydel stations than that of the cost of conventional installation the following considerations are kept in view :

1. The civil engineering work needs to be kept to a *minimum* and designed to fit in with already existing structures *e.g.* irrigation, channels, locks, small dams etc.
2. The machines need to be manufactured in a small range of sizes of simplified design, allowing the use of unified tools and aimed at reducing the cost of manufacture.
3. These installations must be automatically controlled to reduce attending personnel.
4. The equipment must be simple and robust, with easy accessibility to essential parts for maintenance.
5. The units must be light and adequately subassembled for ease of handling and transport and to keep down erection and dismantling costs.

Micro-hydel plants (micro-stations) *make use of standardised bulb sets with unit output ranging from 100 to 1000 kW working under heads between 1.5 to 10 metres.*

6.7. HYDRAULIC TURBINES

A ***hydraulic turbine*** *converts the potential energy of water into mechanical energy which in turn is utilised to run an electric generator to get electric energy.*

6.7.1. Classification of Hydraulic Turbines

The hydraulic turbines are classified as follows :

(*i*) According to the head and quantity of water available.

(*ii*) According to the name of the originator.

(*iii*) According to the action of water on the moving blades.

(*iv*) According to the direction of flow of water in the runner.

(*v*) According to the disposition of the turbine shaft.

(*vi*) According to the specific speed N_s.

1. According to the head and quantity of water available :

(*i*) *Impulse turbine*—requires *high head* and *small quantity of flow.*

(*ii*) *Reaction turbine*—requires *low head* and *high rate of flow.*

Actually there are two types of reaction turbines, one for medium head and medium flow and the other for low head and large flow.

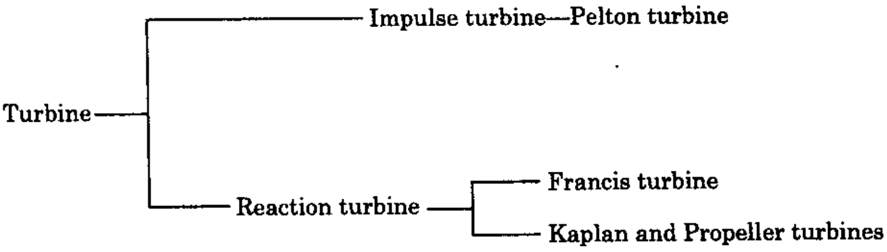
2. According to the name of the originator :

(*i*) *Pelton turbine*—named after Lester Allen Pelton of California (USA). It is an impulse type of turbine and is used for *high head* and *low discharge.*

(*ii*) *Francis turbine*—named after James Bichens Francis. It is a reaction type of turbine for *medium high to medium low heads* and *medium small to medium large quantities of water.*

(*iii*) *Kaplan turbine*—named after Dr. Victor Kaplan. It is a *reaction type of turbine for low heads and large quantities of flow.*

3. According to action of water on the moving blades :



4. According to direction of flow of water in the runner :

(*i*) Tangential flow turbine (Pelton turbine)

(*ii*) Radial flow turbine (no more used)

(*iii*) Axial flow turbine (Kaplan turbine)

(*iv*) Mixed (radial and axial) flow turbine (Francis turbine)

In *tangential flow* turbine of Pelton type the water strikes the runner tangential to the path of rotation.

In *axial flow* turbine water flows parallel to the axis of the turbine shaft. Kaplan turbine is an axial flow turbine. In Kaplan turbine the runner blades are *adjustable and can be rotated* about pivots fixed to the boss of the runner. If the runner blades of the axial flow turbines are *fixed*, these are called *"Propeller turbines"*.

In *mixed flow* turbines the water enters the blades radially and comes out axially, parallel to the turbine shaft. Modern Francis turbines have mixed flow runners.

5. According to the disposition of the turbine shaft :

Turbine shaft may be either vertical or horizontal. In modern turbine practice, Pelton turbines usually have horizontal shafts whereas the rest, especially the large units, have vertical shafts.

6. According to specific speed :

The *specific speed* of a turbine is defined as the speed of a geometrically similar turbine that would develop *one brake horsepower* under the *head of one metre.* All geometrically similar turbines (irrespective of their sizes) will have the same specific speed when operating under the same conditions of head and flow.

$$\text{Specific speed} \qquad N_s = \frac{N\sqrt{P_t}}{H^{5/4}}$$

where, N = The normal working speed in r.p.m.,

P_t = Power output of the turbine, and

H = The net or effective head in metres.

The specific speeds for the various types of runners are given below :

Type of turbine	*Type of runner*	*Specific speed (N_s)*
Pelton	Slow	10 to 20
	Normal	20 to 28
	Fast	28 to 35
Francis	Slow	60 to 120
	Normal	120 to 180
	Fast	180 to 300
Kaplan	—	300 to 1000

Turbines with low specific speeds work under a high head and low discharge condition, while high specific speed turbines work under low head and high discharge conditions.

6.7.2. Description of Various Types of Turbines

6.7.2.1. Impulse Turbines

Pelton wheel, among the various impulse turbines that have been designed and utilized, is by far the important. The Pelton wheel or Pelton turbine is a *tangential flow impulse turbine*. It consists of a rotor, at the periphery of which are mounted equally spaced double-hemispherical or double-ellipsoidal buckets. Water is transferred from a high head source through penstock pipes. A branch pipe from each penstock pipe ends in a nozzle, through which the water flows out as a high speed jet. A needle or spear moving inside the nozzle controls the water flow through the nozzle and at the same time, provides a smooth flow with negligible energy loss. All the available *potential energy is thus converted into kinetic energy* before the jet strikes the buckets. The pressure all over the wheel is *constant and equal to atmosphere, so that energy transfer occurs due to purely impulse action.*

Fig. 6.21 shows a schematic diagram of a Pelton wheel, while Fig. 6.22 shows two views of its bucket.

The jet emerging from the nozzle hits the splitter symmetrically and is equally distributed into the two halves of hemispherical bucket as shown. *The bucket centre-line cannot be made exactly like a mathematical cusp, partly because of manufacturing difficulties and partly because the jet striking the cusp invariably carries particles of sand and other abrasive materials which tend to wear it down.* The inlet angle of the jet is therefore between 1° and 3°, but it is always assumed to be zero in all calculations. Theoretically, if the bucket were exactly hemispherical, it would deflect the jet through 180°. Then, the relative velocity of the jet leaving the bucket, C_{r_2}, would be opposite in direction to the relative velocity of the entering jet C_{r_1}. This cannot be achieved in practice since the jet leaving the bucket would then strike the *back of the succeeding bucket to cause splashing and interference so that the overall turbine efficiency would fall to low values.* Hence, in practice, the angular deflection of the jet in the bucket is limited to about 165° or 170°, and the *bucket is therefore slightly smaller than a hemisphere in size.*

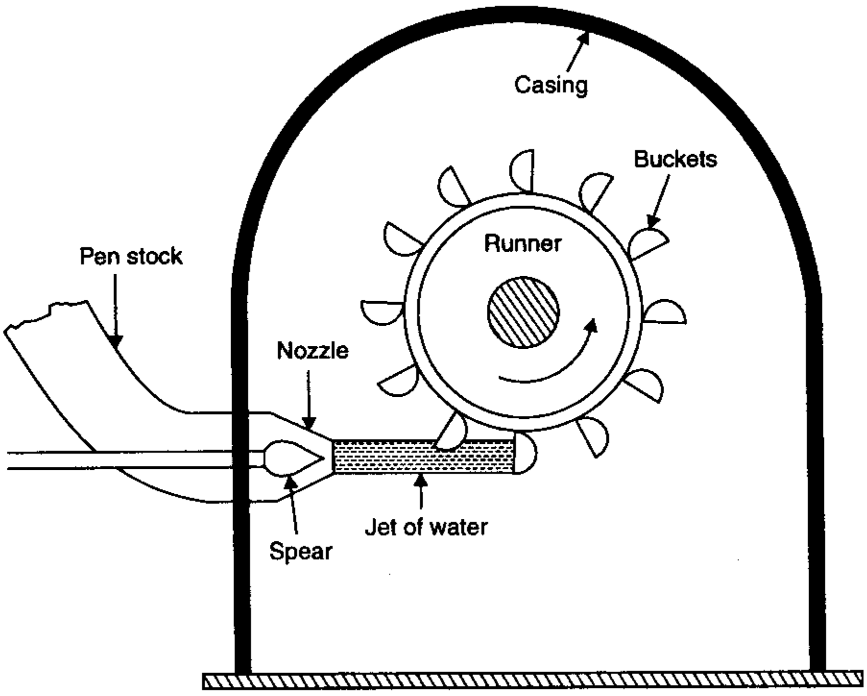
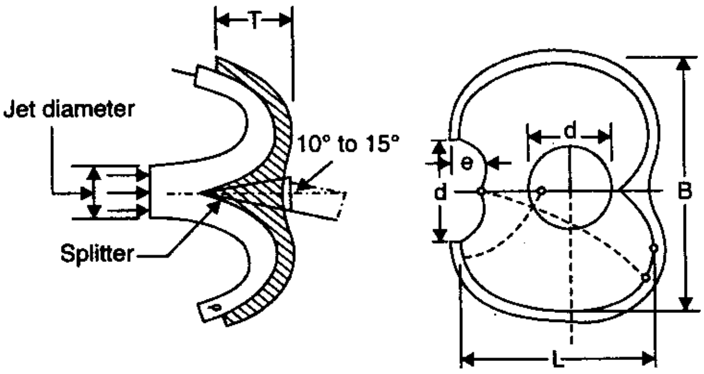


Fig. 6.21. Pelton wheel.



$\frac{L}{d} = 2.5 - 2.8$, $\frac{D}{d} = 14 - 16$, $\frac{T}{d} = 0.95$, Notch (width) = 1.1d + 5 mm

Fig. 6.22. The bucket dimensions.

Fig. 6.23 shows a section through horizontal-impulse turbine.

Velocity triangles

Refer Fig. 6.24.

Let, C_{bl} = Peripheral (or circumferential) velocity of runner. It will be same at inlet and outlet of the runners at the mean pitch diameter (*i.e.*, $C_{bl_1} = C_{bl_2} = C_{bl}$),

C_1 = absolute velocity of water jet at inlet,

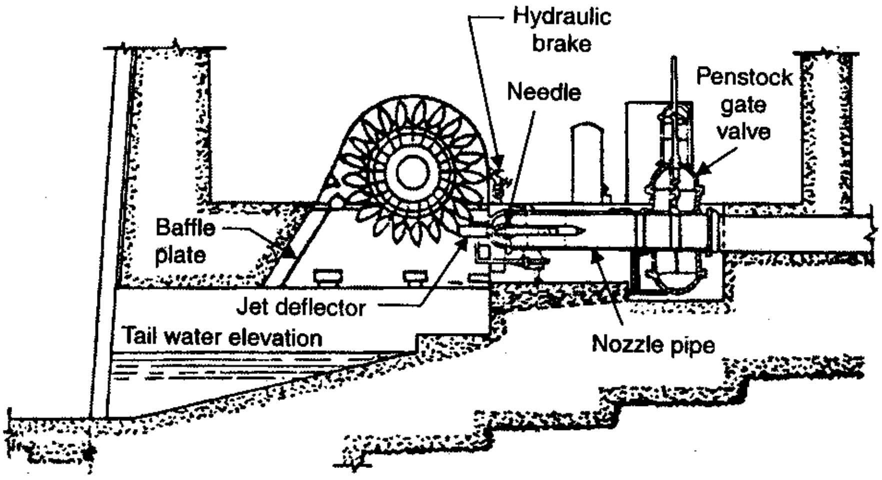


Fig. 6.23. Section through horizontal-impulse turbine.

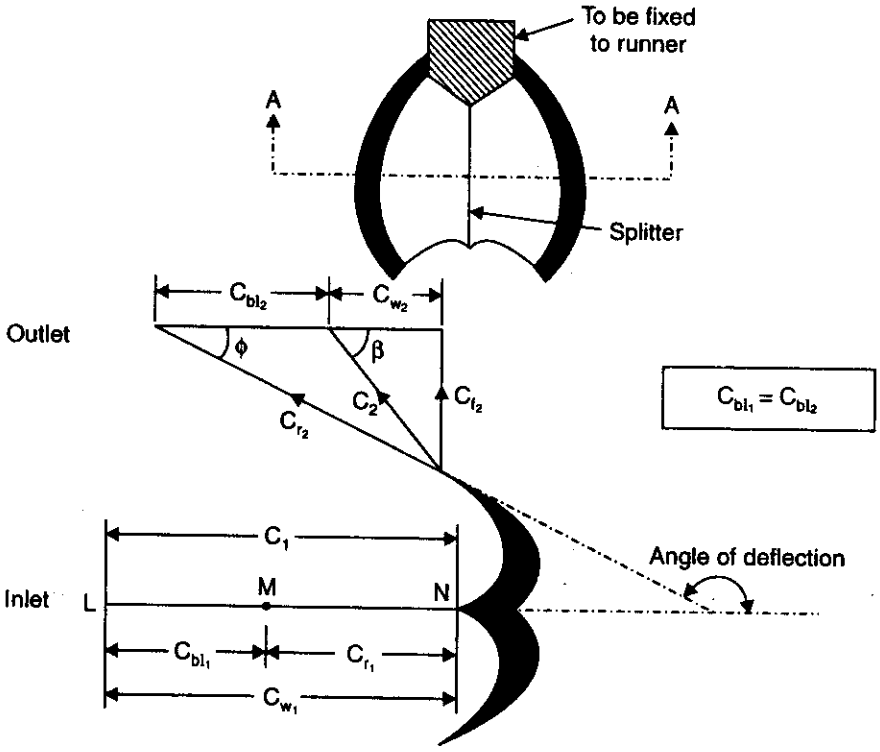


Fig. 6.24

C_{r_1} = Jet velocity relative to vane/bucket at inlet,

α = Angle between the direction of the jet and direction of motion of the vane/bucket (also called *guide angle*),

θ = angle made by the relative velocity (C_{r_1}) with the direction of motion at inlet (also called *vane angle at inlet*),

C_{w_1} and C_{f_1} = the components of the velocity of the jet C_1, in the direction of motion and perpendicular to the direction of motion of the vane respectively.

C_{w_1} is also known as *velocity of whirl* at inlet

C_{f_1} is also known as *velocity of flow* at inlet

C_2 = Velocity of jet, leaving the vane or velocity of jet at outlet of the vane.

C_{r_2} = Relative velocity of the jet with respect to the vane at outlet.

ϕ = Angle made by the relative velocity C_{r_2}, with the direction of motion of vane at outlet and also called *vane angle at outlet.*

β = Angle made by the velocity C_2 with the direction of motion of the vane at outlet.

C_{w_2} and C_{f_2} = Components of the velocity C_2, in the direction of motion of vane and perpendicular to the direction of motion of vane at outlet.

C_{w_2} is also called the *velocity of whirl at outlet*

C_{f_2} is also called *velocity of flow at outlet.*

Inlet. The velocity triangle at *inlet* will be a straight line where

$$C_{r_1} = C_1 - C_{bl_1} = C_1 - C_{bl}$$

$$C_{w_1} = C_1$$

$$\alpha = 0 \quad \text{and} \quad \theta = 0$$

Outlet. From the velocity triangle at outlet, we have

$$C_{r_2} = C_{r_1} \text{ (assuming no friction)}$$

and

$$C_{w_2} = C_{r_2} \cos\phi - C_{bl_2} = C_{r_2} \cos\phi - C_{bl}$$

The force exerted by the jet of water in the direction of motion is given as

$$F = \rho a C_1 (C_{w_1} + C_{w_2}) \quad \text{...(6.1)}$$

[ρ and a are mass density and area of jet ($a = \pi/4\, d^2$) respectively]

Now the work done by the jet on the runner per second

$$= F \times C_{bl}$$

$$= \rho a C_1 (C_{w_1} + C_{w_2}) \times C_{bl} \quad \text{....(6.2)}$$

Work done/sec per unit weight of water striking

$$= \frac{\rho a C_1 (C_{w_1} + C_{w_2}) \times C_{bl}}{\text{Weight of water striking}} = \frac{\rho a C_1 (C_{w_1} + C_{w_2}) \times C_{bl}}{\rho a C_1 \times g}$$

$$= \frac{1}{g}(C_{w_1} + C_{w_2}) \times C_{bl} \quad \text{...(6.3)}$$

The energy supplied to the jet at inlet is in the form of kinetic energy and is equal to $\frac{1}{2} mC^2$.

$\therefore$ Kinetic energy (K.E.) of jet per second = $\frac{1}{2}(\rho a C_1) \times C_1^2$

$\therefore$ Hydraulic efficiency, $\eta_h = \dfrac{\text{Work done per second}}{\text{K.E. of jet per second}} = \dfrac{\rho a C_1 (C_{w_1} + C_{w_2}) \times C_{bl}}{\frac{1}{2}(\rho a C_1) \times C_1^2}$

$$= \frac{2(C_{w_1} + C_{w_2}) \times C_{bl}}{C_1^2} \qquad \text{...(6.4)}$$

Now $C_{w_1} = C_1,\ C_{r_1} = C_1 - C_{bl_1} = (C_1 - C_{bl})$

$\therefore$ $C_{r_2}\ (= C_{r_1}) = C_1 - C_{bl}$

and $C_{w_2} = C_{r_2} \cos\phi - C_{bl_2} = C_{r_2} \cos\phi - C_{bl} = (C_1 - C_{bl}) \cos\phi - C_{bl}$

Substituting the value of C_{w_1} and C_{w_2} in eqn. (6.4), we get

$$\eta_h = \frac{2[C_1 + (C_1 - C_{bl}) \cos\phi - C_{bl}] \times C_{bl}}{C_1^2} = \frac{2[(C_1 - C_{bl}) + (C_1 - C_{bl}) \cos\phi] \times C_{bl}}{C_1^2}$$

$$= \frac{2(C_1 - C_{bl})(1 + \cos\phi)\, C_{bl}}{C_1^2} \qquad \text{...(6.5)}$$

The efficiency will be maximum for a given value of C_1 when

$$\frac{d}{dC_{bl}}(\eta_h) = 0$$

or

$$\frac{d}{dC_{bl}}\left[\frac{2\, C_{bl}\,(C_1 - C_{bl})(1 + \cos\phi)}{C_1^2}\right] = 0$$

$$\frac{(1 + \cos\phi)}{C_1^2} \cdot \frac{d}{dC_{bl}}(2C_{bl}\, C_1 - 2C_{bl}^2) = 0$$

or

$$\frac{d}{dC_{bl}}(2C_{bl}\, C_1 - 2C_{bl}^2) = 0 \qquad \left(\because\ \frac{1 + \cos\phi}{C_1^2} \neq 0\right)$$

$$2C_1 - 4C_{bl} = 0$$

$$C_{bl} = \frac{C_1}{2} \qquad \text{...(6.6)}$$

The above equation states that *hydraulic efficiency of a Pelton wheel is maximum when the velocity of the wheel is half the velocity of the jet of water at inlet.* The maximum efficiency can be obtained by substituting the value of $C_{bl} = \frac{C_1}{2}$ in eqn. (6.5).

$$\therefore \quad \text{Max. } \eta_h = \frac{2\left[C_1 - \frac{C_1}{2}\right](1 + \cos\phi) \times \frac{C_1}{2}}{C_1^2} = \frac{2 \times \frac{C_1}{2}(1 + \cos\phi)\frac{C_1}{2}}{C_1^2}$$

$$= \left(\frac{1 + \cos\phi}{2}\right) \qquad \text{...(6.7)}$$

Important relations for Pelton wheel :

1. The velocity of the jet at inlet is given by

$$C_1 = C_v \sqrt{2gH}$$

where C_v = Coefficient of velocity = 0.98 or 0.99 and H = Net head on turbine.

2. The velocity of wheel (C_{bl}) is given by

$$C_{bl} = \phi \sqrt{2gH}$$

where ϕ = Speed ratio. It varies from 0.43 to 0.48.

3. The angle of deflection of the jet through buckets is taken as 165° if no angle of deflection is given.

4. The mean diameter or the pitch diameter D of the Pelton wheel is given by

$$C_{bl} = \frac{\pi DN}{60} \quad \text{or} \quad D = \frac{60C_{bl}}{\pi N}.$$

5. Jet ratio $(M) = \frac{D}{d}$ (= 12 for most cases) ...(6.8)

$$\begin{bmatrix} D = \text{Pitch diameter of the Pelton wheel} \\ d = \text{Diameter of the jet} \end{bmatrix}$$

6. Number of *buckets* on a runner $= 15 + \frac{D}{2d} = 15 + 0.5M$ ...(6.9)

7. *Number of jets* is obtained by dividing the total rate of flow through the turbine by the rate of flow of water through a single jet.

6.7.2.2. Reaction turbines

In reaction turbines, the *runner utilizes both potential and kinetic energies*. As the water flows through the stationary parts of the turbine, whole of its pressure energy is not transferred to kinetic energy and when the water flows through the moving parts, there is a change both in the pressure and in the direction and velocity of flow of water. As the water gives up its energy to the runner, both its pressure and absolute velocity get reduced. The water which acts on the runner blades is under *a pressure above atmospheric and the runner passages are always completely filled with water*.

Francis turbines

Refer Fig. 6.25 (*a*), (*b*). The modern Francis water turbine is an *inward mixed flow reaction turbine i.e.* the water under pressure, *enters the runner from the guide vanes towards the centre in radial direction and discharges out of the runner axially*. The Francis turbine operates under *medium heads* and also requires *medium quantity* of water. It is employed in the medium head power plants. This type of turbine covers a wide range of heads. Water is brought down to the turbine and directed to a number of stationary orifices fixed all around the circumference of the runner. These stationary orifices are commonly termed as *guide vanes or wicket gates*.

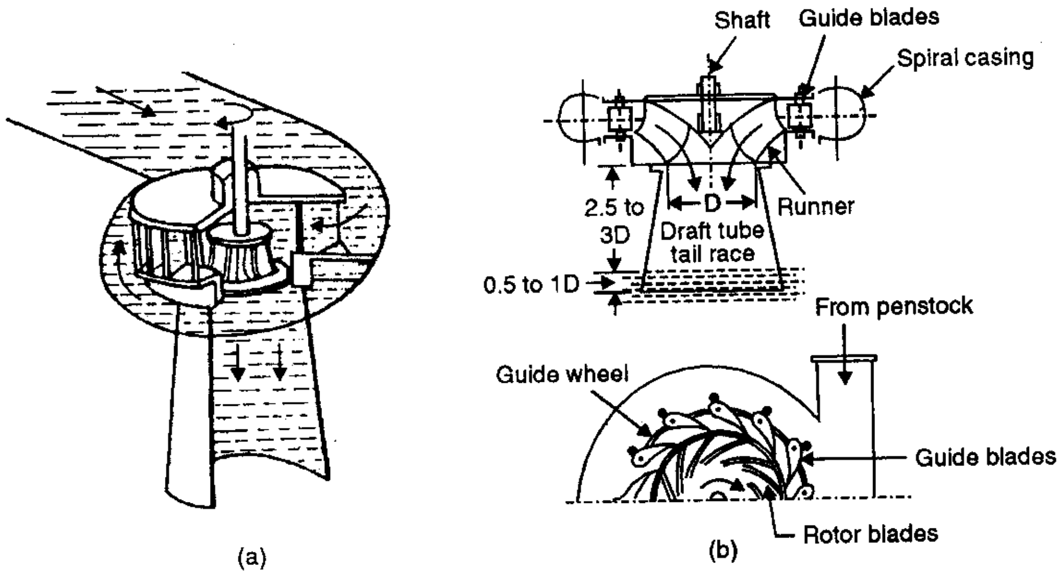


Fig. 6.25. Schematic diagram of a Francis turbine.

The head acting on the turbine is partly transformed into kinetic energy and the rest remains as pressure head. There is a difference of pressure between the guide vanes and the runner which is called the *reaction pressure* and is responsible for the motion of the runner. That is why a Francis turbine is also known as *reaction turbine.*

In Francis turbine the pressure at the inlet is more than that at the outlet. This means that the water in the turbine must flow in a closed conduit. Unlike the Pelton type, where the water strikes only a few of the runner buckets at a time, in the Francis turbine the *runner is always full of water. The moment of the runner is affected by the change of both the potential and the kinetic energies of water.* After doing its work the water is discharged to the tail race through a closed tube of gradually enlarging section. This tube is known as *draft tube*. It does not allow water to fall freely to tail race level as in the Pelton turbine. The free end of the draft tube is submerged deep in the tail water making, thus, the entire water passage, right from the head race upto the tail race, totally enclosed.

The inlet and outlet triangles are shown in the Fig. 6.26.

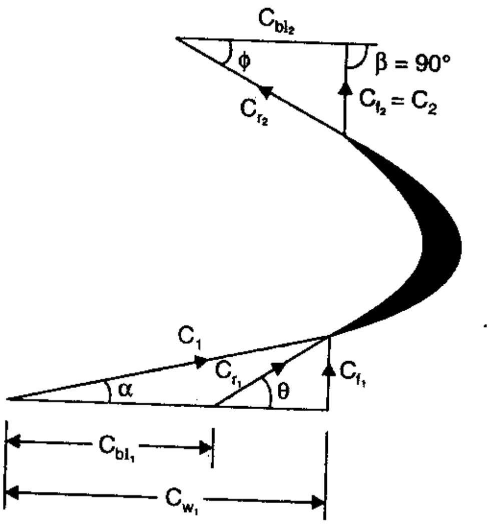


Fig. 6.26

As in case of Francis turbine, the discharge is axial at outlet, the velocity of whirl at outlet (*i.e.*, C_{w_2}) will be zero. Hence the work done by water on the runner per second will be

$$= \rho Q(C_{w_1} \; C_{bl_1})$$

And work done per second per unit weight of water

$$= \frac{1}{g} [C_{w_1} \; C_{bl_1}]$$

Hydraulic efficiency will be given by,

$$\eta_h = \frac{C_{w_1} C_{bl_1}}{gH} \qquad ...(6.10)$$

Important relations for Francis turbine :

1. The ratio of width of the wheel to its diameter varies from 0.10 to 0.40.
2. Flow ratio = $\frac{C_{f_1}}{\sqrt{2gH}}$ and varies from 0.15 to 0.30.

3. The speed ratio = $\frac{C_{bl_1}}{\sqrt{2gH}}$ and varies from 0.6 to 0.9.

Fig. 6.27 shows a plate-steel spiral-case setting of vertical Francis turbine, welded casing.

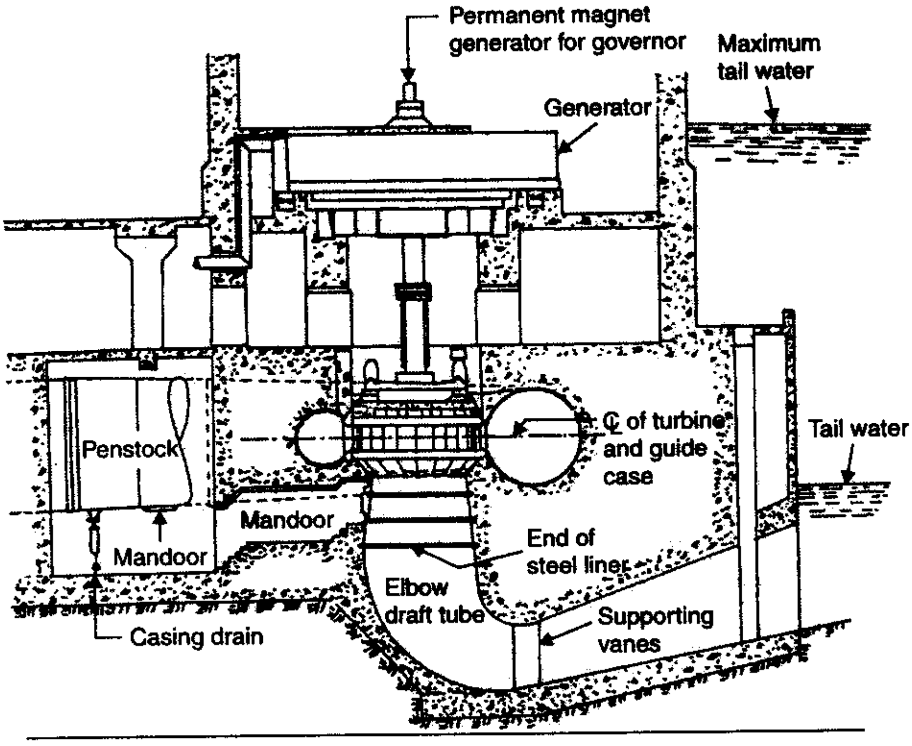


Fig. 6.27. Plate-steel spiral-case setting of vertical Francis turbine, welded casing.

Propeller and Kaplan turbines

The need to utilize low heads where large volumes of water are available makes it essential to provide a large flow area and to run the machine at very low speeds. The propeller turbine is a reaction turbine used for heads between 4 m and 80 m, and has a specific speed ranging from 300 to 1000. It is purely *axial-flow* device providing the largest possible flow area that will utilize a large volume of water and still obtain flow velocities which are not too large.

The propeller turbine (Fig. 6.28) consists of an axial-flow runner with four to six or at most ten blades of air-foil shape. The spiral casing and guide blades are similar to those in Francis turbines. In the **propeller turbine** as in Francis turbine the runner blades are *fixed* and *non-adjustable*. However in a *Kaplan turbine* (Fig. 6.29), which is modification of propeller turbine the runner blades are *adjustable and can be rotated about pivots fixed to the boss of the runner. The blades are adjusted automatically by servo-mechanism so that at all loads the flow enters them without shock.*

Kaplan turbines have taken the place of Francis turbines for certain medium head installations. Kaplan turbines with shoping guide vanes to reduce the overall dimensions are being used.

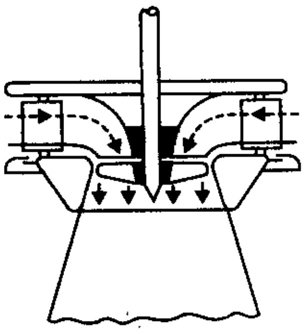


Fig. 6.28. Propeller turbine.

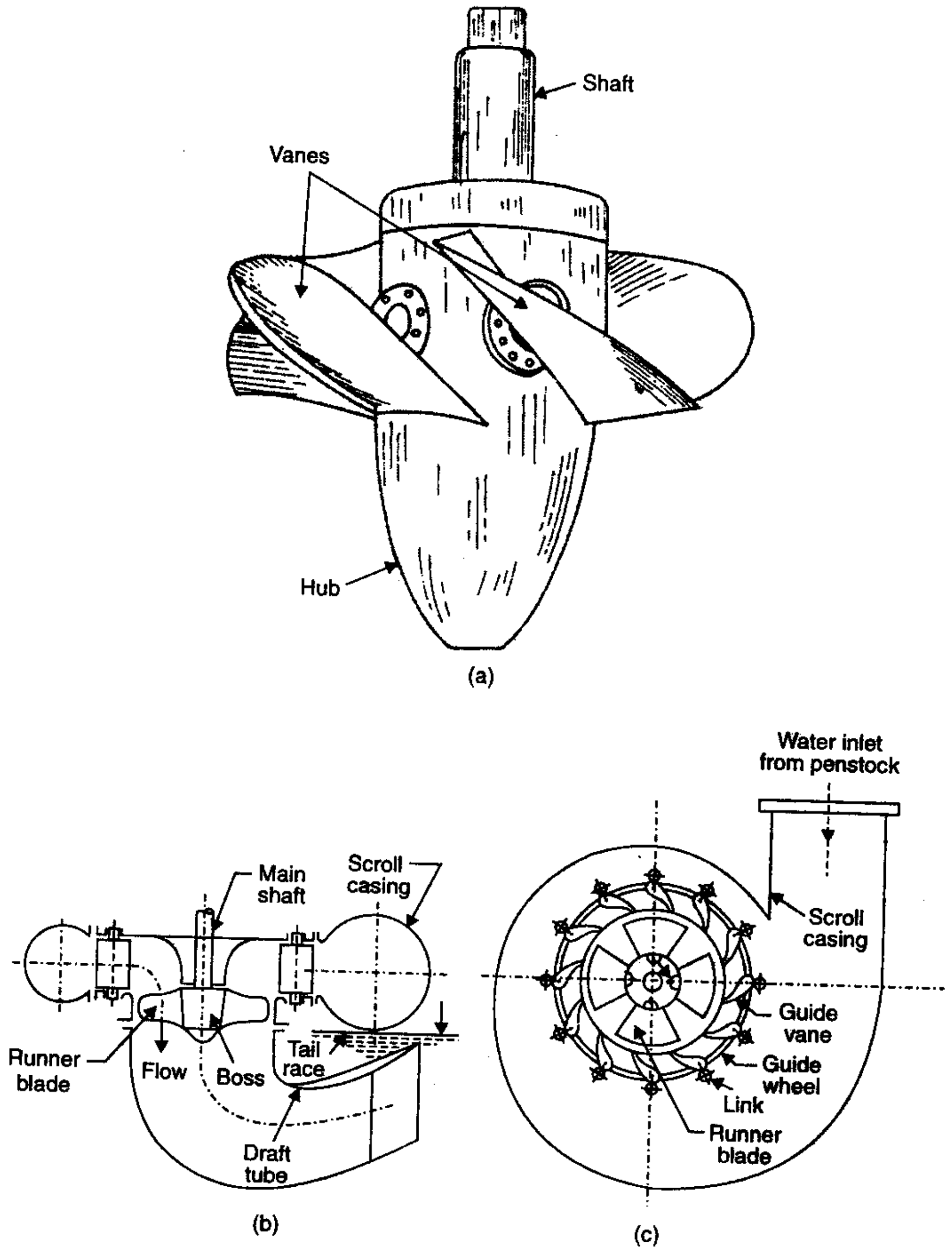


Fig. 6.29. Schematic diagram of a Kaplan turbine.

Fig. 6.30 shows a cross-section of typical low head concrete spiral-case setting, with Kaplan turbine.

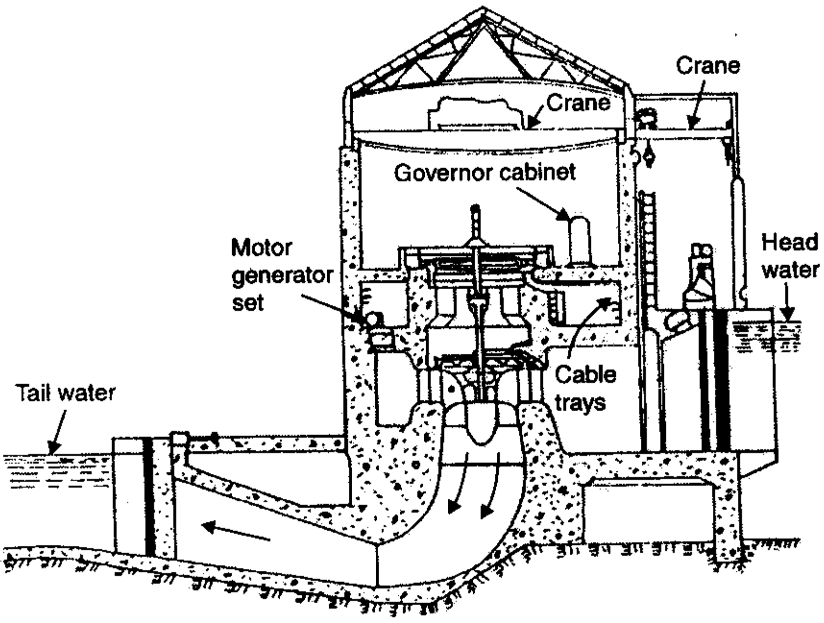


Fig. 6.30. Cross-section of typical low head concrete spiral-case setting, with Kaplan turbine.

Important Kaplan Turbine Installations in India

S.No.	Scheme/Project	Location (State)	Source of water
1.	Bhakra-Nangal project	Gangwal & Kota (Punjab)	Nangal hydel
2.	Hirakud dam project	Hirakud (Orissa)	Mahanadi river
3.	Nizam Sagar project	Nizam sagar (Andhra Pradesh)	Nanjira river
4.	Radhanagri hydroelectric scheme	Kolhapur (Maharashtra)	Bhagvati river
5.	Tungbhadra hydroelectric scheme	Tungbhadra (Karnataka)	Tungbhadra river

Differences between Francis Turbine and Kaplan Turbine

S.No.	Aspect	Francis turbine	Kaplan turbine
1.	*Type of turbine*	Radially inward or mixed flow	Partially axial flow
2.	*Disposition of shaft*	Horizontal or vertical	Only vertical
3.	*Adjustability of runner vanes*	Runner vanes are *not* adjustable	Runner vanes are adjustable
4.	*Number of vanes*	Large, 16 to 24 blades	Small 3 to 8 blades
5.	*Resistance to be overcome*	Large, (owing to large number of vanes and greater area of contact with water)	Less (owing to fewer number of vanes and less wetted area)
6.	*Head*	Medium (60 m to 250 m)	Low (upto 30 m)
7.	*Flow rate*	Medium	Large
8.	*Specific speed*	50-250	250-850
9.	*Type of governor*	Ordinary	Heavy duty

Working proportions :

The expressions for work done, efficiency and power developed by axial flow propeller and Kaplan turbines are identical to those of a Francis turbine, and the working proportions are obtained in an identical fashion. However, the following *deviations need to be noted carefully.*

1. In case of a propeller/Kaplan turbine, the ratio n is taken as $\frac{D_b}{D_0}\left(\text{and not } \frac{B}{D}\right)$,

where, D_0 = Outside diameter of the runner, and

D_b = Diameter of boss (or hub).

Discharge Q = Area of flow × velocity of flow

$$= \frac{\pi}{4}(D_0^2 - D_b^2) \times V_f = \frac{\pi}{4}(D_0^2 - D_b^2) \times K_f\sqrt{2gH} \qquad \text{(where } K_f = \text{flow ratio)}$$

or

$$Q = \frac{\pi}{4}D_0^2(1-n^2) \times K_f\sqrt{2gH} \qquad \ldots(6.9) \quad \left(\because\ n = \frac{D_b}{D_0};\ D_b = nD_0\right)$$

The value of n ranges from 0.35 to 0.60.

The value of $K_f \simeq 0.70$.

2. The peripheral velocity u of the runner vanes depends upon the radius of the point under consideration and thus the blade angles vary from the rim to the boss and the vanes are *warped* ; this is necessary to *ensure shock free entry and exit.*

3. The *velocity of flow remains constant throughout.*

Fig. 6.31 shows the comparison of efficiencies of propeller (fixed blades) and Kaplan turbines.

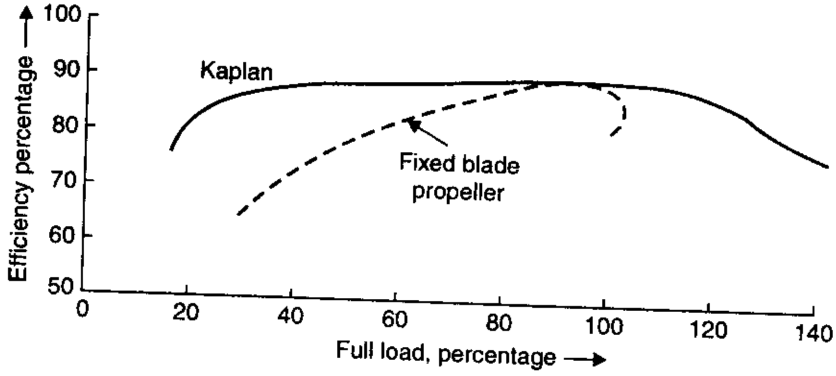


Fig. 6.31. Comparison of efficiencies of propeller (fixed blades and Kaplan turbines).

Tubular (or Bulb) turbines

Kaplan turbine when employed for very low head has to be installed below the tail race level, thus requiring a *deep excavation.* Further for Kaplan turbine installation there are a number of bends at inlet casing and the draft tube of elbow type through which the water flows describing 'Z' path giving rise to *continuous losses at the bends.* Whenever the turbine is repaired or dismantled, the generator has to be removed first. The cost of turbine and that of civil engineering works using conventional Kaplan turbine with deep excavation is very high. The efficiency of such plants working under low head is less due to excessive losses at the bends. Therefore, efforts have been made to *reduce the overall cost* and *improve the efficiency of the power plant* keeping these two things in view.

In 1937 Arno Fischer developed in Germany a modified axial flow turbine which is known as *tubular turbine.* The turbo-generator set using tubular turbine has an outer casing having the shape of a bulb. Such a set is now termed as *bulb set* and the turbine used for the set is called a *bulb* *turbine*. The bulb unit is a water tight assembly of turbine and generator with horizontal axis, submerged in a stream of water. The economical harnessing of fairly low heads on major rivers is now possible with high-output bulb turbines.

Fig. 6.32 shows a power station (87300 kW) under a head of 10 m, provided with six 14550 kW bulb sets running at 125 r.p.m.

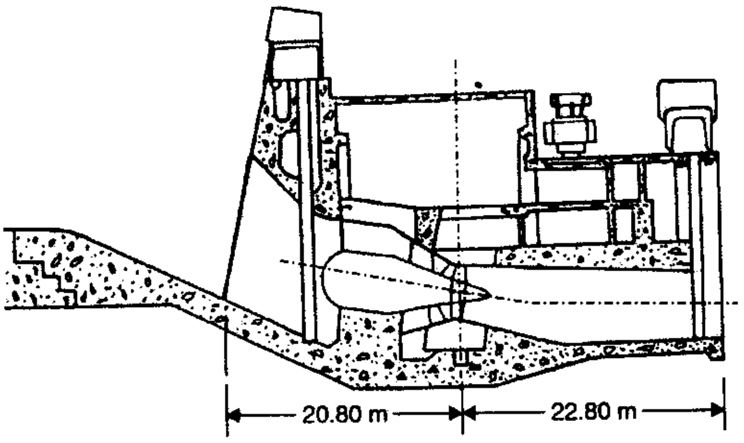


Fig. 6.32. Power station—using bulb turbines.

Runaway speed

'Runaway speed' is the maximum speed, governor being disengaged, at which a turbine would run when there is no external load but operating under design head and discharge. All the rotating parts including the rotor of alternator should be designed for the centrifugal stresses caused by this maximum speed.

The practical values of run away speeds for various turbines with respect to their *rated speed* N are as follows :

Pelton wheel	... 1.8 to 1.9 N
Francis turbine (mixed flow)	... 2.0 to 2.2 N
Kaplan turbine (axial flow)	... 2.5 to 3.0 N

Draft tube

In the case of mixed and axial flow turbines only a part of available energy is converted into velocity energy at the inlet to the runner ; the rest is in the form of pressure energy. This residual pressure is converted into velocity in the runner, as a consequence of which the outlet velocity increases. With the increase in the value of specific speed N_s, the exit velocity energy $\frac{V_2^2}{2g}$ increases compared with H (the available energy).

In the *Pelton Wheel* all the available energy is converted into velocity energy before it strikes the wheel. As such it works under *atmospheric conditions* and the wheel *has to be placed above the maximum tail water level.* The loss of energy due to exit velocity varies from 1 to 4%.

In the case of *mixed and axial flow turbines* a large portion of the energy is associated with the water as it leaves the runner. This exit energy varies from 4 to 25% for mixed flow turbines and from 20 to 50% of the total head for axial flow turbines. As this energy cannot be used in the runner, therefore, it becomes necessary to find a way out to extract this energy. *An expanding pressure* *conduit hermetically fixed at runner outlet and having the other end below the minimum tail water level helps to convert the velocity head into pressure or potential head. This expanding device is called* **draft tube.** Draft tube is an *integral part* of mixed and axial flow turbines. Because of the draft tube *it is possible to have the pressure at runner outlet much below the atmospheric pressure.*

The draft tube serves the following two *purposes* :

1. *It allows the turbine to be set above tail-water level, without loss of head, to facilitate inspection and maintenance.*
2. *It regains, by diffuse action, the major portion of the kinetic energy delivered to it from the runner.*

At rated load, the velocity at the upstream end of the tube for modern units ranges from 7 to 9 m/s, representing from 2.7 to 4.8 m head. As the specific speed (it is the speed of a geometrically similar turbine running under a unit head and producing unit power) is increased and the head reduced, it becomes increasingly important to have an efficient draft tube. Good practice limits the velocity at the discharge end of the tube from 1.5 to 2.1 m/s, representing less than 0.3 m velocity head loss.

Draft tube theory :

Consider a turbine fitted with a draft tube (conical) as shown in Fig. 6.33.

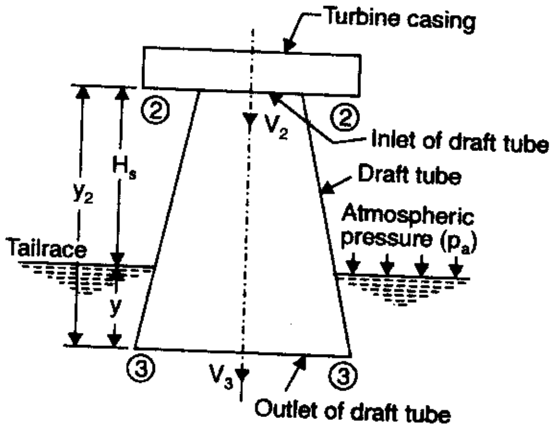


Fig. 6.33. Draft tube theory.

Let y = Distance of the bottom of draft tube from tail race, and p_a = atmospheric pressure at the surface of tail race.

Applying Bernoulli's equation to the section 2-2 (representing the runner exit or inlet of the draft tube) and the section 3-3 (representing the draft tube exit) ; assuming section 3-3 as the datum line, we have

$$\frac{p_2}{w} + \frac{V_2^2}{2g} + y_2 = \frac{p_3}{w} + \frac{V_3^2}{2g} + 0 + h_f \qquad ...(i)$$

where h_f = Loss of energy between sections 2-2 and 3-3.

Rewriting the above expression (i) for $\frac{p_2}{w}$, we obtain

$$\frac{p_2}{w} = \frac{p_3}{w} - y_2 - \left(\frac{V_2^2 - V_3^2}{2g} - h_f\right) \qquad ...(ii)$$

Substituting $\frac{p_3}{w} = \frac{p_a}{w} + y$ in expression (*ii*), we get

$$\frac{p_2}{w} = \frac{p_a}{w} + (y - y_2) - \left(\frac{V_2^2 - V_3^2}{2g} - h_f\right)$$

The term $(y_2 - y)$ which represents the vertical distance between the runner exit and the tail water level is called the **suction head of draft tube** and is denoted by H_s. Correspondingly the factor $\frac{V_2^2 - V_3^2}{2g}$ is called the **dynamic head.**

$$\therefore \quad \frac{p_2}{w} = \frac{p_a}{w} - H_s - \left(\frac{V_2^2 - V_3^2}{2g} - h_f\right) \quad \text{...[6.10 (a)]}$$

In eqn. [6.10 (*a*)], $\frac{p_2}{w}$ is *less than atmospheric pressure.*

The **efficiency of a draft tube** (η_d) is defined as the *ratio of net gain in pressure head to the velocity head at entrance of draft tube.* Thus

$$\eta_d = \frac{\text{Net gain in pressure head}}{\text{Velocity head at entrance of draft tube}} = \frac{\left(\frac{V_2^2 - V_3^2}{2g} - h_f\right)}{\frac{V_2^2}{2g}} \quad \text{...(6.11)}$$

where, V_2 = Velocity of water at section 2-2 (inlet of draft tube).

V_3 = Velocity of water at section 3-3 (outlet of draft tube).

$$[h_f = \frac{V_2^2 - V_3^2}{2g} - \eta_d \times \frac{V_2^2}{2g} \quad \text{...(6.11 (a)]}$$

Types of draft tubes :

The following two types of draft tubes are commonly used :

1. The straight conical or concentric tube ;
2. The elbow type.

Properly designed, the two types are about equally efficient, *over 85 percent.*

1. **Conical type.** The conical type draft tube is *generally* used on *low-powered units for all specific speeds, frequently, on large-head units.* The side angle of flare ranges from 4 to 6°, the length from 3 to 4 times the diameter and the discharge area from four to five times the throat area. Fig. 6.34 shows a straight *conical* draft tube.

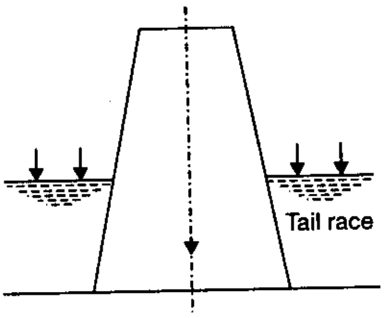


Fig. 6.34. Straight conical draft tube.

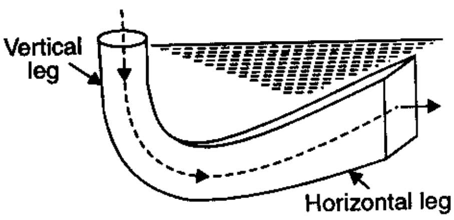


Fig. 6.35. Elbow type draft tube.

2. **Elbow type.** The elbow type of tube is used with *most* turbine installations. This type of draft tube is designed to turn the water from the *vertical to the horizontal direction with a minimum depth of excavation and at the same time having a high efficiency*. The transition from a circular section in the vertical leg to a rectangular section in the horizontal leg takes place in the bend. The horizontal portion of the draft tube is generally *inclined upwards to lead the water gradually to the level of the tail race and to prevent entry of air from the exit end*. The *exit* end of the draft tube *must be totally immersed in water*. Fig. 6.35 shows an elbow type draft tube. One or two vertical piers are placed in the horizontal portion of the tube, for structural and hydraulic reasons.

Moody spreading draft tube. Fig. 6.36 shows a *Moody's spreading draft tube*. It is provided with a *solid central core* of conical shape which *reduces whirling action of discharge water*. The efficiency of such a draft tube is about 85%. It is suited particularly for *helical flows* which occur when the water leaves the runner with a whirl component.

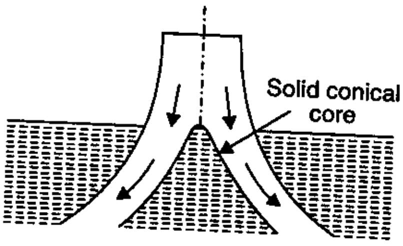


Fig. 6.36. Moody's spreading draft tube or 'Hydrocone'.

Comparison of hydraulic turbines :

A. Francis turbine versus Pelton wheel

The Francis turbine claims the following *advantages* over Pelton wheel :

1. In Francis turbine the variation in the operating head can be more easily controlled.
2. In Francis turbine the ratio of maximum and minimum operating head can be even two.
3. The operating head can be utilized even when the variation in the tail water level is relatively large when compared to the total head.
4. The mechanical efficiency of Pelton decreases faster with wear than Francis.
5. The size of the runner, generator and powerhouse required is small and economical if the Francis turbine is used instead of Pelton wheel for same power generation.

Drawbacks of Francis turbine

As compared with Pelton wheel, the Francis turbine has the following drawbacks :

1. Water which is not clean can cause very rapid wear in high head Francis turbine.
2. The overhaul and inspection is much more difficult comparatively.
3. Cavitation is an ever-present danger.
4. The water hammer effect is more trouble some with Francis turbine.
5. If Francis turbine is run below 50% head for a long period it will not only lose its efficiency but also the cavitation danger will become more serious.

B. Kaplan verses Francis turbine

Kaplan turbine claims the following *advantages* over Francis turbine :

1. For the same power developed Kaplan turbine is more compact in construction and smaller in size.
2. Part-load efficiency is considerably high.
3. Low frictional losses (because of small number of blades used).

6.7.3. Specific Speed of a Turbine

The ***specific speed*** of a turbine is defined *as the speed of a turbine which is identical in shape, geometrical dimensions, blade angles, gate opening etc., with the actual turbine but of such a size that it will develop unit horse power when working under unit head.*

The specific speed may be *derived* as follows :

The overall efficiency (η_0) of any turbine is given by

$$\eta_0 = \frac{\text{Power available at the shaft of the turbine}}{\text{Power supplied at the inlet of the turbine}} = \frac{P}{w \times Q \times H} \qquad ...(i)$$

where, P = Shaft power (S.P.),

Q = Discharge through turbine,

H = Head under which turbine is working,

w = Weight density of water.

From eqn. (*i*),

$$P = \eta_0 \times w \times Q \times H$$

$$\propto Q \times H \text{ (as } \eta_0 \text{ and } w \text{ are constants)} \qquad ...(ii)$$

Now let,

D = Diameter of actual turbine,

N = Speed of actual turbine,

C_{bl} = Tangential velocity of the turbine,

N_s = Specific speed of the turbine, and

C = Absolute velocity of water.

The relation between C, C_{bl} and H is as given below

$$C_{bl} \propto C \text{ where } C \propto \sqrt{H}$$

$$\propto \sqrt{H} \qquad ...(iii)$$

But the tangential velocity C_{bl} is given by

$$C_{bl} = \frac{\pi DN}{60} \propto DN \qquad ...(iv)$$

$\therefore$ From eqns. (*iii*) and (*iv*), we have

$$\sqrt{H} \propto DN \quad \text{or} \quad D \propto \frac{\sqrt{H}}{N} \qquad ...(v)$$

The discharge (Q) through the turbine is given by

$$Q = \text{Area} \times \text{velocity}$$

But Area $\propto B \times D$ (where B = width)

$\propto D^2$ ($\because$ $B \propto D$)

$$\therefore \quad Q \propto D^2 \sqrt{H} \propto \left(\frac{\sqrt{H}}{N}\right)^2 \sqrt{H} \qquad \left[\because \text{ From eqn. } (v),\ D \propto \frac{\sqrt{H}}{N}\right]$$

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

Substituting the value of Q in eqn. (*ii*), we get

$$P \propto \frac{H^{3/2}}{N^2} \times H \propto \frac{H^{5/2}}{N^2}$$

$$\therefore \quad P = K\frac{H^{5/2}}{N^2} \qquad \text{where } K = \text{constant of proportionality.}$$

If P = 1 kW, H = 1 m, the speed N = specific speeds N_s. Substituting these values in the above equation, we get

$$1 = \frac{K \times 1^{5/2}}{N_s^2} \quad \text{or} \quad N_s^2 = K$$

$$\therefore \quad P = N_s^2 \frac{H^{5/2}}{N^2} \quad \text{or} \quad N_s^2 = \frac{N^2 P}{H^{5/2}}$$

$$\therefore \quad N_s = \sqrt{\frac{N^2 P}{H^{5/2}}} = \frac{N\sqrt{P}}{H^{5/4}}$$

i.e.,

$$\text{Specific speed } N_s = \frac{N\sqrt{P}}{H^{5/4}} \qquad \ldots(6.12)$$

(where P is in kW and H in metres)

[N_s (S.I. Units) = 0.86 N_s (metric)]

Specific speed plays an important role for *selecting the type of the turbine*. Also the *performance of a turbine can be predicted* by knowing the specific speed of the turbine.

To compare the characteristics of machines of different types, it is necessary to know a characteristic of an imaginary machine identical in shape. The imaginary turbine is called a *specific turbine*. The specific speed provides a means of comparing the speed of all types of hydraulic turbines on the basis of head and horse power capacity.

If a runner of *high specific speed* is used for a given head horse power output, the *overall cost* of installation is *lower*. The selection of *too* high specific speed reaction runner would reduce the size of the runner to such an extent that the discharge velocity of water into the throat of draft tube would be excessive. This is objectionable because a *vacuum* may be created in the extreme case.

The runner of *too high* specific speed with available head *increases the cost of turbine* on account of high mechanical strength required. The runner of *too low* specific speed with low available head *increases the cost of generator* due to the low turbine speed.

An increase in specific speed of turbine is accompanied by lower maximum efficiency and greater depth of excavation of the draft tube. In choosing a high specific speed turbine, an increase in cost of excavation of foundation and draft tube should be considered in addition to the efficiency. The weighted efficiency over the operating range of turbine is more important in the selection of a turbine instead of maximum efficiency.

Table 6.1 gives the specific speeds for various turbines.

Table 6.1. Specific speeds

Type of turbine		*Specific speed (N_s)*	
		M.K.S. Units	*S.I. Units*
Impulse (Pelton)	Slow	4—10	3.5—8.5
	Normal	10—25	8.5—21.5
	Fast	25—60	21.5—51.5
Radial and mixed flow (Francis and Deriaz)	Slow	60—150	51.5—130
	Normal	150—250	130—215
	Fast	250—400	215—345
Axial flow (Kaplan)	Slow	300—450	255—385
	Normal	450—700	385—600
	Fast	700—1000	600—860

Unit Quantities :

Let us consider a *single unit*. When the head on the unit is changed/varied then the speed of an ungoverned turbine changes. The velocities at various points do not change direction but their magnitudes vary in proportion to the *square root of the head.*

At a given point in the turbine under a head H, let

V = Absolute velocity,
V_r = Relative velocity,
u = Peripheral velocity, and
V', V_r', u' = Corresponding values at a different head H', then as velocity is proportional to $\sqrt{H}$, we have

$$\frac{u}{u'} = \frac{V_r}{V_r'} = \frac{V}{V'} = \frac{\sqrt{H}}{\sqrt{H'}} \quad \text{...(6.13)}$$

If the discharges are Q and Q' then

$$\frac{Q}{Q'} = \frac{V}{V'} = \frac{N}{N'} = \frac{\sqrt{H}}{\sqrt{H'}} \quad \text{...(6.14)}$$

If the power outputs are P and P' then

$$\frac{P}{P'} = \frac{QH}{Q'H'} = \frac{\sqrt{H}}{\sqrt{H'}} \times \frac{H}{H'} = \left(\frac{H}{H'}\right)^{3/2} \quad \text{...(6.15)}$$

$$\left(\because \frac{Q}{Q'} = \frac{\sqrt{H}}{\sqrt{H'}}\right)$$

The hydraulic efficiency of the turbine under these two heads may be considered to be nearly same, as the velocity triangles at these heads are similar at a point.

If the various quantities are *reduced to a theoretical one metre head* the comparison of performance data and computations of experimental values on a single unit are *considerably simplified,*

Then

$$N_u = \frac{N}{\sqrt{H}} \quad \text{...(6.16)}$$

$$Q_u = \frac{Q}{\sqrt{H}} \quad \text{...(6.17)}$$

$$P_u = \frac{P}{H^{3/2}} \quad \text{...(6.18)}$$

The above quantities are called **unit quantities** of a turbine. *Unit speed is the hypothetical speed of the turbine operating under one metre head.* Similarly other proportionality constants in eqns. (6.17) and (6.18) are defined.

For presenting the performance of geometrically similar turbines independent of the actual head, discharge and power output the ***unit characteristics*** prove quite helpful. **Geometrically similar turbines will have the same unit characteristics under similar operating conditions.** Thus with the help of a model the performance of a prototype can be predicted within certain limits.

If a turbine is working under different heads the behaviour of the turbine can be easily known from the values of the *unit quantities* as follows :

Let H_1, H_2 = Heads under which a turbine works,
N_1, N_2 = Corresponding speeds,

Q_1, Q_2 = Corresponding discharges, and

P_1, P_2 = Corresponding power developed.

Then using eqn. (6.16), (6.17), (6.18), respectively, we obtain

$$N_u = \frac{N_1}{\sqrt{H_1}} = \frac{N_2}{\sqrt{H_2}} \quad \text{...(6.19)}$$

$$Q_u = \frac{Q_1}{\sqrt{H_1}} = \frac{Q_2}{\sqrt{H_2}} \quad \text{...(6.20)}$$

$$P_u = \frac{P_1}{H_1^{3/2}} = \frac{P_2}{H_2^{3/2}} \quad \text{...(6.21)}$$

Model Relationship :

(*i*) **Head co-efficient, C_H :**

The tangential velocity of the runner, $u = K_u\sqrt{2gH} = \frac{\pi DN}{60}$

or
$$N = \frac{60\, K_u\sqrt{2gH}}{\pi D} \quad \text{or} \quad N \propto \frac{\sqrt{H}}{D}$$

$\therefore$
$$ND \propto \sqrt{H} \quad \text{or} \quad \frac{H}{N^2D^2} = \text{constant} \quad \text{...(6.22)}$$

The parameter $\frac{H}{N^2D^2}$ is called **head co-efficient,** C_H.

(*ii*) **Capacity or flow co-efficient, C_Q :**

Discharge through the turbine, Q = Area × velocity = $A \times V_f$

But $A \propto D^2$ and $V_f = K_f\sqrt{2gH} \propto \sqrt{H}$

$\therefore$ $Q \propto D^2\sqrt{H}$

Substituting the value of Q in eqn. (6.22), we obtain

$Q \propto D^2 \times ND \propto ND^3$

or $\frac{Q}{ND^3}$ = constant ...(6.23)

The parameter, $\frac{Q}{ND^3}$ is called the **capacity or flow co-efficient, C_Q.**

(*iii*) **Power co-efficient C_p :**

The shaft power available from a turbine,

$$P = \eta_0 \times wQH \propto Q.H.$$

But $Q \propto ND^3$ and $H \propto N^2D^2$ $\therefore$ $P \propto ND^3 \times N^2D^2 \propto N^3D^5$

or
$$\frac{P}{N^3D^5} = \text{constant} \quad \text{...(6.24)}$$

The parameter $\frac{P}{N^3D^5}$ is called the **power co-efficient, C_P.**

With the use of above relations it is possible to present the behaviour of a prototype from the test runs made on a geometrically similar model ; the model is presumed to have the same values of speed ratio K_u, flow ratio K_f and specific speed N_s. A group of geometrically similar machines are said to belong to a homologous series. All machines of such a series have the same value of C_H, C_Q or C_P or their combinations.

6.7.4. Efficiencies of a Turbine

The important efficiencies of a turbine are as under :

1. Hydraulic efficiency, η_h
2. Mechanical efficiency, η_m
3. Volumetric efficiency, η_v
4. Overall efficiency, η_o.

1. **Hydraulic efficiency,** (η_h). It is defined as the *ratio of power developed by the runner of a turbine to the power supplied by the water at the inlet of the turbine.*

$$\eta_h = \frac{\text{Power developed by runner}}{\text{Power developed at inlet}} \qquad ...(6.25)$$

2. **Mechanical efficiency** (η_m). It is defined as the *ratio of power available at the shaft of the turbine* (known as S.H.P. or B.H.P.) *to the power developed by the runner.*

$$\eta_m = \frac{\text{Power available at the shaft of the turbine}}{\text{Power developed by the runner}} \qquad ...(6.26)$$

3. **Volumetric efficiency** (η_v). *The ratio of the volume of the water actually striking the runner to the volume of water supplied to the turbine is called volumetric efficiency.*

$$\eta_v = \frac{\text{Volume of water actually striking the runner}}{\text{Volume of water supplied to the turbine}} \qquad ...(6.27)$$

4. **Overall efficiency** (η_0). It is defined as the *ratio of power available at the shaft of the turbine to the power supplied by the water at the inlet of the turbine.*

$$\eta_0 = \frac{\text{Power available at the shaft of the turbine}}{\text{Power supplied at the inlet of the turbine}} = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{wQH}$$

If η_g is the efficiency of a generator, then power output of a hydro-unit (turbine + hydro generators)

$$= (wQH) \times \eta_o \times \eta_g.$$

6.7.5. Cavitation

It is known that when velocity of flow increases, the pressure falls. In liquids, the pressure cannot fall below vapour pressure which depends upon the temperature and height above mean sea level of the site. *In any turbine part if the pressure drops below the evaporation pressure, the liquid boils and a large number of small bubbles of vapour are formed.* These bubbles mainly formed *on account of low pressure* are carried by the stream to higher pressure zones where the vapours condense and the *bubbles suddenly collapse*, as the vapours are condensed to liquid again. This results in the *formation of a cavity* and the surrounding liquid rushes to fill it. The streams of liquid coming from all directions collide at the centre of cavity giving rise to a *very high local pressure* whose magnitude may be as high as 7000 atmospheres. Formation of cavity and high pressure are repeated many thousand times a second. This causes *pitting on the metallic surface of runner blades or draft tube*. The material then *fails by fatigue*, added perhaps by corrosion. During this process some parts like runner blades may be torn away completely.

'Cavitation' may thus be defined as the "*phenomenon which manifests itself in the pitting of the metallic surfaces of turbine parts because of formation of cavities*".

During 'cavitation' the cavities may be formed on the solid surface or near to it. In case it does not form on solid surface, the *pressure generated in the cavity is propagated by the pressure waves* similar to ones occurring in water hammer. The intense pressure is accompanied by a *considerable vibration and noise.*

Cavitation factor. Prof. Dietrich Thoma of Munich (Germany) suggested a cavitation factor σ (sigma) to *determine the zone* where turbine can work *without being affected from cavitation*. The *critical* value of cavitation factor (σ_c) is given by

$$\sigma_c = \frac{(H_a - H_v) - h}{H} \qquad \text{...(6.28)}$$

where. H_a = Atmospheric pressure head in metre of water,

H_v = Vapour pressure in metre of water corresponding to the water temperature,

H = Working head of turbine (difference between head race and tailrace level in metres), and

h = Height of turbine outlet above tailrace level in metres.

The values of critical factor depends upon the specific speed of the turbine (Refer table 6.2).

Methods to avoid cavitation :

The following methods may be used to *avoid cavitation* :

1. Runner/turbine may be *kept under water*. But it is not advisable as the inspection and repair of the turbine is difficult. The other method to avoid cavitation zone without keeping the runner under water is *to use the runner of low specific speed.*
2. The *cavitation free runner* may be designed to fulfill the given conditions with extensive research.
3. It is possible to reduce the cavitation effect by *selecting materials* which can *resist better the cavitation effect.* The cast steel is better than cast iron and stainless steel or alloy steel is still better than cast steel.
4. The cavitation effect can be reduced by *polishing* the surfaces. That is why the cast steel runners and blades are coated with stainless steel.
5. The 'cavitation' may be avoided by *selecting a runner of proper specific speed for given head.*

Table 6.2. Cavitation factors

Francis		Kaplan	
N_s	σ_c	N_s	σ_c
50	0.04	300 to 450	0.35 to 0.40
100	0.05	450 to 550	0.40 to 0.45
150	0.07	550 to 600	0.46 to 0.6
200	0.1	650 to 700	0.85
250	0.14	700 to 800	1.05
300	0.2	—	—
350	0.27	—	—

6.7.6. Performance of Hydraulic Turbines

In dimensional analysis we may arrive at the following relations :

Head co-efficient or parameter, $\frac{gH}{N^2D^2}$

Capacity or discharge parameter, $\frac{Q}{ND^3}$ or $\frac{Q}{D^2\sqrt{H}}$

Power co-efficient, $\frac{P}{\rho N^3 D^5}$ or $\frac{P}{\rho D^2 H^{3/2}}$

Efficiency of operation, η

The laws of performance are stated as follows from the fact that each of these parameters should remain constant for the same machine or a family of similar machines :

		For the same machine	*For a similar machine*
Discharge Q	$\propto$	N	D^3
Head H	$\propto$	N^2	D^2
Power P	$\propto$	N^3	D^5

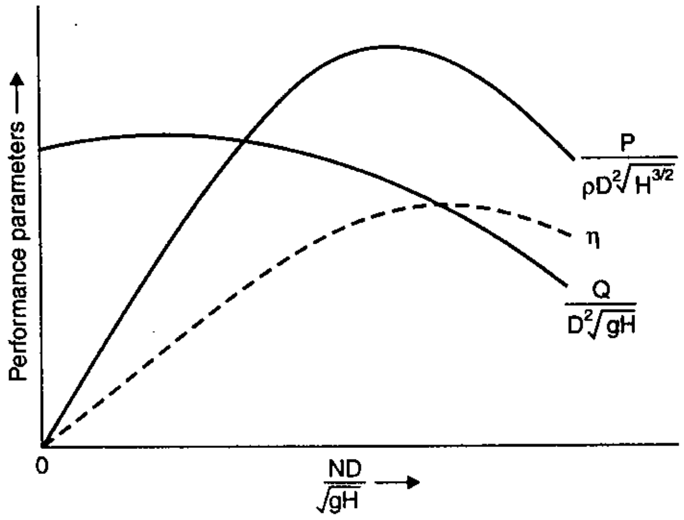
The specific speed $N_s = \dfrac{N\sqrt{P/\rho}}{(gH)^{5/4}}$

Which is the type number of fluid machines that must also remain the same for a family of similar machines operating at the optimum efficiency.

The terms '*unit speed*', '*unit power*' and '*unit discharge*' are frequently used to express the operational features of hydraulic turbines. The unit quantities are theoretical features for a head of 1 metre for the same turbine. Sometimes, the unit quantities are referred to a head of 1 metre for a turbine of 1 metre diameter.

	For unit head	*For unit head and unit diameter*
Unit speed N_u	$\dfrac{N}{\sqrt{H}}$	—
Unit power P_u	$\dfrac{P}{H^{3/2}}$	$\dfrac{P}{D^2H^{3/2}}$
Unit discharge Q_u	$\dfrac{Q}{\sqrt{H}}$	$\dfrac{Q}{D^2\sqrt{H}}$

These definitions follow from the definitions of the head, discharge and power coefficients respectively.



(a) Dimensionless turbine curves

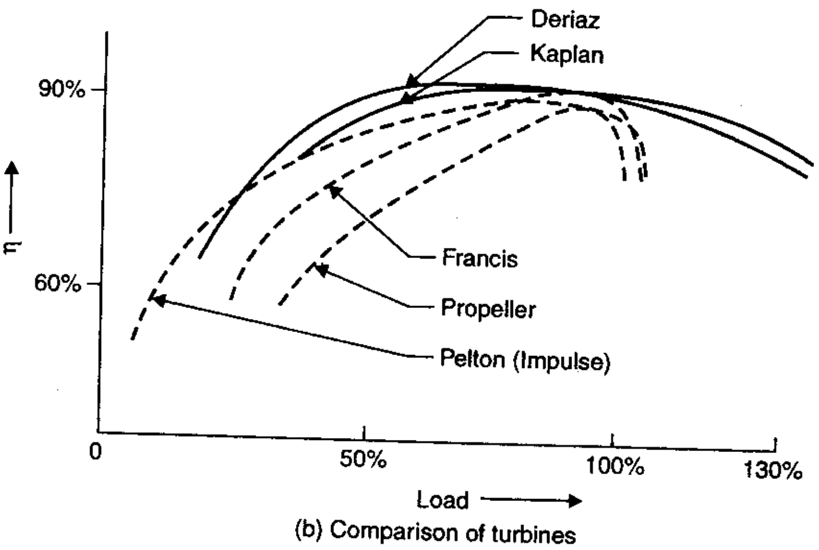
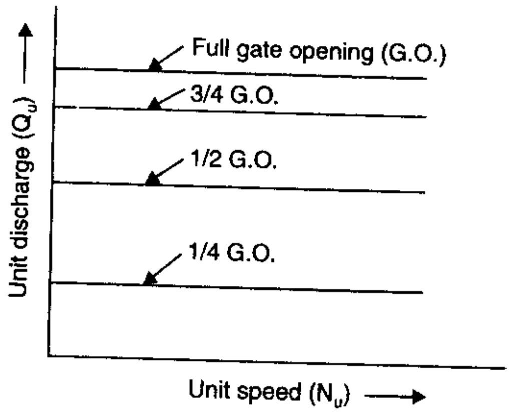


Fig. 6.37. Performance of hydraulic turbines.

The characteristic curves for hydraulic reaction turbines are usually plotted in terms of unit quantities *vs* '*unit*' speed. A set of performance curves are shown plotted in Fig 6.37 (*a*). A comparative set of curves for different types of turbines is shown in Fig 6.37 (*b*). It can be seen that the *Deriaz and Kaplan turbines have the highest efficiency in the entire load range*. This is due to the fact that the runner blades of these two types of turbines are *adjustable during operation*. Consequently the flow is efficient and well-guided by the runner blades at all flow conditions unlike the other turbines where the rotor-vane adjustability is not provided. The guide vanes of each of reaction turbines are adjusted for varying the discharge.

Fig. 6.38 and Fig. 6.39 shows the *main characteristic curves* for a Pelton wheel and reaction turbine respectively.



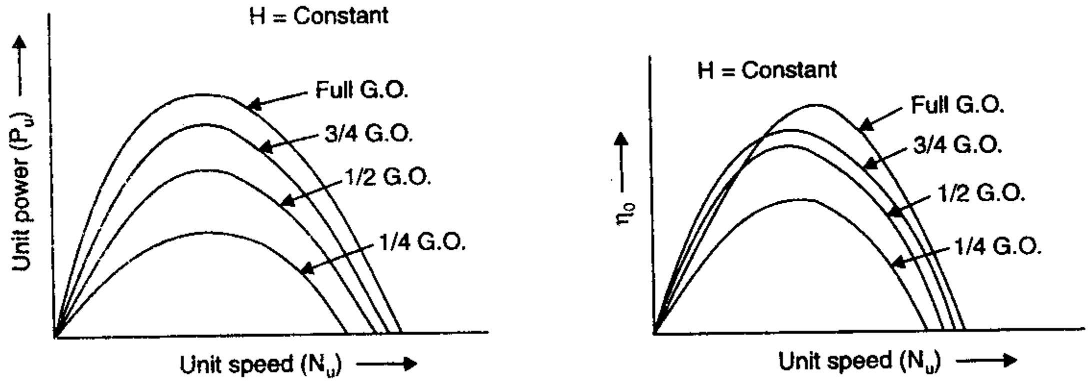
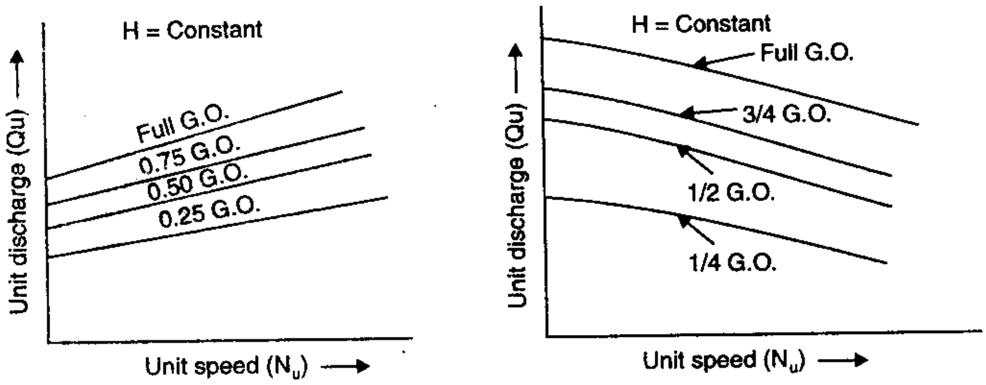


Fig. 6.38. Main characteristic curves for a Pelton wheel.



(a) For Kaplan turbine

(b) For Francis turbine

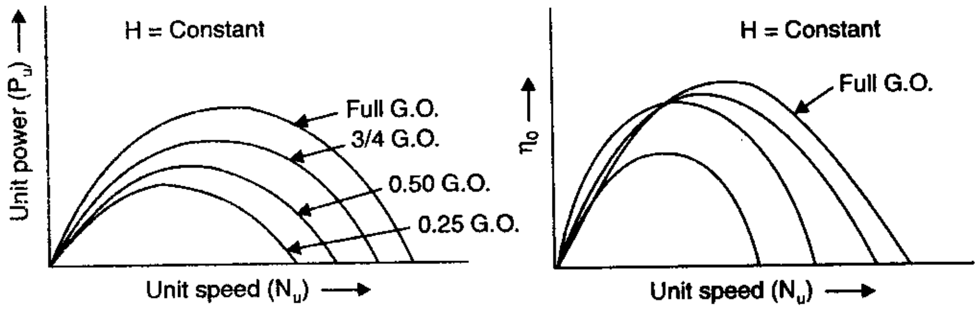


Fig. 6.39

Efficiency load curves

The *efficiency load curves* of various types of *reaction turbines* are shown in Fig 6.40. The efficiency load curve of a Pelton turbine is shown in Fig. 6.41. The efficiency curve of a Pelton turbine remains slightly lower than that of a Francis turbine but is less affected by variation of load.

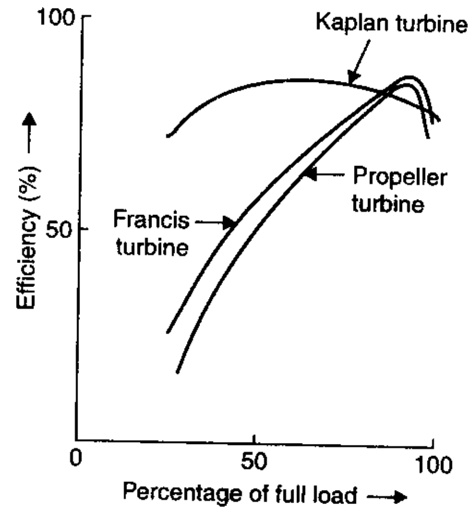


Fig. 6.40. Efficiency-load curves of reaction turbines.

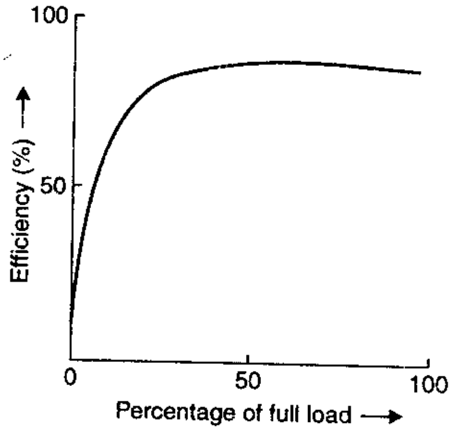


Fig. 6.41. Efficiency-load curve of a Pelton turbine.

6.7.7. Governing of Hydraulic Turbines

Governing of a hydraulic turbine means *speed regulation*. Under normal conditions the turbine should run at a constant speed irrespective of changes in load. This is achieved by means of a governor called oil pressure governor.

Governing of impulse turbine. The quantity of water rejected from the turbine nozzle and from striking the buckets may be regulated in one of the following ways :

1. Spear regulation
2. Deflector regulation
3. Combined spear and deflector regulation.

The spear and deflector in all cases are operated by the servomotor mechanism.

1. Spear regulation. To and fro movement of the spear inside the nozzle alters the cross-sectional area of stream, thus, making it possible to regulate the rate of flow according to the load. Spear regulation is satisfactory *when a relatively large penstock feeds a small turbine and the fluctuation of load is small*. With the sudden fall in load, the turbine nozzle has to be closed suddenly which way create *water hammer in the penstock*.

2. Deflector regulation. The deflector is generally a plate connected to the oil pressure governor by means of levers. When it is required to deflect the jet, the plate can be brought in between the nozzle and buckets, thereby diverting the water away from the runner and directing into the tailrace. Deflector control is adopted *when supply of water is constant* but the *load fluctuates*. The spear position can be adjusted by hand. As the nozzle has always a constant opening, it involves considerable wastage of water and *can be used only when supply of water is abundant*.

3. Combined spear and deflector regulation. Since both the above methods have some disadvantages, the modern turbines are provided with double regulation which is the combined spear and deflector control. Double regulation means regulation of speed and pressure. *The speed is regulated by spear and the pressure is regulated by deflector arrangement.*

Fig. 6.42 shows an arrangement for governing of Pelton turbine when the turbine is running at the *normal speed*.

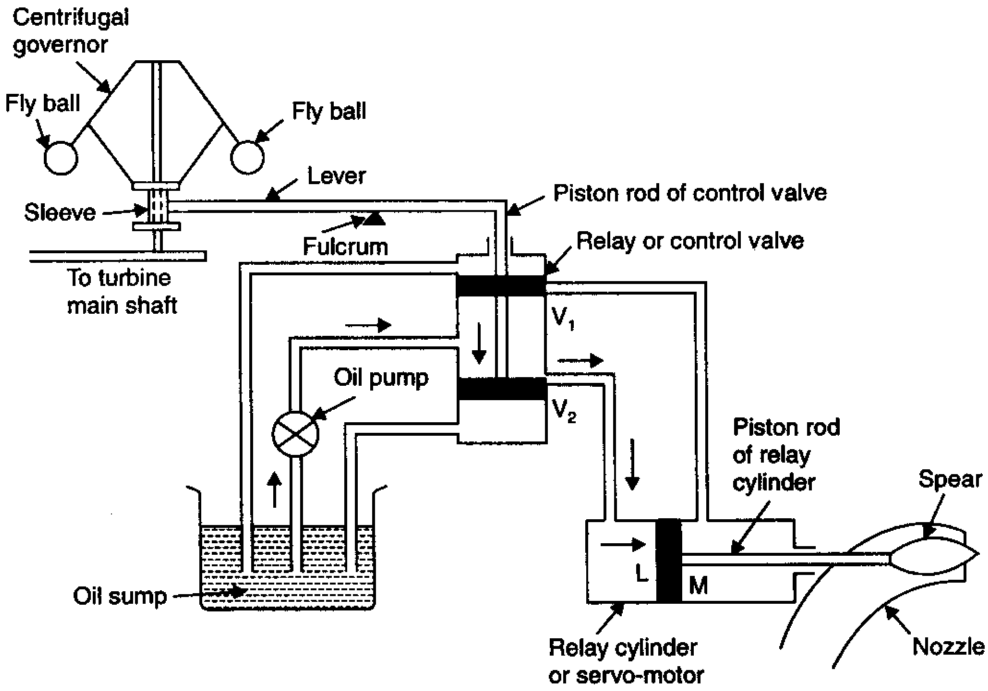


Fig. 6.42. Governing of Pelton turbine.

When the load on the generator decreases, the speed of the generator *increases* and consequently the speed of the turbine and hence centrifugal governor increases beyond the normal speed. Due to increased speed the fly-ball of the centrifugal governor move outwards/upwards (due to increased centrifugal force) causing upward movement of the sleeve. As the sleeve moves up, the lever (a horizontal lever, supported over a fulcrum, connects the sleeve and the piston rod of control valve) turns about the fulcrum and the piston rod of the control valve moves downward. Subsequently the V_1 closes and valve V_2 opens as shown in Fig. 6.42. The oil, pumped from the oil sump to the control valve or relay valve, under pressure will flow through the valve V_2 to the servomotor (or relay cylinder) and will exert force on the face L of the piston of the relay cylinder. The piston along with piston rod and spear will move towards *right*. This will decrease the area of flow of water at the outlet of the nozzle and as a consequence of this the flow rate to the turbine is reduced and the speed of the turbine falls. After the speed of the turbine becomes normal the fly balls, sleeve, lever etc. will come to normal position.

On the other hand, when the load on the generator increases, the speed of the generator and hence that of the turbine and the centrifugal governor decreases due to which its (governor) balls move downward, the sleeve moves down and piston rod of the control valve moves in the upward direction. Subsequently valve V_1 opens and valve V_2 closes. The oil under pressure will move through valve V_1 and exert a force on face M of the piston. This will make the piston move towards left thereby increasing the area of flow of water at the outlet of the nozzle and hence increase the rate of flow of water to the turbine. As a result, the speed of the turbine will increase till it becomes normal.

Governing of reaction turbines

Refer Fig. 6.43. The guide blades of a reaction turbine are pivoted and connected by levers and links to the regulating ring. To the regulating ring are attached two long regulating rods connected to the regulating lever. The regulating lever is keyed to a regulating shaft which is turned by a servomotor piston of oil pressure governor. The penstock which feeds the turbine inlet, has a relief valve better known as *'Pressure Regulator'*. When the guide vanes have to the suddenly closed, the relief valve opens and diverts the water direct to the tailrace. Its function is therefore, similar to that of deflector in Pelton turbines. Thus the double regulation, which is the simultaneous operation, of two elements is accomplished by moving the guide vanes and relief valve in Francis turbines, by the governor.

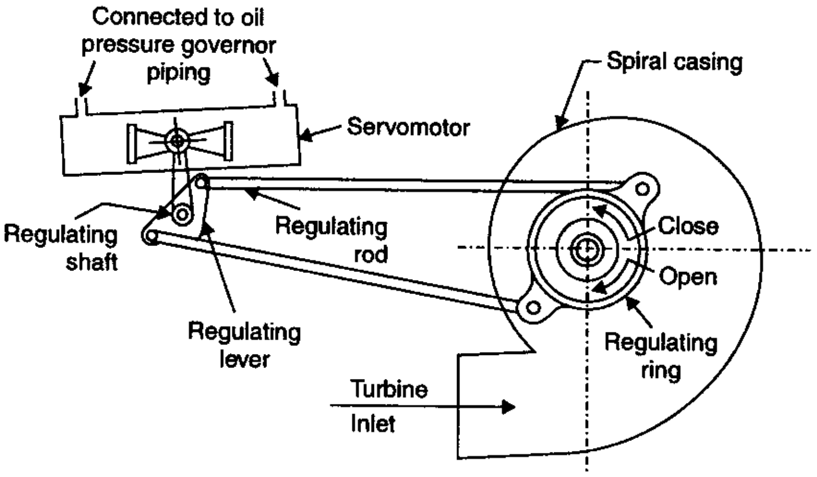


Fig. 6.43. Governing of reaction turbines.

Fig. 6.44 shows the speed governing systems for by hydraulic turbines schematically.

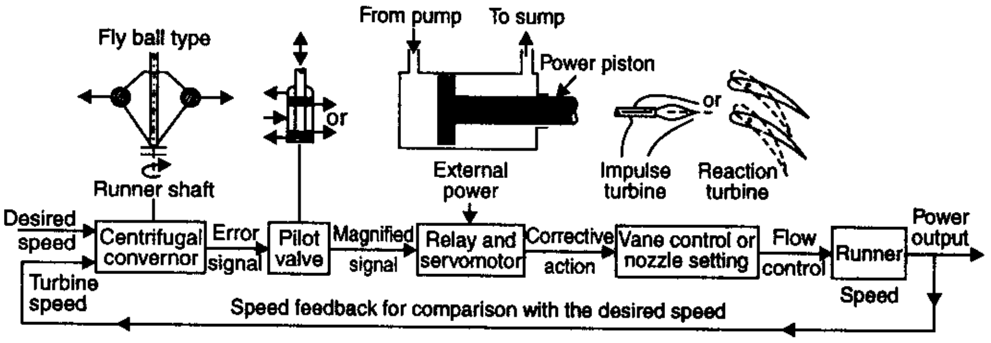


Fig. 6.44. Speed governing systems for hydraulic turbines.

6.7.8. Selection of Turbines

The following points should be considered while selecting the right type of hydraulic turbine :

1. Specific speed. High specific speed is essential where head is low and output is large, because otherwise the rotational speed will be low which means cost of turbo-generator and power house will be high. On the other hand there is practically no need of choosing a high value of specific speed for high head installations, because even with low specific speed, high rotational speed can be attained with medium capacity plants.

2. Rotational speed. Rotational speed depends on specific speed. Also the rotational speed of an electrical generator with which the turbine is to be directly coupled, depends on the frequency and number of pair of poles. The *value of specific speed adopted should be such that it will give the synchronous speed of the generator.*

3. Efficiency. The turbine selected should be such that it gives the *highest overall efficiency for various operating conditions.*

4. Part load operation. In general the efficiency at part-loads and overloads is less than normal. For the sake of economy the turbine should always run with maximum possible efficiency to get more revenue.

When the turbine has to run at part or overload conditions Deriaz turbine is employed. Similarly, for low heads, Kaplan turbine will be useful for such purposes in place of propeller turbine.

5. Cavitation. The installation of water turbines of reaction type over the tailrace level is effected by *cavitation.* The critical value of cavitation factor must be obtained to see that the turbine works in safe zone. Such a value of cavitation factor also effects the design of turbine, especially of Kaplan, propeller and bulb types.

6. Disposition of turbine shaft. Experience has shown that the vertical shaft arrangement is better for large-sized reaction turbines, therefore it is almost universally adopted. In case of large size impulse turbine, horizontal shaft arrangement is mostly employed.

7. Head. (*i*) *Very high heads (350 m and above).* For heads greater than 350 m, Pelton turbine is generally employed and there is practically no choice except in very special cases.

(*ii*) *High heads (150 m to 350 m).* In this range either Pelton or Francis turbine may by employed. *For higher specific speeds Francis turbine is more compact and economical than the Pelton turbine* which for the same working conditions would have to be much bigger and rather cumbersome.

(*iii*) *Medium heads (60 m to 150 m).* A *Francis turbine* is usually employed in this range. Whether a high or low specific speed unit would be used depends on the selection of speed.

(*iv*) *Low heads (below 60 m).* Between 30 to 60 *m* heads both Francis and Kaplan turbines may be used. The latter is more expensive but yields a higher efficiency at part loads and overloads. It is therefore preferable for variable loads. *Kaplan turbine is generally employed for heads under 30 m.* Propeller turbines are, however, commonly used for heads upto 15 m. *They are adopted only when there is practically no load variation.*

(*v*) *Very low heads.* For very low **heads** *bulb turbines* are employed these days. Although Kaplan turbines can also be used for heads from 2 m to 15 m but they are *not economical.*

6.8. PLANT LAYOUT

The plant layout is considerably affected by the nature of project.

In *low head plants,* the width of the dam is usually small and *suitable space* for fixing the turbines and generators is *limited.* On the other hand, in high head schemes the site for the power plants can be selected more conveniently to give desired layouts.

The *size and type of units* proposed to be installed also affect the layout of the power station.

For *reaction machines with vertical single runner,* the arrangement with the machines in a *line parallel to the length of the turbine house is usually preferred* ; the spacing between two units being controlled by the width of the flume or scroll case at entrance to the runner or the width of the draft tube at its month, or sometimes by the overall diameter of the alternator. *Horizontal machines of the reaction type* are best located at *right angles to the length of the turbine house* while for impulse machines with horizontal setting the wheel shaft is placed parallel to the longitudinal axis of the turbine house.

Unlike the reaction machines, the spacing of the impulse machines is fixed by the machine dimensions and necessary clearances rather than by the penstock flume or tailrace, as the amount of water discharged is comparatively small. For impulse machines with vertical setting the arrangement with centres on a line parallel to axis of turbine house is suggested. The use of such machines is rare.

6.9. HYDRO-PLANT AUXILIARIES

The following auxiliaries are essential for *starting the generating unit* :

(*i*) Exciter
(*ii*) Governor oil system
(*iii*) Lubricating oil pump.

The station can start usually independent of external power, but stand-by auxiliaries are needed for emergency service. Exciter for the main generator may be direct connected, motor-generator type engine driven or auxiliary water turbine driven. *Direct connected exciters make the unit independent of auxiliary power and also have higher efficiency than the other types.* Motor generator exciters depend upon electric power for starting, whereas an engine driven exciter is an independent unit. *The efficiency of water turbine driven exciter is very low and this is not suited for any other use except during emergencies.* The exciter is an essential piece of equipment and it is important to select a drive that is reliable and at the same time reasonably low in first cost and operation. The pressurised oil system for the governor is driven from the turbine main shaft and sufficient pressure is usually maintained in the oil tanks during the shut down, so that the turbine can be started. A stand-by motor driven pump is also installed for emergency service. The lubricating oil pumps may be driven from the turbine shaft and would work as soon as the unit starts. Sometimes a stand-by lubricating pump is also installed.

During starting of hydroplants the following auxiliaries are *not directly* needed :

(*i*) Coolant pumps
(*ii*) Air compressors
(*iii*) Drainage pumps
(*iv*) Fans and cooling oil pumps
(*v*) Cranes
(*vi*) Gate hoists
(*vii*) Valves
(*viii*) Battery charging units etc.

These auxiliaries are generally electrically driven. Water may be used to cool the bearings of the turbine and generator and transformers and is circulated through water pumps. *Air compressors* maintain a supply of air under pressure for operation of generator brakes and other uses in the power station. Unwatering of turbine pits may be required during repairs or check up for which *water pumps* are necessary. *Fans* are required for ventilation of the turbine and switch gear room or for cooling transformers. *Oil pumps* handle transformer oil through the cleaning and cooling system. *Cranes* are required during machinery repairs and installations to lift heavy parts or place them in position. The head works *control gates* with *hoists* which may be manually or electrically operated. *Storage batteries* are needed to supply low voltage D.C. power for switch gear control. During failure of the main generators lighting and power for the station may also be obtained from the batteries.

Most of the station auxiliaries are electrically driven due to obvious advantages of using such drivers.

6.10. COST OF HYDRO-PLANT

The cost of hydro-plant varies from Rs. 850 to Rs. 950 per kW of capacity. A typical subdivision of investment under various items (*e.g.* as dam, tailrace, reservoir, turbines, generators, land, building and foundations, switching and wiring, switchyard etc.) is as follows :

1. Reservoir, dam, intake, tailrace	35%
2. Turbines and generators	20%
3. Land, building and foundations	30%
4. Switching and wiring	5%
5. Switchyard	5%
6. Miscellaneous	5%

6.11. AVERAGE LIFE OF HYDRO-PLANT COMPONENTS

The average life (approximate) of various components of hydro-electric power plant is given below :

Components	*Average life (years)*
1. Reservoirs	70—80
2. Dams	
(*i*) Earthen, concrete or masonry	150
(*ii*) Loose rock	60
3. Water ways	
(*i*) Canals, tunnels	50—100
(*ii*) Penstocks	
(*a*) Steel	40—50
(*b*) Concrete	25—50
4. Power house and Equipment	
(*i*) Building	35—50
(*ii*) Generators	25
(*iii*) Transformers	30
(*iv*) Turbines (hydraulic)	5
(*v*) Pumps	20—25

6.12. HYDRO-PLANT CONTROLS

The various controls which are provided in an hydro-electric power plant are enumerated and discussed below :

1. Hydraulic controls
2. Machine controls—Starting and stopping
3. Machine controls—Loading and frequency
4. Voltage control of generator and system
5. Machine protection.

1. **Hydraulic controls.** In a hydro-plant the following *hydraulic controls are provided* :

(*i*) Storage level indicators—primary and secondary
(*ii*) Flood control
(*iii*) River flow control
(*iv*) Intake gate control.

2. **Machine controls—Starting and stopping.** The control of water flowing to the turbine is exercised by providing gates and valves in the supplying conduit and at the turbine inlet. The quantity of water flowing to the turbine is regulated according to the load on the generator by the use of a governor system. While starting the turbines the casing should be filled gradually and to limit the rate of water flow by-pass valves are provided.

3. **Machine controls—Loading and frequency.** The load on the machine is controlled as follows :

(*i*) By adjusting the governor speed control
(*ii*) By controlling system frequency.

4. **Voltage control of generator and system.** The voltage regulators are employed to ensure that electric power is supplied at proper voltage.

5. **Machine protection.** In a hydro-plant provision of protective devices should be made to guard against breakdown of turbo-generator and auxiliary services, like transformers, switchgears, overhead lines etc. Protection measures are also required to guard against incorrect operation and failure of control system.

Automatic controls are efficient, safe and reliable

The control room should be designed for convenience of operation and the equipment should be so arranged/spaced that it is easily accessible.

6.13. ELECTRICAL AND MECHANICAL EQUIPMENT IN A HYDRO-PLANT

In an hydro-electric power plant the electrical and mechanical equipment comprise of the following :

A. *Electrical equipment*

In electrical equipment the following elements items are included :

(*i*) Generators (*ii*) Exciters

(*iii*) Voltage regulators (*iv*) Transformers

(*v*) Switch gear (*vi*) Control room equipment.

Generators. The generators employed in a hydro-plant are usually 3-phase synchronous machines and have either a vertical shaft arrangement or horizontal shaft arrangement ; but *vertical shaft arrangement is preferred.*

The generator cooling may be achieved by air circulation through the stator ducts. Cooling by water cooled heat exchangers is common.

The power output of a 3-phase alternator is given by :

$$P = \sqrt{3}\ VI \cos\phi \times 10^{-6}\ \text{MW}$$

where, P = Power output,

V = Voltage (in volts),

I = Current (in amperes), and

$\cos\phi$ = power factor (varies from 0.9 to 0.95).

Transformers. These may be of single phase or three phase type. They are oil filled for insulation and cooling purposes. The generated voltage is stepped up by means of step up transformers. Transformers may be of power or distribution type.

Switchgear. A switchgear consists of *switches, isolators, surge arrestors and circuit breakers*. Its main function is to *make and break the circuits.*

For generated voltage it is preferred to locate switchgear indoors whereas outdoor location is used for transmission voltage.

When switchgears and transformers are located outside they should be provided adequate lightening protection.

Control room equipment. It performs the following functions : (*i*) Machine starting and stopping (*ii*) Generator and system voltage control (*iii*) Machine loading control (*iv*) Frequency control (*v*) Hydraulic control (*vi*) Machine running control.

B. *Mechanical equipment*

Mechanical equipment include the following :

(*i*) Compressors and air ducts

(*ii*) Shaft, coupling, bearings etc.

(*iii*) Braking equipment for the generator
(*iv*) The oil circuits and pumps
(*v*) Cranes and other lifting equipment
(*vi*) Ventilation and cooling systems
(*vii*) Equipment for water supply and drainage
(*viii*) Equipment for power house lighting.

6.14. COMBINED HYDRO AND STEAM POWER PLANTS

An electrical power system should fulfil the following objectives :

1. To ensure an *adequate and reliable electric power supply* at all loads and at all times.
2. The source of energy should be such as to give the *minimum overall cost of the system as a whole.*

The above objectives (unless a country/region is rich either in abundant supply of cheap fuel or ample water power resources which can be developed at suitable site) can be best realised by a *judicious combination of both hydro and thermal power.* Hydropower represents a renewable source of energy which enjoys many intrinsic advantages as compared to thermal power. Although the cost of construction of hydro power plant is nearly same as that of a coal based steam power plant in terms of investment for MW, but hydro-power plant uses water for power generation which is available in abundance in nature.

It is known as that *hydro-plant can meet the demands of load variations more rapidly and easily.* Thus, *when the rate of flow of water is low, the steam plant can work at constant load producing a better efficiency and the hydro-plant will work most effectively as peak load plant and its output can be varied to meet the load fluctuations.* The steam and hydro-plants reverse their functions (*steam plant providing the peak load and the hydro-plant providing base load*) when high rate of water flow is available. But even under this condition, the *steam plant output will remain constant* and the hydro-plant output *will be varied to meet the load fluctuations.*

6.15. COMPARISON OF HYDRO-POWER STATION WITH THERMAL POWER STATIONS

The comparison between hydro-power stations and thermal power stations is given below :

S. No.	Aspects	Hydro-power station	Thermal power station
1.	*Raw material consumption*	Nil. Water power is in exhaustible and perpetual and is continuously replenished by the direct agency of sun.	Huge quantity of coal consumed, thereby exhausting "fuel reserves".
2.	*Cost of energy*	Cheaper.	Costlier.
3.	*Cost of energy generation*	Immune to inflation.	Very much influenced by the increase in the cost of fuel.
4.	*Life of plant*	Long useful life.	Not so long comparatively. The component parts deteriorate and become obsolete at a faster rate.
5.	*Pollution*	Free from problems of pollution.	Causes pollution and subsequently create health hazards.

6.	*Design, construction and reliability*	Simple in design, robust in construction and reliable in operation.	Comparatively more complicated in design, less robust in construction and less reliable in operation.
7.	*Running below a certain minimum load factor.*	Can be run.	Cannot be run.
8.	*Reserve capacity and variation in power demands.*	Particularly suited to provide reserve capacity as well as meeting the exacting needs of daily variation in power demands.	Comparatively not suited for the mentioned requirements.
9.	*Employment potential*	More. Affords a relatively high employment potential and better utilization of the available local talent and resources.	Less
10.	*Man power required* *Labour problem*	Small Less	Large More
11.	*Foreign exchange requirements for equipment*	Less	More
12.	*Construction time required*	Almost same as thermal power station.	Almost same as hydro-power station.
13.	*Overall capital expenditure requirements*	Low (Rs. 4000 per kW app.)	High (Rs. 6000 per kW app.) [Power generation equipment —Rs. 4500 per kW Mining of fuel —Rs. 750 per kW Transportation of fuel —Rs. 750 per kW.]

6.16. UNDERGROUND HYDRO-PLANTS

The conventional hydro-plant is usually located overground at the foot of a dam or a hill slope on the banks of a river. The first of these plants was set up in U.S.A as far back as 1898. Since then several underground stations have been set up in Germany, France, Sweden, Switzerland and other countries.

Consideration supporting the construction of underground hydro-plants

1. A suitable site for a conventional surface station/plant and good slope for penstock *not available*.
2. There may be danger of falling rocks and snow avalanches particularly in narrow valleys.
3. Availability of underground sound rock and avoidance of a long pressure tunnel and facility for a convenient tailrace outlet.
4. Possibility of elimination of surge tank required for surface station due to long pressure channel.
5. The rugged topographical features and the difficulties in finding a suitable short and steep slope for pipe lines make it more economical to install the water conduit, the machine, transformer hall and tailrace system underground.

Types of layouts for underground hydro-plant

The following are two distinctly different types of layouts for underground hydro-power stations :

(*i*) The head development (*ii*) The tail development.

In the *head development* the powerhouse is located at the intake and provides a long unlined tailrace tunnel. The necessity of surge shafts and penstocks is eliminated and quicker opening and closing of the turbine is possible. The same crew can operate the power house and headworks which gives an operational advantage.

In the *tail development* the power house is placed at the surge end of the low pressure tunnel. This requires a short tailrace. Access tunnels and shafts are necessary in both types. Between these two extreme layouts there is a wide range of intermediate possibilities for plant location.

Before taking a decision in favour of the underground station, *thorough geological investigations of the site are essential. Rock should be properly tested to devise economical tunneling method which may considerably affect the cost of construction of the power station.*

Advantages of the underground Power House/Station

1. Better rock bearing properties.
2. Foundation difficulties are easier to come.
3. In planning the design and location of the principal works surface topography does not interfere at all.
4. There is greater freedom in positioning stations.
5. Maintenance cost of power station including painting, heating etc. are practically eliminated.
6. These stations are safer from defence point of view and are immune to bombardment. They are also protected against such natural hazards as rain, wind, loose rocks etc.
7. There is saving in cost of land.
8. Land acquisition problem is minimum.
9. There is greater uniformity in climatic conditions during all seasons.
10. In steep and rugged countryside, the site selection for an outdoor plant may cause difficulties due to the risk of avalanches and land slips. At some places there might be added hazard due to forest fire.
11. Uninterrupted construction work in adverse weather.
12. Shorter conduit lengths and therefore smaller surge tanks.
13. A tailrace tunnel may be easier to design and construct compared to the headrace pressure tunnel.
14. The useful life of the structures excavated in the rock is considerably longer than that of concrete and reinforced concrete structures.
15. It is possible to improve the governing of the turbines with the construction of underground power station.
16. The construction period is reduced mainly due to the possibility of full-scale construction work in winter.
17. At places, where there is extreme difference in climate of winter and summer, a uniform temperature can be maintained inside the plant with adequate control of ventilation regardless of outside weather.

Disadvantages :

1. The cost of construction of power station and accessories is more.
2. Increased cost of lighting, special ventilation and air conditioning.

3. The tailrace tunnels and additional surge chambers are costly.
4. Additional cost of underground location of transformers etc.

6.17. AUTOMATIC AND REMOTE CONTROL OF HYDRO-STATION

Some automatic controlling devices such as *relays, governors, voltage regulators* etc. are employed in every hydro-station, big or small. However, a few operations may still be needed to start or stop the units and distribute load on two or more units in operation at a time. For stations where full shift operation is not required, the services of the operators are not fully utilized. A saving in working cost of plant can be effected if the functions of the operators are derived from an automatic control system.

An automatic system is more safe, efficient and reliable and usually works through the governor and the voltage regulator. Due to these reasons automatic hydrostations have been developed. Automatic plants may be divided into following three classes :

1. Fully automatic plant
2. Partly automatic plant
3. Remote controlled plant.

1. Fully automatic plant. This type of plant may be controlled by :

(*i*) A time switch (*ii*) A float switch (*iii*) A load sensitive device.

The *time switch* may start and stop the power station at preset clock timings.

The *float switch* works with the change in level of water in the reservoir, so that if the water level rises the generator output is increased and *vice versa*. Thus the station shares the load in interconnected system according to availability of water in the reservoir.

The *load sensitive device* is actuated by the demand for power in the area served by the plant, so that increase in power demand would increase the output of the generators automatically. In case of any trouble arising anywhere in the system, the plant is automatically shut-down till such time as the source of trouble is removed.

2. Partly automatic plant. In partly automatic system the units are manually started and synchronised, but in case of a fault shutdown automatically. The partly automatic system is cheaper than fully automatic control system.

3. Remote control plant. When the control on a power system is exercised from a distance, usually from another generating station or control centre, the automatic control system becomes a remote controlled one. In such a system the operator at the control point transmits a signal to the controlled station and this actuates the automatic system at the station to perform the desired effect such as starting and stopping of the units and load distribution among the sets in operation. The automatic remote control system also receives from the controlled stations all necessary information such as water level in the reservoir, share of load supplied by each unit etc.

Small hydro-plants which are not justified to be developed for manual control, can usually be justified by the application of remote automatic control.

6.18. SAFETY MEASURES IN HYDRO-ELECTRIC POWER PLANTS

Following safety measures need to be taken for the safe operation of an hydro-electric power plant :

1. Surge tanks
2. Screens
3. Sand traps
4. Jet dispersers
5. Pressure regulator.

Surge tanks. A surge tank is used to *prevent sudden increase of pressure* in the supply line or the penstock. It is placed as near as possible to the turbine. The tank may be open at the top or closed. In case it is open at the top, it must not be lower than the level of the water in the reservoir.

Screens. These are provided to prevent logs, fishes, ice blocks and other obstructive elements from entering the pipe lines and turbines.

Sand traps. Sand traps are provided to prevent the sand flowing with water in pipes since sand blast action of solid matter in the water causes rapid wear of nozzles, spears, blades etc. of the turbine.

Jet dispersers. The discharged water at the bottom of the high dams possesses large amount of energy which is likely to cause scouring of the channel below the dam and consequent damage to the dam foundation unless some means are provided to dissipate it. The possible remedies for this are either *to discharge water into a cushion pool* or *to provide a jet dispersers* at the end of outlet pipe so that the end of the outlet pipe is such that the jet is broken up into a conical shower of drops and their energy is absorbed by air.

Pressure regulator. It is usually operated by a governor of the turbine. It is provided on the pipeline near the turbine inlet so that when the turbine gates are suddenly closed, pressure surges so produced are kept within the safe limits of the pipeline. The water discharged from the regulator is passed on to tailrace through a separate pipeline.

6.19. PREVENTIVE MAINTENANCE OF HYDRO-PLANT

The purpose of preventive maintenance is to minimise breakdown and excessive depreciation resulting from neglect. In a hydro-plant (using reaction turbines) monthly, quarterly, half yearly and yearly inspection and maintenance are carried out on the following parts :

Inspection/Maintenance	**Parts**
Monthly	*Turbine cover parts* (*e.g.* leakage unit, drainage holes, servomotor connections, turbine shaft and cover, oil pump etc.)
	Operating ring of turbines
	Guide vane mechanism
Quarterly	*Servomotor*
	Governor oil system
	Ejector cabinet
	Feedback system
Half yearly	*Governor mechanism*
	Gauges
	Grease pumps for guide vanes and guide bearings
	Grease pipes connected to grease pumps
Yearly	*Turbine auxiliaries* (*e.g.* oil pressure tank, turbine guide bearing, turbine instruments)
	Scroll casing runner with guide vanes
	Emergency slide valve
	Pit liner
	Draft tube
	Runner blades checked for cavitational effects, cracks and wearing out.

6.20. CALCULATION OF AVAILABLE HYDRO-POWER

The theoretical power available from falling water can be calculated using the following formula :

$$P_{th.} = \frac{wQH}{1000} \text{ kW} \quad \text{...(6.29)}$$

where, $P_{th.}$ = Theoretical output in *kW*,

w = Weight density of water in *N/m³*,

Q = Flow through turbine (or quantity of water available for hydro-power generation) in m^3/s, and

H = Head available in *metres*.

The actual useful or *effective output* depends upon the efficiency of the various parts of the installation.

If η_1 = Efficiency of pipelines, intake etc., and

η_2 = Efficiency of hydraulic turbine,

Then *overall efficiency* $\eta_0 = \eta_1 \times \eta_2$.

Since the turbine and the generator are directly coupled on common shaft the hydro-electrical power available will be given by the equation :

$$P_{actual} = P_{th.} \times \eta_0 \quad \text{...(6.30)}$$

or

$$P_{actual} = \frac{wQH}{1000} \times \eta_0 \text{ kW} \quad \text{...(6.31)}$$

6.21. COST OF HYDRO-POWER

The initial cost of any hydro-plant is very high but the power produced by it is the cheapest. The following costs are included in development of a hydro-plant :

1. Cost of land and riparian rights
2. Cost of railways and highway required for the construction work
3. Cost of construction
4. Cost of engineering supervision of the project
5. Cost of building etc.
6. Cost of equipment
7. Cost of equipment used for power transmission.

6.22. HYDROLOGY

6.22.1. Introduction

Hydrology may be defined as the *science which deals with the depletion and replenishment of water resources.* It deals with the surface water as well as the ground water. It is also concerned with the *transportation of water* from one place to another, and from one form to another. It helps us in determining the occurence and availability of water.

Hydrology aims at answering the following major questions :

(*i*) How is the water going to precipitate ?

(*ii*) How is water going to behave ?

(*iii*) What will happen to water after precipitation ?

The basic knowledge of this science is a must for every civil engineer, particularly the one who is engaged in the design, planning or construction of irrigation structures, bridges and highway culverts, or flood control works, etc.

6.22.2. The Hydrologic Cycle

Most of the earth's water sources, such as rivers, lakes, oceans and underground sources, etc. get their supplies from rains, while the rain water itself is the evaporation from these sources. Water is lost to the atmosphere as vapour from earth, which is then precipitated back in the form of rain, snow, hail, dew, sleet or frost, etc. This evaporation and precipitation continues for ever, and thereby, a balance is maintained between the two. This process is known as *Hydrologic Cycle*. It can be represented graphically as shown in Fig. 6.45. Hydrologic equation is expressed as follows :

$$P = R + E \qquad ...(6.32)$$

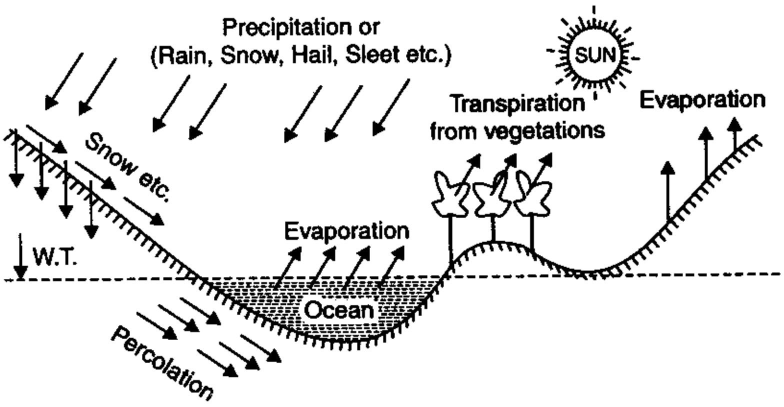


Fig. 6.45. Hydrologic cycle.

where, P = Precipitation,

R = Run-off, and

E = Evaporation.

Precipitation. It includes all the water that falls from atmosphere to earth surface. Precipitation is of two types : (*i*) Liquid precipitation (rain fall). (*ii*) Solid precipitation (snow, hail).

Run-off and surface run-off. Run-off and surface run-off are two different terms and should not be confused. *Run-off* includes all the water flowing in the stream channel at any given section. While the *surface run-off* includes only the water that reaches the stream channel without first percolating down to the water table.

Run-off can, therefore, also be named as Discharge or Stream flow. Rainfall duration, its intensity and a real distribution influence the rate and volume of run-off.

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

Transpiration. The process by which water is released to the atmosphere by the plants is called *transpiration.*

6.22.3. Measurement of Run-off

Run-off can be measured daily, monthly, seasonal or yearly. It can be measured by the following *methods* :

1. From rainfall records.
2. Empirical formulae.

3. Run-off curves and tables.

4. Discharge observation method.

1. From rainfall records. In this method consistent rainfall record for a sufficiently long period is taken and then average depth of rainfall over the catchment is determined. Then considering all the factors which affect run-off process, a coefficient is arrived at for that catchment. Now a simple equation can be used to find out the run-off over the catchment.

$$\text{Run-off} = \text{Rainfall} \times \text{coefficient} \qquad \text{...(6.33)}$$

2. Empirical formulae. In this method an attempt is made to derive a direct relationship between the rainfall and subsequent run-off. For this purpose some constants are established which give fairly accurate result for a specified region. Some important formulae are given below :

(*a*) Khosla's formula :

$$R = P - 4.811\,T$$

where, R = Annual run-off in mm,

P = Annual rainfall in mm, and

T = Mean temperature in °C.

(*b*) Inglis formulae for hilly and plain areas of Maharashtra :

For *Ghat region*

$$R = 0.88\,P - 304.8$$

For *plain region*

$$R = \frac{(P - 177.8) \times P}{2540}$$

(*c*) *Lacey's formula* :

$$R = \frac{P}{1 + \dfrac{3084\,F}{PS}}$$

where, R = Monsoon run-off in mm,

P = Monsoon rainfall in mm,

S = Catchment area factor, and

F = Monsoon duration factor.

Values of S for various types of catchment are given below :

Type of catchment	*Value of S*
Flat, cultivated and black cotton soils	0.25
Flat, partly cultivated, various soils	0.6
Average catchment	1.00
Hills and places with little cultivation	1.70
Very hilly and steep, with hardly any cultivation	3.45

Values of F for various durations of monsoon are given below :

Class of monsoon	*Value of F*
Very short	0.50
Standard length	1.00
Very long	1.50

3. Run-off curves and tables. Each region has its own catchment area and rainfall characteristics. Thus formulae given above and coefficients derived there in cannot be applied universally.

However, for the same region the characteristics mostly remain unchanged. Based on this fact the run-off coefficients are derived once for all. Then a graph is plotted in which one axis represents rainfall and the other run-off. The curves obtained are called *run-off curves*. Alternatively a *table* can be prepared to give the run-off for a certain value of rainfall for a particular region.

4. Discharge observation method. By actual measurement of discharge at an outlet of a drainage basin run-off over a catchment can be computed. The complication in this method is that the discharge of the stream at the outlet comprises surface run-off as well as sub-surface flow. To find out the sub-surface run-off it is essential to separate the sub-surface flow from the total flow. The separation can be done on an approximate basis but with correct analysis.

Factors affecting the run-off

The following factors affect run-off :

1. *Rainfall pattern*
2. Character of catchment area
3. Topography
4. Shape and size of the catchment area
5. Vegetation
6. Geology of the area
7. Weather conditions.

6.22.4. Hydrograph

Hydrograph is defined as *a graph showing discharge (run-off) of flowing water with respect to time for a specified time.* Discharge graphs are known as flood or run-off graphs. Each hydrograph has a reference to a particular river site. The time period for discharge hydrograph may be hour, day, week or month.

Hydrograph of stream of river will depend on the characteristics of the catchment and precipitation over the catchment. Hydrograph will access the flood flow of rivers hence it is essential that anticipated hydrograph could be drawn for river for a given storm.

Hydrograph indicates the power available from the stream at different times of day, week or year.

Typical hydrographs are shown in Fig. 6.46 and 6.47.

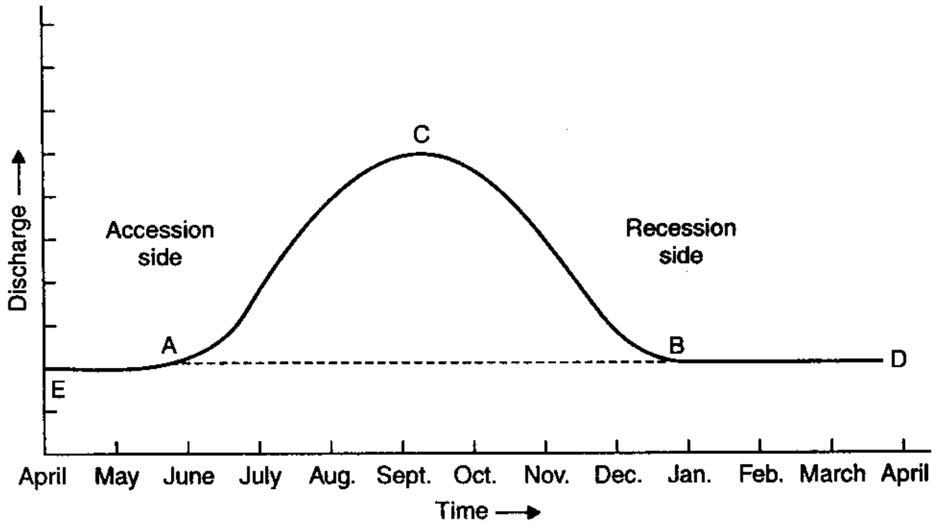


Fig. 6.46. Typical hydrograph.

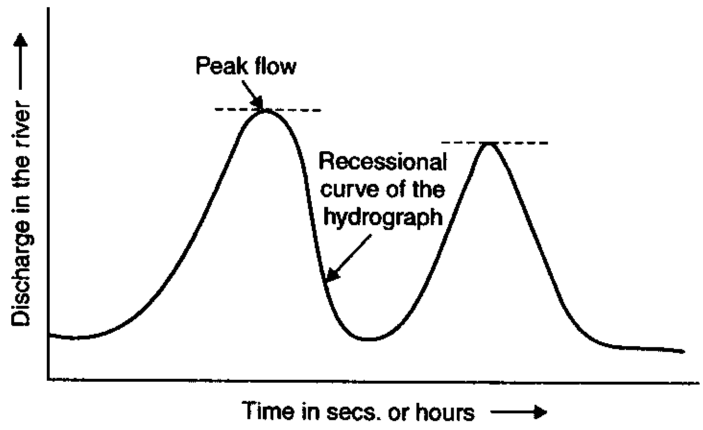


Fig. 6.47. Typical hydrograph.

The Unit Hydrograph

The peak flow represents a momentary value. Therefore the peak flow alone does give sufficient information about the run-off. It is necessary to understand the full hydrograph of flow. Introduction of unit hydrograph theory in 1932 made it possible to predict a run-off hydrograph corresponding to an observed or hypothetical storm. *The basic concept of unit hydrograph is that the hydrographs of run-off from two identical storms would be the same.* In practice identical storms occur very rarely. The rainfall generally varies in duration, amount and areal distribution. This makes it necessary to construct a typical hydrograph for a basin which could be used as a unit of measurement of run-off.

A ***unit hydrograph*** may be defined as a *hydrograph which represents unit run-off resulted from an intense rainfall of unit duration and specific areal distribution.*

The *following steps* are used for the *construction of unit hydrograph :*

1. Choose an isolated intense rainfall of unit duration *from past records.*
2. Plot the discharge hydrograph for outlet from the rainfall records.
3. Deduct the base flow from stream discharge hydrograph to get hydrograph of surface run-off.
4. Find out the volume of surface run-off and convert this volume into cm of run-off over the catchment area.
5. Measure the ordinates of surface run-off hydrograph.
6. Divide these ordinates by obtained run-off in cm to get ordinates of unit hydrograph.

Thus for any catchment unit hydrograph can be prepared once. Then whenever peak flow is to be found out, *multiply the maximum ordinate of unit hydrograph by the run-off value expressed in cm.* Similarly to obtain run-off hydrograph of the storm of same unit duration multiply the ordinates of the unit hydrograph by the run-off value expressed in cm. If the storm is of longer duration calculate the run-off in each unit duration of the storm. Then super-impose the run-off hydrographs in the same order giving a lag of unit period between each of them. Finally draw a summation hydrograph by adding all the overlapping ordinates. Generally the computations are done in a tabular form before the hydrograph is plotted.

Fig. 6.48 is self explanatory and shows how a run-off hydrograph is constructed from a unit hydrograph.

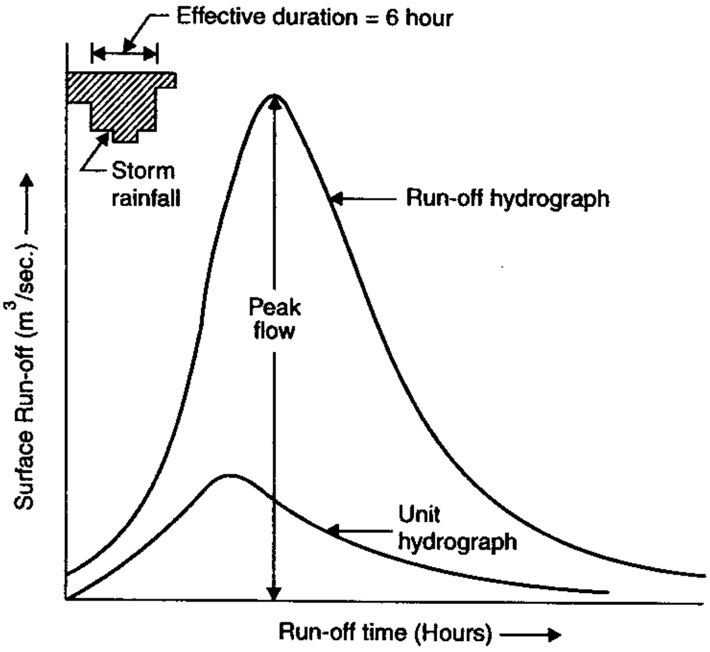


Fig. 6.48

Limitations to the use of unit hydrographs :

1. Its use is limited to areas about 5000 sq. kilometres since similar rainfall distribution over a large area from storm to storm is rarely possible.
2. The odd-shaped basins (particularly long and narrow) have very uneven rainfall distribution, therefore, unit hydrograph method is not adopted to such basins.
3. In mountain areas, the areal distribution is very uneven, even then unit hydrograph method is used because the distribution pattern remains same from storm to storm.

6.22.5. Flow Duration Curve

Refer Fig. 6.49. Flow duration curve is another useful form *to represent the run-off data for the given time. This curve is plotted between flow available during a period versus the fraction of time.* If the magnitude on the ordinate is the potential power contained in the stream flow, then the curve is known as *"power duration curve"*. This curve is a very useful tool in the analysis for the development of water power.

The flow duration curve is drawn with the help of a hydrograph from the available run-off data and, here it is necessary to find out the length of time duration which certain flows are available. This information either from run-off data or from hydrograph is tabulated. Now the flow duration curve taking 100 percent time on X-axis and run-off on Y-axis can be drawn.

The area under the flow duration curve (Fig. 6.49) gives the total quantity of run-off during that period as the flow duration curve is representation of graph with its flows arranged in order of descending magnitude.

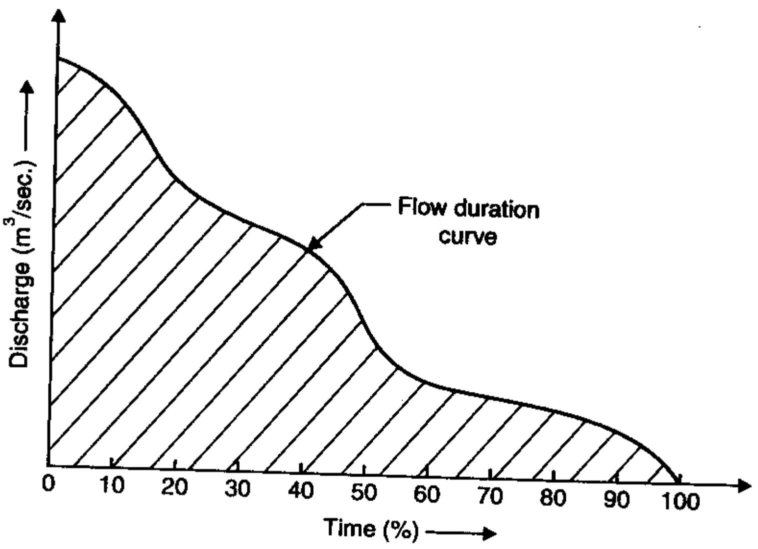


Fig. 6.49. Flow duration curve.

If the head of discharge is known, the possible power developed from water in kW can be determined from the following equation :

$$\text{Power (kW)} = \frac{wQH}{1000} \times \eta_0$$

where, Q = Discharge, m³/sec.,

H = Head available, m,

w = Weight density of water, N/m³, and

η_0 = Overall efficiency.

Thus the *flow duration curve can be converted to a power duration with some other scale on the same graph.*

Flow duration curves are most useful in the following cases :

(*i*) *For preliminary studies* (*ii*) *For comparison between streams.*

Uses of flow duration curve

1. A flow duration curve allows the evaluation of low level flows.

2. It is highly useful in the planning and design of water resources projects. In particular, for hydropower studies, the flow duration curve serves to determine the potential for *firm power* generation. In the case of a run-of-the-river plant, with no storage facilities, the firm power is usually computed on the basis of flow available 90 to 97 percent of the time. The *firm power* is also known as the *primary power*. *Secondary power* is the power generated at the plant utilising water other than that used for the generation of firm power.

3. If a sediment rating curve is available for the given stream, the flow duration curve can be converted into cumulative sediment transport curve by multiplying each flow rate by its rate of sediment transport. The area under this curve represents the total amount of sediment transported.

4. The flow duration curve also finds use in the design of drainage systems and in flood control studies.

5. A flow duration curve plotted on a log-log paper provides a qualitative description of the run-off variability in the stream. If the curve is having steep slope throughout, it indicates a stream with highly variable discharge. This is typical of the conditions where the flow is mainly from surface

run-off. A flat slope indicates small variability which is a characteristic of the streams receiving both surface run-off and ground water run-off. A flat portion at the lower end of the curve indicates substantial contribution from ground water run-off, while the flat portion at the upper end of the curve is characteristic of streams with large flood plain storage, such as lakes and swaps, or where the high flows are mainly derived from snowmelt.

6. The shape of the flow duration curve may change with the length of record. This aspect of the flow duration curve can be utilised for extrapolation of short records.

Shortcomings/Defects of Flow Duration Curve

1. It does not present the flows in natural source of occurence.

2. It is also not possible to tell from flow duration curve whether the lowest flows occured in consecutive periods or were scattered throughout the considered period.

6.22.6. Mass Curve

*A '**mass curve**' is the graph of the cumulative values of water quantity (run-off) against time.* A mass curve is an *integral curve of the hydrograph* which expresses the area under the hydrograph from one time to another.

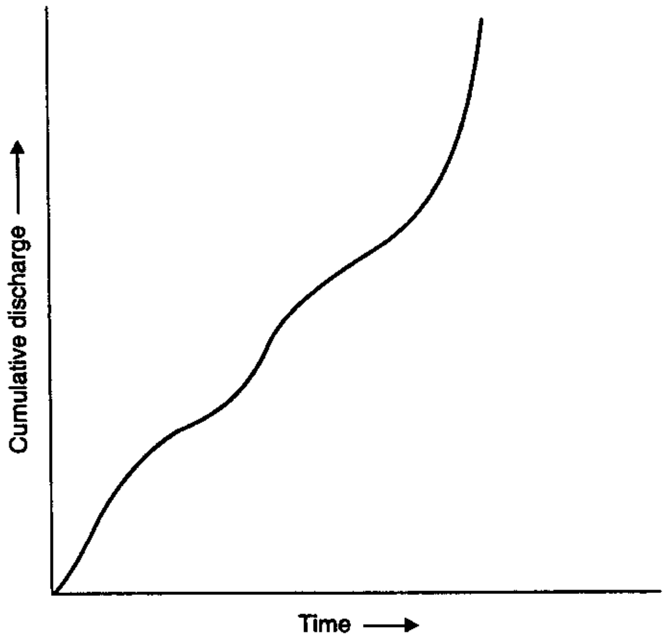


Fig. 6.50. Mass curve.

It is a convenient device *to determine storage requirement* that is needed to produce a certain dependable flow from fluctuating discharge of a river by a reservoir.

Mass curve can also be used to solve the reserve problem of determining the maximum demand rate that can be maintained by a given storage volume. However, it is a trial and error procedure.

The mass curve *will always have a positive shape* but of a greater or less degree depending upon the variations in the quantity of inflow water available. The negative inclination of mass curve would show that the amount of water flowing in the reservoir was less than the loss due to evaporation and seepage.

6.23. HYDRO-POWER DEVELOPMENT IN INDIA

Hydropower is a renewable source of energy which entails many intrinsic advantages. In India the scope of water power development is tremendous. The first hydropower station in India dates back to year 1897 when a small power station of 200 kW capacity was constructed at Darjeeling. Since then many big and small hydropower stations have been installed in the country. Total hydro potential in our country is estimated to be equivalent to about 75000 MW at 60 percent load factor of which only 12 to 14 percent has been exploited so far.

Important hydro plants in India

State / Name of power plant	*Installed capacity (MW)*
Andhra Pradesh	
Machkand (stage I and II)	114
Upper silern	120
Lower silern	600
Srisailam	770
Nagarjun sagar pumped storage	100
Assam	
Umiam	54
Gujarat	
Ukai	300
Himachal Pradesh	
Baira suil	200
Jammu and Kashmir	
Salal	270
Karnataka	
Tungabhadra	72
Sharavati	890
Kailindi	396
Kerala	
Parambikulam-Aliyar	185
Sabarigiri	300
Idikki (Stage I)	390
Maharashtra	
Koyna (stages I, II and III)	860
Manipur	
Loktak	70
Orissa	
Hirakud (stages I and II)	270
Balimela	480
Punjab	
Bhakra Nangal	1084
Beas-Sutlej link	780
Rajasthan	
Chambal	287

Uttar Pradesh	
Rihand	300
Yamuna (stage I and II)	424
Tamil Nadu	
Kundah (stages I, II and III)	425
Kodiar	100

Although the present utilization of hydropower in over country is relatively small with the present tempo of development and need for power resources it would not be long before the available potential is fully harnessed. Hydro-field provides immense scope for sophisticated study requiring application of modern mathematical and operational research techniques with the help of computers.

WORKED EXAMPLES

Penstock

Example 6.1. *A penstock is working under a water head of 210 metres. Its diameter is 2.4 metres. Find its thickness if the joint efficiency is 82 percent and allowable stress in the material is 105 MN/m².*

Solution. Working head, $H = 210$ m

Diameter of the penstock, $d = 2.4$ m

Efficiency of the joint, $\eta = 82\%$

Allowable stress in the material, $f = 105$ MN/m²

Thickness, t :

Pressure, $p = wH$

(w = weight density of water = 9810 N/m³)

i.e.
$$p = \frac{9810 \times 210}{10^6} = 2.06 \text{ MN/m}^2$$

Using the relation

$$f = \frac{pd}{2t\eta}$$

or
$$t = \frac{pd}{2f\eta} = \frac{2.06 \times 2.4}{2 \times 105 \times 0.82} = 0.0287 \text{ m or } 28.7 \text{ mm}$$

Hence thickness of the penstock = **28.7 mm. (Ans.)**

Hydraulic Turbines

Example 6.2. *A Pelton wheel is receiving water from a penstock with a gross head of 510 m. One-third of gross head is lost in friction in the penstock. The rate of flow through the nozzle fitted at the end of the penstock is 2.2 m³/sec. The angle of deflection of the jet is 165°. Determine :*

(i) The horse power given by the water to the runner

(ii) Hydraulic efficiency of the Pelton wheel.

Take C_v (co-efficient of velocity = 1.0) and speed ratio = 0.45.

Solution. Gross head, $H_g = 510$ m

Head lost in friction, $h_f = \frac{H_g}{3} = \frac{510}{3} = 170$ m

∴ Net head, $H = H_g - h_f = 510 - 170 = 340$ m

Discharge, $Q = 2.2\ \text{m}^3/\text{s}$

Angle of deflection $= 165°$

∴ Angle ϕ $= 180 - 165° = 15°$

Coefficient of velocity, $C_v = 1.0$

Speed ratio $= 0.45$

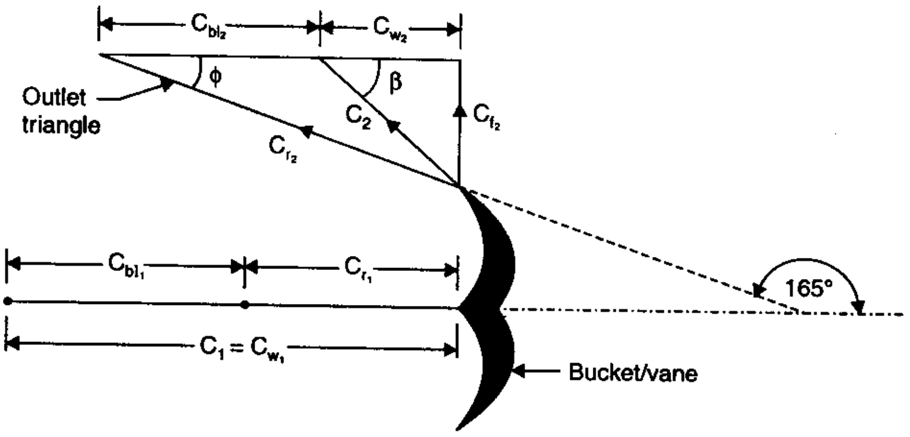


Fig. 6.51

Velocity of jet, $C_1 = C_v\sqrt{2gH}$

$= 1.0\sqrt{2 \times 9.81 \times 340} = 81.67$ m/s

Velocity of wheel, $C_{bl} = \text{Speed ratio} \times \sqrt{2gH}$

$C_{bl} = C_{bl_1} = C_{bl_2} = 0.45 \times \sqrt{2 \times 9.81 \times 340}$

$= 36.75$ m/s

$C_{r_1} = C_1 - C_{bl_1} = 81.67 - 36.75 = 44.92$ m/s

Also $C_{w_1} = C_1 = 81.67$ m/s

From outlet velocity triangle, we have

$C_{r_2} = C_{r_1} = 44.92$ m/s

Also $C_{r_2}\cos\phi = C_{bl_2} + C_{w_2}$

$44.92\cos 15° = 36.75 + C_{w_2}$

or $C_{w_2} = 44.92\cos 15° - 36.75$

$= 6.64$ m/s

Work done by the jet on the runner per second is given by the equation

$= \rho Q\,(C_{w_1} + C_{w_2}) \times C_{bl}$

$= 1000 \times 2.2\,(81.67 + 6.64) \times 36.75$

$= 7139863$ Nm/s

(*i*) **Power given by the water to the runner**

$= 7139863$ J/s or W $\simeq$ **7139.8 kW.** **(Ans.)**

(*ii*) **Hydraulic efficiency of the turbine,**

$$\eta_h = \frac{2(C_{w_1} + C_{w_2}) \times C_{bl}}{C_1^2} = \frac{2(81.67 + 6.64) \times 36.75}{(81.67)^2}$$

$$= \mathbf{0.973 \text{ or } 97.3\%}. \quad \textbf{(Ans.)}$$

Example 6.3. *A Pelton wheel is to be designed for the following specifications :*

Power	*9650 kW*
Head	*350 metres*
Speed	*750 r.p.m.*
Overall efficiency	*85%*
Jet diameter	*not to exceed* $\frac{1}{6}$*th of the wheel diameter*

Determine the following :

(*i*) *The wheel diameter,* (*ii*) *Diameter of the jet,*

(*iii*) *The number of jets required.*

Take $C_v = 0.985$, *speed ratio* = *0.45.*

Solution. Shaft or brake power, = 9650 kW

Head, $H = 350$ m

Speed, $N = 750$ r.p.m.

Overall efficiency, $\eta_0 = 85\%$

Ratio of jet dia. to wheel dia. $= \dfrac{d}{D} = 1/6$

Coefficient of velocity, $C_v = 0.985$

Speed ratio, = 0.45

(*i*) **Wheel diameter, D :**

Velocity of jet, $C_1 = C_v \sqrt{2gH}$

$$= 0.985 \sqrt{2 \times 9.81 \times 350} = 81.62 \text{ m/s}$$

The velocity of wheel, $C_{bl} = C_{bl_1} = C_{bl_2}$

$$= \text{Speed ratio} \times \sqrt{2gH}$$

$$= 0.45 \times \sqrt{2 \times 9.81 \times 350} = 37.3 \text{ m/s}$$

But $$C_{bl} = \frac{\pi DN}{60}$$

or $$37.3 = \frac{\pi \times D \times 750}{60}$$

$\therefore$ $$D = \frac{37.3 \times 60}{\pi \times 750} = \mathbf{0.95 \text{ m}}. \quad \textbf{(Ans.)}$$

(*ii*) **Diameter of the jet, d :**

$$\frac{d}{D} = 1/6 \quad \text{(Given)}$$

$\therefore$ $$d = 1/6D = 1/6 \times 0.95 = \mathbf{0.158 \text{ m}}. \quad \textbf{(Ans.)}$$

(*iii*) **The number of jets required :**

Discharge of one jet, q = Area of jet × velocity of jet

$$= \frac{\pi}{4} d^2 \times C_1 = \pi/4 \times (0.158)^2 \times 81.62$$

$$= 1.6 \text{ m}^3/\text{s}$$

Now, overall efficiency $\eta_0 = \dfrac{\text{Shaft power}}{\text{Water power}} = \dfrac{9560}{wQH}$

or $0.85 = \dfrac{9560}{9.81 \times Q \times 350}$ $(\because \; w = 9.81 \text{ kN/m}^3)$

or $Q = \dfrac{9560}{9.81 \times 350 \times 0.85} = 3.27 \text{ m}^3/\text{s}$

∴ *Number of jets* $= \dfrac{\text{Total discharge}}{\text{Discharge of one jet}} = \dfrac{Q}{q}$

$$= \frac{3.27}{1.6} = 2 \text{ jets.} \quad \textbf{(Ans.)}$$

Example 6.4. *A Francis turbine with an overall efficiency of 76% is required to produce 150 kW. It is working under a head of 8 m. The peripheral velocity = 0.25 $\sqrt{2gH}$ and the radial velocity of flow at inlet is 0.95 $\sqrt{2gH}$. The wheel runs at 150 r.p.m. and the hydraulic losses in the turbine are 20% of the available energy. Assuming radial discharge, determine :*

(i) The guide blade angle *(ii) The wheel angle at inlet*

(iii) Diameter of the wheel at inlet, and *(iv) Width of the wheel at inlet.*

Solution. Overall efficiency, $\eta_0 = 76\%$

Shaft power produced, $P = 150$ kW

Head, $H = 8$ m

Peripheral velocity, $C_{bl} = 0.25 \sqrt{2gH}$

Radial velocity of flow at inlet, $C_{f_1} = 0.95\sqrt{2gH}$

Wheel speed, $N = 150$ r.p.m.

Since discharge at the outlet is radial,

∴ $C_{w_2} = 0$ and $C_{f_2} = C_2$

Hydraulic losses in the turbine = 20% of available energy

Now, $C_{bl_1} = 0.25\sqrt{2 \times 9.81 \times 8} = 3.13$ m/s

$$C_{f_1} = 0.95\sqrt{2 \times 9.81 \times 8} = 11.9 \text{ m/s}$$

Hydraulic efficiency is given as

$$\eta_h = \frac{\text{Total head at inlet} - \text{Hydraulic losses}}{\text{Head at inlet}}$$

$$= \frac{H - 0.2H}{H} = 0.8$$

But $\eta_h = \dfrac{C_{w_1} C_{bl_1}}{gH}$ ∴ $0.8 = \dfrac{C_{w_1} \times 3.13}{9.81 \times 8}$

or $C_{w_1} = \dfrac{0.8 \times 9.81 \times 8}{3.13} = 20$ m/s

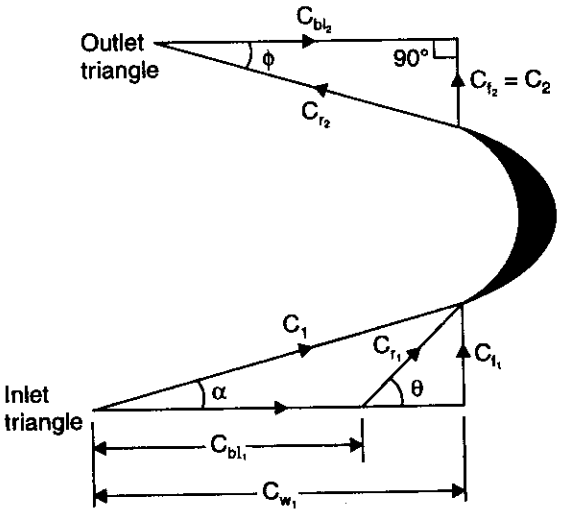


Fig. 6.52

(*i*) **The guide blade angle, α :**

From inlet velocity triangle (Fig. 6.52),

$$\tan \alpha = \frac{C_{f_1}}{C_{w_1}} = \frac{11.9}{20} = 0.595$$

$\therefore$ $\alpha = \tan^{-1}(0.595) = \mathbf{30°45'}$. **(Ans.)**

(*ii*) **The wheel vane angle at inlet, θ :**

$$\tan \theta = \frac{C_{f_1}}{C_{w_1} - C_{bl_1}} = \frac{11.9}{20 - 3.13} = 0.705$$

$\therefore$ $\theta = \tan^{-1}(0.705) = \mathbf{35°\ 11'}$. **(Ans.)**

(*iii*) **Diameter of the wheel at inlet, D_1 :**

Using the relation, $$C_{bl_1} = \frac{\pi D_1 N}{60}$$

or $$D_1 = \frac{C_{bl_1} \times 60}{\pi N} = \frac{3.13 \times 60}{\pi \times 150} = \mathbf{0.398\ m}. \quad \textbf{(Ans.)}$$

(*iv*) **Width of the wheel at inlet, B_1 :**

$$\eta_0 = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{wQH}$$

or $$0.76 = \frac{150}{9.81 \times Q \times 8}$$

$\therefore$ $$Q = \frac{150}{0.76 \times 9.81 \times 8} = 2.515 \text{ m}^3/\text{s}$$

Also, $$Q = \pi D_1 B_1 C_{f_1}$$

or $$2.515 = \pi \times 0.398 \times B_1 \times 11.9$$

$\therefore$ $$B_1 = \frac{2.515}{\pi \times 0.398 \times 11.9} = \mathbf{0.169\ m}. \quad \textbf{(Ans.)}$$

Example 6.5. *The following data relate to a Francis turbine :*

Net head	*70 m*
Speed	*700 r.p.m.*
Shaft power	*330 kW*
Overall efficiency	*85%*
Hydraulic efficiency	*92%*
Flow ratio	*0.22*
Breadth ratio	*0.1*
Outer diameter of the runner	*= 2 × inner diameter of runner*
Velocity of flow	*constant*
Outlet discharge	*radial*

The thickness of vanes occupy 6 percent of circumferential area of the runner. Determine :

(i) Guide blade angle,

(ii) Runner vane angles at inlet and outlet,

(iii) Diameters of runner at inlet and outlet, and

(iv) Width of the wheel at inlet.

Solution. Net head, $H = 70$ m ; Speed, $N = 700$ r.p.m.

Shaft power $= 330$ kW

Overall efficiency, $\eta_0 = 85\%$; Hydraulic efficiency, $\eta_h = 92\%$

Flow ratio = 0.22 ; Breadth ratio, $\frac{B_1}{D_1} = 0.1$; D_1 (= outer dia.) = $2D_2$ (inner dia.)

Thickness of vanes = 6% of circumferential area of runner

$$C_{f_1} = C_{f_2}$$

Now,
$$\text{flow ratio} = 0.22 = \frac{C_{f_1}}{\sqrt{2gH}}$$

or
$$C_{f_1} = 0.22 \times \sqrt{2gH} = 0.22 \times \sqrt{2 \times 9.81 \times 70}$$
$$= 8.15 \text{ m/s}$$

Actual area of flow
$$= \left(1 - \frac{6}{100}\right) \pi D_1 B_1 = 0.94\, \pi\, D_1 B_1$$

Since discharge at outlet is radial

$$C_{w_2} = 0 \quad \text{and} \quad C_{f_2} = C_2$$

Using relation,
$$\eta_0 = \frac{\text{Shaft power}}{\text{Water power}}$$

$$0.85 = \frac{330}{wQH} = \frac{330}{wQH} = \frac{330}{9.81 \times Q \times 70}$$

or
$$Q = \frac{330}{0.85 \times 9.81 \times 70} = 0.565 \text{ m}^3/\text{s}.$$

But
$$Q = \text{Actual area of flow} \times \text{velocity of flow}$$
$$= 0.94\, \pi D_1 B_1 \times C_{f_1}$$

$$0.565 = 0.94\, \pi \times D_1 \times 0.1\, D_1 \times 8.15 \qquad \left(\because \frac{B_1}{D_1} = 0.1 \quad \text{...Given}\right)$$

$$\therefore \quad D_1 = \left(\frac{0.565}{0.94 \times \pi \times 0.1 \times 8.15} \right)^{1/2} = 0.484 \text{ m}$$

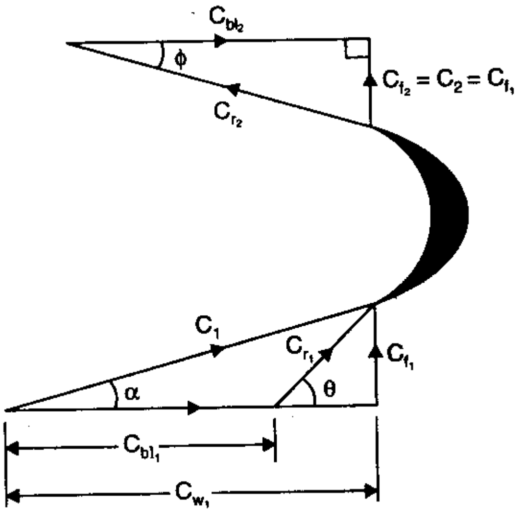


Fig. 6.53

But $\frac{B_1}{D_1} = 0.1$

$\therefore \quad B_1 = 0.1\, D_1 = 0.1 \times 0.484 = 0.0484 \text{ m} = 4.84 \text{ cm}$

Tangential speed of the runner at inlet

$$C_{bl_1} = \frac{\pi D_1 N}{60} = \frac{\pi \times 0.484 \times 700}{60} = 17.74 \text{ m/s}$$

Using relation for hydraulic efficiency,

$$\eta_h = \frac{C_{w_1} C_{bl_1}}{gH} \qquad (\because \; C_{w_2} = 0)$$

$$0.92 = \frac{C_{w_1} \times 17.74}{9.81 \times 70}$$

$$\therefore \quad C_{w_1} = \frac{0.92 \times 9.81 \times 70}{17.74} = 35.6 \text{ m/s}$$

(*i*) **Guide blade angle, α :**

From inlet velocity triangle,

$$\tan \alpha = \frac{C_{f_1}}{C_{w_1}} = \frac{8.15}{35.6} = 0.229$$

$\therefore \quad \alpha = \tan^{-1}(0.229) = \mathbf{12.9°}$. **(Ans.)**

(*ii*) **Runner vane angles at inlet and outlet θ, ϕ = ?**

$$\tan \theta = \frac{C_{f_1}}{C_{w_1} - C_{bl_1}} = \frac{8.15}{35.6 - 17.74} = 0.456$$

$\therefore \quad \theta = \tan^{-1}(0.459) = \mathbf{24.5°}$. **(Ans.)**

From outlet velocity triangle,

$$\tan\phi = \frac{C_{f_2}}{C_{bl_2}} = \frac{C_{f_1}}{C_{bl_2}} \qquad \text{...}(i)$$

But

$$C_{bl_2} = \frac{\pi D_2 N}{60} = \frac{\pi \times D_1}{2} \times \frac{N}{60} \qquad \left[\because\ D_2 = \frac{D_1}{2}\ (\text{given})\right]$$

$$= \frac{\pi \times 0.484 \times 700}{2 \times 60} = 8.87 \text{ m/s}$$

Putting the value of C_{bl_2} in eqn. (*i*), we get

$$\tan\phi = \frac{8.15}{8.87} = 0.9188$$

or

$$\phi = \tan^{-1}(0.9188) = \mathbf{42.58°}. \quad \textbf{(Ans.)}$$

(*iii*) **Diameters of the runner at inlet and outlet, D_1, D_2 :**

$$D_1 = \mathbf{0.484\ m.} \quad \textbf{(Ans.)}$$

$$D_2 = \frac{0.484}{2} = \mathbf{0.242\ m.} \quad \textbf{(Ans.)}$$

(*iv*) **Width of the wheel at inlet, B_1 = 4.84 cm. (Ans.)**

Example 6.6. *A Kaplan turbine develops 22,000 kW at an average head of 35 metres. Assuming a speed ratio of 2, flow ratio of 0.6, diameter of the boss equal to 0.35 times the diameter of the runner and an overall efficiency of 88%, calculate the diameter, speed and specific speed of the turbine.*

Solution. Shaft power, $P = 22,000$ kW

Head, $H = 35$ m

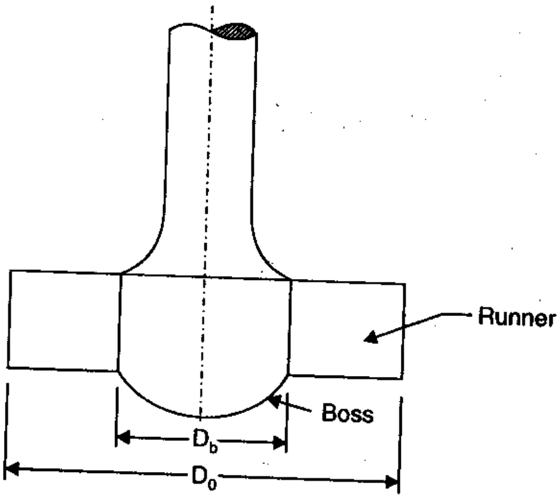


Fig. 6.54. Kaplan turbine runner.

Speed ratio,

$$\frac{C_{bl_1}}{\sqrt{2gH}} = 2.0$$

$$C_{bl_1} = 2 \times \sqrt{2gH} = 2 \times \sqrt{2 \times 9.81 \times 35} = 52.4 \text{ m/s}$$

Flow ratio, $\frac{C_{f_1}}{\sqrt{2gH}} = 0.6$

$$C_{f_1} = 0.6\sqrt{2gH} = 0.6 \times \sqrt{2 \times 9.81 \times 35}$$
$$= 15.7 \text{ m/s}$$

Diameter of boss $= 0.35 \times$ diameter of the runner

$\therefore$ $D_b = 0.35\, D_0$

Overall efficiency, $\eta_0 = 88\%$.

(*i*) Diameter of the runner, D_0 :

Using the relation,

$$\eta_0 = \frac{\text{Shaft power (P)}}{\text{Water power}} = \frac{22000}{wQH}$$

$\therefore$ $$0.88 = \frac{22000}{w \times Q \times H} = \frac{22000}{9.81 \times Q \times 35}$$

or $$Q = \frac{22000}{0.88 \times 9.81 \times 35} = 72.8 \text{ m}^3\text{/s}$$

Also $Q = \pi/4\, (D_0^2 - D_b^2) \times C_{f_1}$

$\therefore$ $72.8 = \pi/4\, [D_0^2 - (0.35\, D_0)^2] \times 15.7$ $[\because\ D_b = 0.35\, D_0]$

$= \pi/4\, D_0^2 \times 0.8775 \times 15.7$

$\therefore$ $$D_0^2 = \frac{72.8 \times 4}{\pi \times 0.8775 \times 15.7}$$

and $D_0 = $ **2.6 m/s. (Ans.)**

$\therefore$ $D_b = 0.35 \times 2.6 = $ **0.91 m/s. (Ans.)**

(*ii*) Speed of the turbine, N :

$$C_{bl_1} = \frac{\pi D_0 N}{60}$$

$\therefore$ $$52.4 = \frac{\pi \times 2.6 \times N}{60}$$

or $N = \frac{52.4 \times 60}{\pi \times 2.6} = $ **384.9 r.p.m. (Ans.)**

(*iii*) Specific speed of the turbine, N_s :

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

(where P_t = power output of the turbine)

$= \frac{384.9 \times \sqrt{22000}}{(35)^{5/4}} = $ **670.6 r.p.m. (Ans.)**

Draft Tube

Exmaple 6.7. *A Kaplan turbine develops 1500 kW under a head of 6 m. The turbine is set 2.5 m above the tail race level. A vacuum gauge inserted at the turbine outlet records a suction head of 3.1 m. If the hydraulic efficiency is 82 percent, what would be the efficiency of draft tube having inlet diameter of 3 m ?*

What will be the reading of suction gauge if power developed is reduced to 750 kW, the head and speed remaining constant ?

Solution. Power developed $= 1500$ kW ; Head, $H = 6$ m

Height of turbine above tail race level $= 2.5$ m ; Hydraulic efficiency, $\eta_h = 82\%$

Draft tube inlet diameter, $d_i = 3$ m

Efficiency of draft tube, η_d :

Hydraulic efficiency, $\eta_h = \dfrac{\text{Power developed}}{\text{Water power}} = \dfrac{\text{Power developed}}{wQH}$

∴ Power developed $= wQH \times \eta_h$

$$1500 = 9.81 \times Q \times 6 \times 0.82$$

or

$$Q = \frac{1500}{9.81 \times 6 \times 0.82} = 31.08 \text{ m}^3/\text{s}$$

Velocity of water at inlet of draft tube,

$$V_2 = \frac{Q}{\frac{\pi}{4} d_i^2} = \frac{31.08}{\frac{\pi}{4} \times 3^2} = 4.397 \text{ m/s}$$

Pressure head required $= 3.1 - 2.5 = 0.6$ m

∴ Efficiency of draft tube, $\eta_d = \dfrac{0.6}{\frac{V_2^2}{2g}} = \dfrac{0.6}{\frac{4.397^2}{2 \times 9.81}} = 0.6088$ or **60.88%. (Ans.)**

Reading of suction gauge :

For reduced output of 750 kW assuming constant efficiency, we have

Discharge $Q_1 = \dfrac{Q}{2} = \dfrac{31.08}{2} = 15.54 \text{ m}^3/\text{s}$

Also $V_2 = \dfrac{15.54}{\frac{\pi}{4} \times 3^2} = 2.198$ m/s

Head gained in draft tube $= \eta_d \times \dfrac{2.198^2}{2g}$

$$= 0.6088 \times \frac{2.198^2}{2 \times 9.81} \simeq 0.15 \text{ m}$$

∴ Reading of gauge $= 2.5 + 0.15 =$ **2.65 m. (Ans.)**

Example 6.8. *Determine the overall efficiency of a Kaplan turbine developing 2850 kW under a head of 5.2 m. It is provided with a draft tube with its inlet (diameter 3 m) set 1.8 m above the tail race level. A vacuum gauge connected to the draft tube indicates a reading of 5.2 m of water. Assume draft tube efficiency as 75 percent.*

Solution. Power developed = 2850 kW ; Head, $H = 5.2$ m

Height of draft inlet tube above tail race level, $H_s = 1.8$ m

Reading of the gauge $= -5.2$ m

Draft tube efficiency, $\eta_d = 75\%$

Overall efficiency of the turbine, η_0 :

$$\frac{p_2}{w} = \frac{p_a}{w} - H_s - \left(\frac{V_2^2 - V_3^2}{2g} - h_f\right) \qquad \text{...[Eqn. 6.10(a)]}$$

$$-5.2 = 0 - 1.8 - \left(\frac{V_2^2 - V_3^2}{2g}\right), \text{ neglecting } h_f \text{ (head loss in draft tube)}$$

or $$\frac{V_2^2 - V_3^2}{2g} = 3.4$$

Also, $$\eta_d = \frac{(V_2^2 - V_3^2)/2g}{(V_2^2/2g)} \quad \text{...[Eqn. 6.11]}$$

or $$0.75 = \frac{3.4}{(V_2^2/2g)} \quad \text{or} \quad \frac{V_2^2}{2g} = \frac{3.4}{0.75} = 4.533$$

$\therefore$ $$V_2 = \sqrt{4.533 \times 2g} = \sqrt{4.533 \times 2 \times 9.81} = 9.43 \text{ m/s}$$

Discharge $$Q = \frac{\pi}{4} \times 3^2 \times 9.43 = 66.65 \text{ m}^3\text{/s}$$

$\therefore$ Overall efficiency, $$\eta_0 = \frac{\text{Power developed}}{\text{Water power}} = \frac{2850}{wQH}$$

$$= \frac{2850}{9.81 \times 66.65 \times 5.2} = 0.8382 \quad \text{or} \quad \mathbf{83.82\%.} \ \mathbf{(Ans.)}$$

Example 6.9. *A conical draft tube having inlet and outlet diameters 1.2 m and 1.8 m discharges water at outlet with a velocity of 3 m/s. The total length of the draft tube is 7.2 m and 1.44 m of the length of draft tube is immersed in water. If the atmospheric pressure head is 10.3 m of water and loss of head due to friction in the draft tube is equal to 0.2 × velocity head at outlet of the tube, determine :*

(*i*) *Pressure head at inlet, and* (*ii*) *Efficiency of the draft tube.*

Solution. Inlet diameter of the draft tube, $d_i = 1.2$ m

Outlet diameter, $d_0 = 1.8$ m

Velocity at outlet $V_3 = 3$ m/s

Total length of draft tube,

$$H_s + y = 7.2 \text{ m}$$

Length of draft tube in water, $y = 1.44$ m

$\therefore$ $H_s = 7.2 - 1.44 = 5.76$ m

Atmospheric pressure head, $\frac{p_a}{w} = 10.3$ m

Loss of head due to friction, $h_f = 0.2 \times \text{velocity head at outlet} = 0.2 \frac{V_3^2}{2g}$

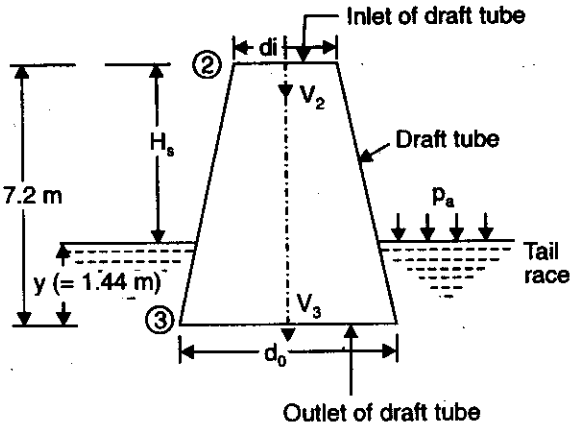


Fig. 6.55

(*i*) **Pressure head at inlet, $\frac{p_2}{w}$:**

Discharge through the draft tube,

$$Q = A_3V_3 = \frac{\pi}{4} \times d_0^2 \times V_3 = \frac{\pi}{4} \times 1.8^2 \times 3 = 7.634 \text{ m/s}$$

Velocity of inlet, $$V_2 = \frac{Q}{A_2} = \frac{7.634}{\frac{\pi}{4} d_i^2} = \frac{7.634}{\frac{\pi}{4} \times 1.2^2} = 6.75 \text{ m/s}$$

Using eqn. (6.10) $$\frac{p_2}{w} = \frac{p_a}{w} - H_s - \left(\frac{V_2^2 - V_3^2}{2g} - h_f\right) = \frac{p_a}{w} - H_s - \left(\frac{V_2^2 - V_3^2}{2g} - 0.2\frac{V_3^2}{2g}\right)$$

$$= 10.3 - 5.76 - \left(\frac{6.75^2 - 3^2}{2 \times 9.81} - 0.2 \times \frac{3^2}{2 \times 9.81}\right)$$

or $$\frac{p_2}{w} = 4.54 - (1.863 - 0.092) = \textbf{2.769 m (abs).} \quad \textbf{(Ans.)}$$

(*ii*) **Efficiency of the draft tube, η_d :**

$$\eta_d = \frac{\left(\frac{V_2^2 - V_3^2}{2g} - h_f\right)}{\frac{V_2^2}{2g}} = \frac{\frac{V_2^2 - V_3^2}{2g} - 0.2\frac{V_3^2}{2g}}{\frac{V_2^2}{2g}} = \frac{\frac{V_2^2}{2g} - \left(\frac{V_3^2}{2g} + 0.2\frac{V_3^2}{2g}\right)}{\frac{V_2^2}{2g}}$$

$$= 1 - 1.2\left(\frac{V_3}{V_2}\right)^2 = 1 - 1.2\left(\frac{3}{6.75}\right)^2 = 0.763 \text{ or } \textbf{76.3\%.} \quad \textbf{(Ans.)}$$

Example 6.10. *Give the range of specific speed of values of the Kaplan, Francis turbines and Pelton Wheels. What factors decide whether Kaplan, Francis or a Pelton wheel type turbine would be used in a hydroelectric project ?* **(UPSC, 1992)**

Solution. The **specific speed** of a turbine is defined as *the speed of a turbine which is identical in shape, geometrical dimensions, blade angles, gate opening etc. which would develop unit power when working under a unit head.*

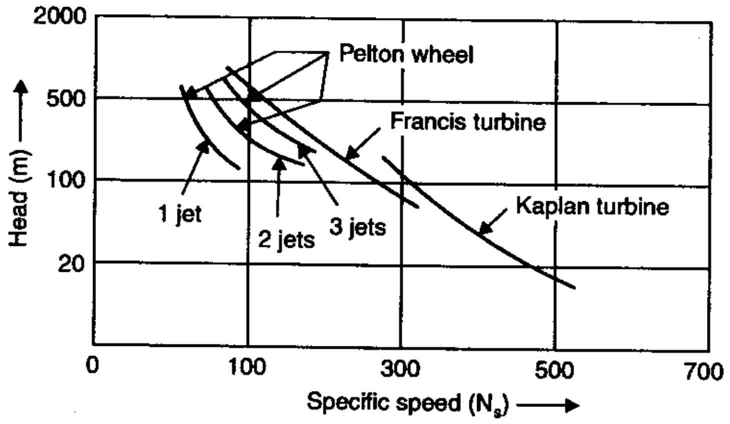


Fig. 6.56

- Based on specific speed, the turbines for the project are selected as shown in the Fig. 6.56.
- In general, the selection of a turbine for hydroelectric project is based on the following considerations :

1. For *high heads, Pelton wheels* are invariably selected.
2. For *intermediate heads, Francis turbines* are selected.
3. For *low head and high discharge,* Kaplan turbines are selected.

Example 6.11. *A turbine develops 6620 kW under a head of 20 metres at 130 r.p.m. Calculate the specific speed of the turbine and state the type of the turbine.*

Solution. Power developed, $P = 6620$ kW

Head, $H = 20$ metres

Speed, $N = 130$ r.p.m.

Specific speed of the turbine, $N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{130 \times \sqrt{6620}}{(20)^{5/4}} = \mathbf{250\ r.p.m.}$ **(Ans.)**

Since for specific speeds between 50 and 350 (SI units) the type of turbine is Francis, therefore as the specific speed lies in this range, the turbine in question is **Francis. (Ans.)**

Example 6.12. *In a hydro-electric station, water is available at the rate of 175 m^3/s under a head of 18 m. The turbines run at a speed of 150 r.p.m. with overall efficiency of 82%. Find the number of turbines required if they have the maximum specific speed of 460.* **(GATE, 1996)**

Solution. *Given :* $Q = 175$ m^3/s ; $H = 18$ m ; $N = 150$ r.p.m. ; $\eta_0 = 82$ % ; $N_s = 460$.

Number of turbines required :

Specific speed of the turbine, $N_s = \frac{N\sqrt{P}}{H^{5/4}}$ ...[Eqn. (6.12)]

$$460 = \frac{150\sqrt{P}}{(18)^{5/4}} \text{ (where } P \text{ is in kW and H is in metres)}$$

or Power available at turbine shaft, $P = \left[\frac{460 \times (18)^{5/4}}{150}\right]^2 = 12927.5$ kW

Power available from turbines $= wQH \times \eta_0 = 9.81 \times 175 \times 18 \times 0.82 = 25339.23$ kW

No. of turbines required $= \frac{25339.23}{12927.5} = 1.96$ say **2. (Ans.)**

Example 6.13. *The turbine is to operate under a head of 24 m at 200 r.p.m. The discharge is 8.5 m^3/s. If the overall efficiency is 88%, determine :*

(i) Power generated, *(ii) Specific speed of the turbine,*

(iii) Type of turbine.

Solution. Head, $H = 24$ m

Speed, $N = 200$ r.p.m.

Discharge, $Q = 8.5$ m^3/s

Overall efficiency, $\eta_0 = 88\%$

(*i*) **Power generated, P :**

$$\eta_0 = \frac{\text{Power developed}}{\text{Water power}} = \frac{P}{wQH}$$

$\therefore$ $P = \eta_0 \times wQH = 0.88 \times 9.81 \times 8.5 \times 24$

or $\mathbf{P = 1761\ kW.}$ **(Ans.)**

(*ii*) **Specific speed of the turbine, N_s :**

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{200 \times \sqrt{1761}}{(24)^{5/4}}$$
$$= \mathbf{158\ r.p.m.} \quad \textbf{(Ans.)}$$

(*iii*) **Type of turbine :**

As the specific speed lies between 50 and 350, the turbine is a **Francis turbine.** **(Ans.)**

Example 6.14. *Calculate the specific speed of a turbine and suggest the type of turbine required for a river having a discharge of 240 litres/sec. with a available head of 45 metres.*

Take the efficiency of the turbine = 82% and speed = 450 r.p.m.

Solution. Discharge, $Q = 240$ litres/s $\left(= \frac{240}{1000} = 0.24 \text{ m}^3/\text{s}\right)$

Head, $H = 45$ m

Turbine efficiency, $\eta = 82\%$

Speed, $N = 450$ r.p.m.

Now, $\eta = \frac{P}{wQH}$

∴ Power developed, $P = \eta \times wQH = 0.82 \times 9.81 \times 0.24 \times 45 = 86.88$ kW

Specific speed, $N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{450 \times \sqrt{86.88}}{(45)^{5/4}} \simeq$ **3.6 r.p.m.** **(Ans.)**

For this specific speed **Pelton turbine** is suitable. **(Ans.)**

Example 6.15. *A hydro-electric power station is desired to be built across a river having a discharge of 28000 litres/s at a head of 11 m. Assuming turbine efficiency 78% and speed ratio as 0.82, determine :*

(*i*) *Can we use two turbines with a speed not less than 120 r.p.m. and specific speed more than 350 r.p.m. ?*

(*ii*) *Specify the type of turbine/runner that can be used. Also calculate the runner diameter.*

Solution. Discharge, $Q = 28000$ litres/sec. $\left(= \frac{28000}{1000} = 28 \text{ m}^3/\text{s}\right)$

Turbine efficiency, $\eta = 78\%$

Speed ratio $= 0.82$

Head, $H = 11$ m

(*i*) Power developed, $P = \eta \times wQH$

$= 0.78 \times 9.81 \times 28 \times 11 = 2356.7$ kW

Using *two* turbines each of capacity 1200 kW, the specific speed of the turbine is calculated as follows :

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{120\sqrt{1200}}{(11)^{5/4}} = 207.5 \text{ r.p.m.}$$

(*ii*) For the specific speed calculated above *Francis* turbine is suitable.

Diameter of the runner, D :

Tangential velocity of the runner,

$$C_{bl} = \text{Speed ratio} \times \sqrt{2gH}$$
$$= 0.82 \times \sqrt{2 \times 9.81 \times 11} = 12.05 \text{ m/s}$$

But $$C_{bl} = \frac{\pi DN}{60}$$

$\therefore$ $$12.05 = \frac{\pi D \times 120}{60}$$

$\therefore$ $$D = \frac{12.05 \times 60}{\pi \times 120} = \mathbf{1.92\ m.}\quad \textbf{(Ans.)}$$

Example 6.16. *The quantity of water available for hydro-electric station is 250 m^3/sec. under a head of 1.6 m. If the speed of the turbine is 50 r.p.m. and efficiency 82% determine the number of turbine units required. Take specific speed as 740.*

Solution. Quantity of water available, $Q = 250\ m^3/s$

Head, $H = 1.6\ m$

Speed, $N = 50$ r.p.m.

Efficiency, $\eta = 82\%$

Specific speed, $N_s = 740$

Number of turbine units required :

Total power (P_{total}) to be developed can be calculated using the following equation,

$$P_{total} = \eta\, wQH$$
$$= 0.82 \times 9.81 \times 250 \times 1.6 = 3217.7\ kW$$

The power developed by each turbine can be calculated be using the following equation :

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

$$740 = \frac{50 \times \sqrt{P}}{(1.6)^{5/4}}$$

$$\sqrt{P} = \frac{740 \times (1.6)^{5/4}}{50}$$

$\therefore$ $$P = \left[\frac{740 \times (1.6)^{5/4}}{50}\right]^2 \quad \text{or} \quad P = 709.3\ kW$$

$\therefore$ Number of turbine units required

$$= \frac{P_{total}}{P} = \frac{3217.7}{7093} = 4.54 \approx \mathbf{5.}\quad \textbf{(Ans.)}$$

☞**Example 6.17.** *At a proposed site of hydro-electric power plant the available discharge and head is 330 m^3/s and 28 m respectively. The turbine efficiency is 86%. The generator is directly coupled to the turbine. The frequency of generator is 50 Hz and number of poles used are 24. Find the least number of machines required if,*

(i) A Francis turbine with a specific speed of 260 is used.

(ii) A Kaplan turbine with a specific speed of 700 is used.

Solution. Available discharge, $Q = 330\ m^3/s$

Head, $H = 28\ m$

Turbine efficiency, $\eta = 86\%$

Frequency of generation, $f = 50$ Hz

Number of poles used, $p = 24$

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

$$\therefore \quad N = \frac{120f}{p} = \frac{120 \times 50}{24} = 250 \text{ r.p.m.}$$

$$P = \eta \times wQH = 0.86 \times 9.81 \times 330 \times 28$$
$$= 77954.2 \text{ kW.}$$

(*i*) The power capacity of each Francis turbine (P_1) can be calculated by using the following formula

$$N_s = \frac{N\sqrt{P_1}}{H^{5/4}}$$

$$260 = \frac{250\sqrt{P_1}}{(28)^{5/4}}$$

$$\therefore \quad P_1 = \left[\frac{260 \times (28)^{5/4}}{250}\right]^2 = 4487 \text{ kW}$$

∴ Number of Francis turbines required

$$= \frac{P}{P_1} = \frac{77954.2}{4487} = 17.4 \approx 18. \quad \textbf{(Ans.)}$$

(*ii*) The power capacity of each Kaplan turbine can be calculated by using the following formula :

$$N_s = \frac{N\sqrt{P_1}}{H^{5/4}}$$

$$770 = \frac{250\sqrt{P_2}}{(28)^{5/4}}$$

$$\therefore \quad P_2 = \left[\frac{700 \times (28)^{5/4}}{250}\right]^2$$
$$= 32524.5 \text{ kW}$$

∴ Number of Kaplan turbines required

$$= \frac{P}{P_2} = \frac{77954.2}{32524.5} = 2.4 \approx 3. \quad \textbf{(Ans.)}$$

Example 6.18. *A turbine is to operate under a head of 25 m at 200 r.p.m. The discharge is 9 m^3/s. If the efficiency is 90 percent determine the performance of turbine under a head of 20 m.*

[M.U.]

Solution. Head under which turbine works, $H_1 = 25$ m

Speed of the turbine, $N_1 = 200$ r.p.m.

Discharge through the turbine, $Q_1 = 9 \text{ m}^3/\text{s}$

Efficiency (overall), $\eta_0 = 90\%$

Performance of turbine under a head of 20 m ; N_2, Q_2, P_2 :

Performance of turbine under a head, $H_2 = 20$ m means to find speed (N_2), discharge (Q_2), and power generated (P_2) by the turbine when working under a head of 20 m.

Overall efficiency,
$$\eta_0 = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{wQH} = \frac{P_1}{wQ_1H_1}$$

$$\therefore \quad P_1 = \eta_0 \times wQ_1H_1 = 0.9 \times 9.81 \times 9 \times 25 = 1986.5 \text{ kW}$$

Now, $$\frac{N_1}{\sqrt{H_1}} = \frac{N_2}{\sqrt{H_2}} \quad \text{...[Eqn. (6.19)]}$$

∴ $$N_2 = \frac{N_1\sqrt{H_2}}{\sqrt{H_1}} = \frac{200 \times \sqrt{20}}{\sqrt{25}} = \mathbf{178.88\ r.p.m.} \quad \textbf{(Ans.)}$$

and $$\frac{Q_1}{\sqrt{H_1}} = \frac{Q_2}{\sqrt{H_2}} \quad \text{...[Eqn. (6.20)]}$$

∴ $$Q_2 = \frac{Q_1\sqrt{H_2}}{\sqrt{H_1}} = \frac{9 \times \sqrt{20}}{\sqrt{25}} = \mathbf{8.05\ m^3/s} \quad \textbf{(Ans.)}$$

and $$\frac{P_1}{{H_1}^{3/2}} = \frac{P_2}{(H_2)^{3/2}} \quad \text{...[Eqn. (6.21)]}$$

∴ $$P_2 = \frac{P_1 \times (H_2)^{3/2}}{(H_1)^{3/2}} = \frac{1986.5 \times (20)^{3/2}}{(25)^{3/2}} = \mathbf{1421.4\ kW} \quad \textbf{(Ans.)}$$

Example 6.19. *A hydro-turbine is required to give 25 MW at 50 m head and 90 r.p.m. runner speed. The laboratory facilities available, permit testing of 20 kW model at 5 m head. What should be the model runner speed and model to prototype scale ratio.* **(GATE, 1992)**

Solution. *Given :* P_p = 25 MW ; H_p = 50 m ; N_p = 90 r.p.m. ; P_m = 20 kW ; H_m = 5 m

$$\mathbf{N_m\ ;\ \frac{D_p}{D_m}\ (= L_r) :}$$

Prototype specific speed, $(N_s)_p = \frac{N_p\sqrt{P_p}}{(H_p)^{5/4}}$ (where P is in kW)

$$= \frac{90 \times \sqrt{25 \times 10^3}}{(50)^{5/4}} = 107$$

For model, $$107 = \frac{N_m\sqrt{P_m}}{(H_m)^{5/4}} \quad [\because\ (N_s)_p = (N_s)_m]$$

or $$\mathbf{N_m} = \frac{107 \times (H_m)^{5/4}}{\sqrt{P_m}} = \frac{107 \times (5)^{5/4}}{\sqrt{20}} = \mathbf{178.89\ r.p.m.} \quad \textbf{(Ans.)}$$

For similar turbines $\frac{P}{H^{3/2}D^2}$ should be equal.

∴ $$\frac{P}{{H_p}^{3/2}{D_p}^2} = \frac{P_m}{{H_m}^{3/2}{D_m}^2}$$

or $$\frac{D_p}{D_m}\ (= L_r) = \sqrt{\frac{P_p}{P_m} \times \left(\frac{H_m}{H_p}\right)^{3/2}} = \sqrt{\frac{25 \times 10^3}{20} \times \left(\frac{5}{50}\right)^{3/2}} = \mathbf{6.287.} \quad \textbf{(Ans.)}$$

Example 6.20. *A water turbine delivering 10 MW power is to be tested with the help of a geometrically similar 1 : 8 model, which runs as the same speed as the prototype.*

(i) Find the power developed by the model assuming the efficiencies of the model and the prototype are equal.

(ii) Find the ratio of the heads and the ratio of mass flow rates between the prototype and the model. **(GATE, 1997)**

Solution. *Given :* $P_p = 10$ MW ; $N_p = N_m$, ; $\frac{L_m}{L_p} = \frac{D_m}{D_p} = \frac{1}{8}$; $\eta_p = \eta_m$.

(*i*) **Power developed by the model, $\mathbf{P_m}$:**

We know that, $P \propto N^3 \times D^5$ ...[Eqn. (6.24)]

(where N is the speed and D is the diameter)

$$\therefore \quad P_p \propto N_p^3 D_p^5 \text{ and } P_m \propto N_m^3 D_m^5$$

or

$$\frac{P_p}{P_m} = \left(\frac{N_p}{N_m}\right)^3 \times \left(\frac{D_p}{D_m}\right)^5 = (1)^3 \times \left(\frac{8}{1}\right)^5 = 8^5 \qquad (\because \; N_p = N_m)$$

$$\therefore \quad P_m = \frac{P_p}{(8)^5} = \frac{10 \times 10^6}{(8)^5} = \mathbf{305.2\ W.} \quad \textbf{(Ans.)}$$

(*ii*) **Ratio of heads $\left(\frac{\mathbf{H_p}}{\mathbf{H_m}}\right)$ and ratio of mass flow rates $\left(\frac{\mathbf{m_p}}{\mathbf{m_m}}\right)$:**

We know that $H \propto N^2 D^2$ ...(Eq. (6.22)]

$$\therefore \quad \frac{H_p}{H_m} = \left(\frac{N_p}{N_m}\right)^2 \times \left(\frac{D_p}{D_m}\right)^2 = (1)^2 \times (8)^2 = \mathbf{64.} \quad \textbf{(Ans.)}$$

Also, Discharge, $Q \propto ND^3$ ...[Eqn. (6.23)]

$$\therefore \quad \text{Ratio of mass flow rates, } \frac{Q_p}{Q_m} = \frac{m_p}{m_m} = \left(\frac{N_p}{N_m}\right)\left(\frac{D_p}{D_m}\right)^3 = 1 \times (8)^3 = \mathbf{512.} \quad \textbf{(Ans.)}$$

Example 6.21. *A hydraulic turbine is to develop 1015 kW when running at 120 r.p.m. under a net head of 12 m. Work out the maximum flow rate and specific speed for the turbine if the overall efficiency at the best operating point is 92 percent. In order to predict its performance, a 1 : 10 scale model is tested under a head of 7.2 m. What would be the speed, power output and water consumption of the model if it runs under the conditions similar to the prototype ?*

Solution. Shaft power, $P = 1015$ kW ; Speed, $N = 120$ r.p.m.

Overall efficiency, $\eta_0 = 92\%$; Head, H = 12 m

Flow rate (Q), Specific speed ($\mathbf{N_s}$) :

$$\eta_0 = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{wQH} \; ; \; Q = \frac{P}{\eta_0 wH}$$

or Flow rate,

$$Q = \frac{1015}{0.92 \times 9.81 \times 12} = \mathbf{9.372\ m^3/s.} \quad \textbf{(Ans.)}$$

Specific speed,

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{120\sqrt{1015}}{(12)^{5/4}} = \mathbf{171.2\ r.p.m.} \quad \textbf{(Ans.)}$$

Model scale $= 1 : 10$ (Given)

Head under which model is tested, $H_m = 7.2$ m (Given)

$\mathbf{N_m}$, $\mathbf{P_m}$, $\mathbf{Q_m}$:

For similar turbines each of the following parameters must be same for both model and prototype.

(*i*) Head co-efficient, $C_H = \frac{H}{N^2 D^2}$; (*ii*) Flow co-efficient $C_Q = \frac{Q}{ND^3}$

(*iii*) Power co-efficient, $C_p = \frac{P}{N^3 D^5}$

(*i*) $$\left(\frac{H}{N^2D^2}\right)_m = \left(\frac{H}{N^2D^2}\right)_p \quad \text{or} \quad \frac{H_m}{N_m{}^2D_m{}^2} = \frac{H_p}{N_p{}^2D_p{}^2} \quad \text{or} \quad N_m{}^2 = N_p{}^2\,\frac{D_p{}^2}{D_m{}^2} \times \frac{H_m}{H_p}$$

∴ Model speed, $N_m = N_p \times \frac{D_p}{D_m} \times \left(\frac{H_m}{H_p}\right)^{1/2} = 120 \times 10 \times \left(\frac{7.2}{12}\right)^{1/2}$ **= 929.5 r.p.m. (Ans.)**

(*ii*) $$\left(\frac{Q}{ND^3}\right)_m = \left(\frac{Q}{ND^3}\right)_p \quad \text{or} \quad \frac{Q_m}{N_mD_m{}^3} = \frac{Q_p}{N_pD_p{}^3}$$

∴ Discharge in the model,

$$Q_m = Q_p \times \frac{N_m}{N_p} \times \left(\frac{D_m}{D_p}\right)^3 = 9.372 \times \frac{929.5}{120} \times \left(\frac{1}{10}\right)^3 = \mathbf{0.0726\ m^3/s.}\quad \textbf{(Ans.)}$$

(*iii*) $$\left(\frac{P}{N^3D^5}\right)_m = \left(\frac{P}{N^3D^5}\right)_p \quad \text{or} \quad \frac{P_m}{N_m{}^3D_m{}^5} = \frac{P_p}{N_p{}^3D_p{}^5}$$

∴ Power produced by the model,

$$P_m = P_p \times \left(\frac{N_m}{N_p}\right)^3 \times \left(\frac{D_m}{D_p}\right)^5 = 1015 \times \left(\frac{929.5}{120}\right)^3 \times \left(\frac{1}{10}\right)^5 = \mathbf{4.72\ kW.}\quad \textbf{(Ans.)}$$

Hydro-electric Power Station

Example 6.22. *The following data relate to a hydro-electric power station :*

Head = 400 m ; Discharge = 4.5 m³/s ; Turbine efficiency = 8.2% ; Generator frequency = 50 Hz. Determine :

(*i*) *Power developed,* (*ii*) *Type of the turbine,*

(*iii*) *Speed of the turbine.*

Solution. Head, $H = 400$ m

Discharge, $Q = 4.5$ m³/s

Turbine efficiency, $\eta = 82\%$

Generator frequency, $f = 50$ Hz

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

$$P = \eta \times wQH = 0.82 \times 9.81 \times 4.5 \times 400$$
$$= \mathbf{14479\ kW.}\quad \textbf{(Ans.)}$$

(*ii*) **Type of turbine :**

Pelton turbine should be used for a head of 400 m. **(Ans.)**

(*iii*) **Speed of the turbine, N :**

N = Actual speed of the turbine

N_s = Specific speed of the turbine.

Choosing an approximate speed of about 50.

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

∴ $$N = \frac{N_s \times (H)^{5/4}}{\sqrt{P}} = \frac{50 \times (400)^{5/4}}{\sqrt{14479}} = 743.3 \text{ r.p.m.}$$

Again, $$N = \frac{120f}{p} \quad \text{or} \quad p = \frac{120f}{N}$$ (where p = Number of poles)

∴ $p = \frac{120 \times 50}{743.3} = 8.07 \approx 8$ (say)

Corrected speed $= \frac{120f}{p} = \frac{120 \times 50}{8}$

$= 750$ **r.p.m. (Ans.)**

Example 6.23. *A flow of 75 m³/s under a head of 110 m is available at a site for a hydro power station. If the efficiency of the turbine is 88% and generator efficiency is 92%, determine :*

(i) Power developed, *(ii) Number of units required and their capacities.*

Solution. Discharge, $Q = 75$ m³/s

Head, $H = 110$ m

Turbine efficiency, $\eta_t = 88\%$

Generator efficiency, $\eta_g = 92\%$

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

$$P = \eta_t \times wQH$$

or $P = 0.88 \times 9.81 \times 75 \times 110 = \mathbf{71220\ kW.}$ **(Ans.)**

(*ii*) **Two turbines** each of $\frac{71220}{2} = 35610$ kW capacity may be used. **(Ans.)**

Generator capacity of each unit $= \eta_g \times 35610$

$= 0.92 \times 35610 = 32761$ kW

Total power generated by the generators

$= 32761 \times 2 =$ **65522 kW or 65.5 MW. (Ans.)**

Example 6.24. *A proposed hydro-electric station has an available head of 120 metres, a catchment area of 200 sq. km, the rainfall of which is 120 cm per annum. If 62% of the total rainfall can be collected, calculate the power that could be generated. Suggest suitable ratings of generators.*

Solution. Available head, $H = 120$ m

Catchment area $A = 200$ sq. km $(= 200 \times 10^6\ \text{m}^2)$

Rainfall $= 120$ cm per annum $(= 1.2$ m$)$

Rainfall collected/annum, $h = 62\%$ of the total rainfall

$= (0.62 \times 1.2)$ m.

Power developed, P :

Total quantity of water available for power generation

$= A \times h = 200 \times 10^6 \times (0.62 \times 1.2)$

$= 148.8 \times 10^6$ m³/year

Hence quantity of water available per second

$$= \frac{148.8 \times 10^6}{(365 \times 24) \times 60 \times 60} = \frac{148.8 \times 10^6}{8760 \times 3600} = 4.7\ \text{m}^3/\text{s}$$

Now, $P = \eta_0 \times wQH$

$= 0.95 \times 9.81 \times 4.7 \times 120$ (Assuming $\eta_0 = 0.95$)

$=$ **5256 kW. (Ans.)**

Suitable ratings of generators :

Two generators of 2800 kW capacity each may be installed. However, ratings of generators may need upward revision if various efficiencies and load factors are taken into account.

☞**Example 6.25.** *The following data relate to a proposed hydro-electric station :*

Available head = 28 m ; Catchment area = 420 sq. km ; rainfall = 140 cm/year ; percentage of total rainfall utilized = 68% ; Penstock efficiency = 94% ; turbine efficiency = 80% ; generator efficiency = 84% and load factor = 44%.

(i) Calculate the power developed.

(ii) Suggest suitable machines and specify the same.

Solution. Head available, $H = 28$ m

Catchment area, $A = 420$ sq. km $(= 420 \times 10^6 \text{ m}^2)$

Rainfall $= 140$ cm/year $(= 1.4$ m$)$

Rainfall utilized, $h = 68\%$ of the total rainfall

$= (0.68 \times 1.4)$ m per year

Penstock efficiency, $\eta_p = 94\%$

Turbine efficiency, $\eta_t = 80\%$

Generator efficiency, $\eta_g = 84\%$

Load factor $= 44\%$.

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

Quantity of water available *per year*

$$= A \times h = (420 \times 10^6) \times (0.68 \times 1.4)$$

$$= 399.84 \times 10^6 \text{ m}^3$$

Hence the quantity of water available *per second,*

$$Q = \frac{399.84 \times 10^6}{(365 \times 24) \times 3600} = 12.6 \text{ m}^3$$

$$\therefore \quad P = \eta_0 \times wQH \quad (\text{where } \eta_0 = \text{Overall efficiency} = \eta_p \times \eta_t \times \eta_g)$$

or

$$P = \eta_p \times \eta_t \times \eta_g \times wQH$$

$$= 0.94 \times 0.8 \times 0.84 \times 9.81 \times 12.6 \times 28 = 2186 \text{ kW}$$

Hence *average output of generating units* = **2186 kW. (Ans.)**

(*ii*) **Machines to be used :**

$$\text{Total ratings of generators} = \frac{2186}{0.44} = 4968 \text{ kW}$$

Providing *two machines* of equal rating,

$$\text{Capacity of each unit} = \frac{4968}{2 \times 0.84} = 2957 \text{ each.}$$

As the available head is low, **Kaplan turbines** (propeller type) are suggested, each having a *generating capacity of* **2957 kW. (Ans.)**

☞**Example 6.26.** *The following data is available for a hydro-power plant :*

Available head = 140 m ; catchment area = 2000 sq. km ; annual average rainfall = 145 cm ; turbine efficiency = 85% ; generator efficiency = 90% ; percolation and evaporation losses = 16%.

Determine the following :

(i) Power developed.

(ii) Suggest type of turbine to be used if runner speed is to be kept below 240 r.p.m.

Solution. Head available, $H = 140$ m

Catchment area, $A = 200$ sq. km $(= 200 \times 10^6 \text{ m}^2)$

Annual average rainfall, $h = 145$ cm $(= 1.45$ m$)$

Turbine efficiency, $\eta_t = 85\%$

Generator efficiency, $\eta_g = 90\%$

Percolation and evaporation losses, $z = 16\% = 0.16$

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

Quantity of water available for power generation *per year*

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

$$= 200 \times 10^6 \times 1.45 \times (1 - 0.16) = 2.436 \times 10^8 \text{ m}^3\text{/year}$$

Hence, quantity of water available per second,

$$Q = \frac{2.436 \times 10^8}{(365 \times 24) \times 3600} = 7.72 \text{ m}^3\text{/s}$$

$$\therefore \quad P = \eta_0 \times wQH$$

$$= \eta_t \times \eta_g \times wQH$$

$$= 0.85 \times 0.9 \times 9.81 \times 7.72 \times 140$$

$$= \mathbf{8111 \text{ kW or } 8.111 \text{ MW}}. \quad \textbf{(Ans.)}$$

(*ii*) **Type of turbine to be used :**

Specific speed, $N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{240\sqrt{8111}}{(140)^{5/4}} = 44.28$ r.p.m.

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

Example 6.27. *From the investigation of a hydro-site the following data is available :*

Available head	*45 m*
Total catchment area	*60 sq. km*
Rainfall per annum	*140 cm*
Percentage of rainfall utilized	*68%*
Turbine efficiency	*82%*
Generator efficiency	*90%*
Percentage efficiency	*74%*

Calculate the suitable capacity of a turbo-generator.

Solution. Head available, $H = 45$ m

Catchment area, $A = 60$ sq. km $(= 60 \times 10^6 \text{ m}^2)$

Available rainfall, $h = (0.68 \times 1.4)$ m

Turbine efficiency, $\eta_t = 82\%$

Generator efficiency, $\eta_g = 90\%$

Penstock efficiency, $\eta_p = 74\%$

Quantity of water available per annum

$$= A \times h = 60 \times 10^6 \times (0.68 \times 1.4)$$

$$= 57.12 \times 10^6 \text{ m}^3\text{/annum}$$

Hence, quantity of water available per second,

$$Q = \frac{57.12 \times 10^6}{(365 \times 24) \times 3600} = 1.81 \text{ m}^3\text{/s}$$

Now overall efficiency, $\eta_0 = \eta_p \times \eta_t \times \eta_g$

$$= 0.74 \times 0.82 \times 0.9 = 0.546$$

∴ Power developed, $P = \eta_0 \times wQH$

$= 0.546 \times 9.81 \times 1.81 \times 45 = 436$ kW

If a load factor of 55 percent is assumed, then

Maximum kW $= \frac{436}{0.55} = 793$ kW

So a generator of 800 kW maximum rating can be selected. **(Ans.)**

∴ *Power of the turbine* $= \frac{793}{0.82} =$ **967 kW. (Ans.)**

For a head of 45 m, which is low, a *vertical shaft Francis* or *Kaplan turbine* may be employed.

Example 6.28. *A hydro-electric power plant produces 20 MW under a head of 15 metres. If the overall efficiency of the plant is 72%, determine :*

(i) Type of turbine *(ii) Synchronous speed of the generator.*

Solution. Power developed, $P = 20$ MW $(= 20 \times 10^3$ kW)

Head, $H = 15$ m

Overall efficiency, $\eta_0 = 72\%$

(*i*) **Type of turbine :**

$$P = \eta_0 \times wQH$$

$$20 \times 10^3 = 0.72 \times 9.81 \times Q \times 15$$

$$\therefore \quad Q = \frac{20 \times 10^3}{0.72 \times 9.81 \times 15} = 188.8 \text{ m}^3/\text{s}$$

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

(*ii*) **Synchronous speed of the generator, N_{syn} :**

Specific speed, $N_s = \frac{1150}{H^{1/4}}$ (approx.)

$$= \frac{1150}{(15)^{1/4}} = 584.3 \text{ r.p.m.}$$

Speed of rotation, $N = \frac{N_s \times H^{5/4}}{\sqrt{P}}$ $\left(\because N_s = \frac{N\sqrt{P}}{H^{5/4}}\right)$

$$= \frac{584.3 \times (15)^{5/4}}{\left(\frac{20 \times 10^3}{0.7355}\right)^{1/2}} = 104.6 \text{ r.p.m.}$$

For generator, $N = \frac{120f}{p}$

$$104.6 = \frac{120 \times 50}{p}$$

[where f = frequency (= 50 Hz)]

$$\therefore \quad p = \frac{120 \times 50}{104.6} = 57.36 = 60 \text{ (say)}$$

(as the number of poles is necessarily an even number)

Again, $N_{syn.} = \frac{120f}{p} = \frac{120 \times 50}{60} =$ **100 r.p.m. (Ans.)**

☞**Example 6.29.** *Calculate the power developed in MW from a hydro-electric power plant with the following data :*

Available head	*50 m*
Catchment area	*250 sq. km*
Average annual rainfall	*120 cm*
Rainfall lost due to evaporation	*20%*
Turbine efficiency	*82%*
Generator efficiency	*84%*
Head lost in penstock	*4%*

Solution. Head available, $H = 50$ m

Catchment area, $A = 250$ sq. km (= 250×10^6 m^2)

Average annual rainfall = 120 cm (= 1.2 m)

Evaporation loss = 20%

$\therefore$ Average annual rainfall available, $h = (1 - 0.2) \times 1.2 = 0.96$ m

Turbine efficiency, $\eta_t = 82\%$

Generator efficiency, $\eta_g = 84\%$

Penstock efficiency, $\eta_p = 100 - 4 = 96\%$

Quantity of water available *per annum*

$$= A \times h = 250 \times 10^6 \times 0.96 = 2.4 \times 10^8 \text{ m}^3$$

Hence, quantity of water available *per second,*

$$Q = \frac{2.4 \times 10^8}{(365 \times 24) \times 3600} = 7.61 \text{ m}^3/\text{s}$$

Overall efficiency, $\eta_0 = \eta_p \times \eta_t \times \eta_g$

$$= 0.96 \times 0.82 \times 0.84 = 0.66$$

Power developed, $P = \eta_0 \times wQH$

$$= 0.66 \times 9.81 \times 7.61 \times 50 \text{ kW}$$

$$= 2463.6 \text{ kW or } 2.463 \text{ MW}$$

Hence power developed = **2.463 MW. (Ans.)**

Example 6.30. *The following data is supplied for a hydro-electric power station :*

Catchment area	*100 sq. km*
Annual rainfall	*1200 mm*
Available head	*220 m*
Load factor	*45%*
Yield factor to allow for run-off and evaporation loss	*55%*
Power plant efficiency	*72%*

Calculate the following :

(i) Average power produced

(ii) Capacity of the power plant.

Solution. Volume of water available per annum

= Catchment area × annual rainfall × yield factor

$$= 100 \times 10^6 \times 1.2 \times 0.55 = 6.6 \times 10^7 \text{ m}^3$$

Hence, quantity of water available per second

$$= \frac{6.6 \times 10^7}{(365 \times 24) \times 60 \times 60} = 2.09 \text{ m}^3/\text{s}$$

(*i*) **Average power produced, P :**

$$P = \eta \times wQH \text{ kW}$$
$$= 0.72 \times 9.81 \times 2.09 \times 220 \text{ kW}$$
$$= \mathbf{3247.6 \text{ kW}}. \quad \textbf{(Ans.)}$$

(*ii*) **Capacity of the power plant :**

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

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

$$= \frac{3247.6}{0.45} = 7216.9 \text{ kW}$$

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

∴ *Capacity* = **7216.9 kW. (Ans.)**

☞**Example 6.31.** *In a hydro-electric power plant the reservoir is 225 m above the turbine house. The annual replenishment of reservoir is 3.5 × 10^{12} N. Calculate the energy available at the generating station bus bars if the loss of head in the hydraulic system is 25 m and the overall efficiency of the system is 85%.*

If maximum demand of 45 MW is to be supplied determine the diameter of two steel penstocks.

Solution. Actual head available, $H = 225 - 25 = 200$ m

Overall efficiency, $\eta_0 = 85\%$

Annual replenishment, $W = 3.5 \times 10^{12}$ N

(*i*) **Energy output :**

E = Energy available at the turbine house

$$= WH = 3.5 \times 10^{12} \times 200 = 7 \times 10^{14} \text{ Nm or J}$$

$$= \frac{7 \times 10^{14}}{36 \times 10^5} = 1.944 \times 10^8 \text{ kWh} \qquad [\because \ 1 \text{ kWh} = 36 \times 10^5 \text{ J}]$$

Energy output $= \eta_0 \times E$

$$= 0.85 \times 1.944 \times 10^8 = \mathbf{1.652 \times 10^8 \text{ kWh}}. \quad \textbf{(Ans.)}$$

(*ii*) **Diameter of steel penstock, D :**

Kinetic energy of water = Loss of potential energy

$$\therefore \quad \frac{1}{2} mC^2 = mgH$$

$$\therefore \quad C = \sqrt{2gH} = \sqrt{2 \times 9.81 \times 200} = 62.64 \text{ m/s}$$

(where C = Velocity water in each penstock, m = mass of water in kg)

Now $\frac{1}{2} mC^2$ = Energy to be supplied

$$\frac{1}{2} m \times (62.64)^2 = 45 \times 10^6 \text{ W}$$

$\therefore$ $$m = \frac{45 \times 10^6 \times 2}{(62.64)^2} = 22937 \text{ kg}$$

Let A = Area of two penstocks, m^2,

A_1 = Area of each penstock = $\frac{A}{2}$,

D = Diameter of each penstock,

Then, $m = A \times C \times \rho$

(where ρ = Mass density of water)

$$22973 = A \times 62.64 \times 1000 \qquad \left(\rho = \frac{w}{g} - \frac{9810}{9.81} = 1000 \text{ kg/m}^3\right)$$

$$A = \frac{22973}{62.64 \times 1000} = 0.366 \text{ m}^2$$

and $$A_1 = \frac{A}{2} = \frac{0.366}{2} = 0.183 \text{ m}^2$$

Now, $$0.183 = \frac{\pi}{4} D^2$$

$\therefore$ $$D = \left(\frac{0.183 \times 4}{\pi}\right)^{1/2} = \mathbf{0.483 \text{ m.}} \quad \textbf{(Ans.)}$$

Example 6.32. *It is observed that a run-of-river plant operates as peak load plant with a weekly load factor of 25% all this capacity being firm capacity. Determine the minimum flow in river so that power plant may act as a base load plant. The following data is supplied : Rated installed capacity of generating plant = 10 MW, operating head = 16 m. Plant efficiency = 86%.*

If the stream flow is 15 m^3/s, find the daily load factor of the plant.

Solution. Weekly load factor = 25%

Rated installed capacity of generating plant = 10 MW (= 10000 kW)

Operating head, $H = 16$ m

Plant efficiency, $\eta_0 = 86\%$

Minimum flow in river in m^3/sec, Q :

$\because$ Load factor $= \dfrac{\text{Average load}}{\text{Maximum demand}}$

$\therefore$ Average load = Load factor × Maximum demand

$= 0.25 \times 10000 = 2500$ kW

E = Total energy generated in one *week*

$= 2500 \times 24 \times 7 = 42 \times 10^4$ kWh

Now, Power developed, $P = \eta_0 \, wQH$ kW

$= 0.86 \times 9.81 \times Q \times 16 \text{ kW} = 134.98\, Q$ kW

$\therefore$ E_1 = Total energy generated in one *week*

$= 134.98\, Q \times 24 \times 7 = 22676.6\, Q$ kWh

Now $E = E_1$

$$42 \times 10^4 = 22676.6\, Q$$

$\therefore$ $$Q = \frac{42 \times 10^4}{22676.6} = 18.52 \text{ m}^3\text{/s}$$

Hence minimum flow rate = **18.52 m^3/s. (Ans.)**

Power developed when stream flow is 15 m³/s,

$$P_1 = 134.98 \times 15 = 2024.7 \text{ kW}$$

Energy generated per day,

$$E_2 = P_1 \times \text{time} = 2024.7 \times 24 = 48592.8 \text{ kWh}$$

$\therefore$ *Daily load factor* $= \dfrac{\text{Average load}}{\text{Maximum load}}$

$$= \frac{48592.8}{10000 \times 24} = \mathbf{0.2025 \text{ or } 20.25\%}. \quad \textbf{(Ans.)}$$

Example 6.33. *Calculate the firm capacity of a run-of-river hydro-power plant to be used as 8 hours peaking plant assuming daily flow in a river to be constant at 15 m³/s. Also calculate pondage factor and pondage if the head of the plant is 11 m and overall efficiency is 85%.*

Solution. Discharge, $Q = 15$ m³/s

Plant head, $H = 11$ m

Overall efficiency, $\eta_0 = 85\%$

Specific weight of water, $w = 9.81$ kN/m³

P = Firm capacity without pondage

$= \eta_0 \times wQH = 0.85 \times 9.81 \times 15 \times 11 = 1375.8$ kW

$$PF = \text{Pondage factor} = \frac{t_1}{t_2}$$

where, t_1 = Total hours in one day = 24, and

t_2 = Number of hours for which plant runs = 8

[***Pondage factor*** *is the ratio of total inflow hours in a given period to the total number of hours for which plant runs during the same period.*]

$$PF = \frac{24}{8} = \mathbf{3}. \quad \textbf{(Ans.)}$$

$Q_1 = 15 \times 3 = 45$ m³/s

P_1 = Firm power with pondage

$= 1375.8 \times 3 = 4127.4$ kW

Pondage (magnitude) $= (24 - 8) = 16$ hours flow

$= 16 \times 60 \times 60 \times 15 = \mathbf{8.64 \times 10^5 \text{ m}^3}$. **(Ans.)**

Example 6.34. *The following data relate to a pump storage power plant :*

Gross head	*280 m*
Dia. of headrace tunnel	*4.0 m*
Length of headrace tunnel	*620 m*
Flow velocity	*6.5 m/s*
Friction factor	*0.018*
Pumping efficiency	*85%*
Generation efficiency	*90%*

If the power plant discharges directly in the lower reservoir determine the plant efficiency.

Solution. Head, $H = 280$ m

Dia. of headrace tunnel, $D = 4.0$ m

Length of headrace tunnel, $L = 620$ m

Flow velocity, $C = 6.5$ m/s

Friction factor, $f = 0.018$

Pumping efficiency, $\eta_p = 85\%$

Generation efficiency, $\eta_g = 90\%$

Plant efficiency, η_{plant} :

Loss of head due to friction (h_f) is given by the equation :

$$h_f = \frac{fLC^2}{2gD} = \frac{0.018 \times 620 \times 6.5^2}{2 \times 9.81 \times 4.0} = 6.0 \text{ m}$$

Now $h_f = xH$

$$6 = x \times 280 \quad \therefore \quad x = \frac{6}{280} = 0.0214$$

$$\therefore \quad \eta_{plant} = \frac{1-x}{1+x} \times \eta_p \times \eta_g = \frac{(1-0.0214)}{(1+0.0214)} \times 0.85 \times 0.9$$

$= \mathbf{0.7329}$ **or 73.29%. (Ans.)**

Hydrology

Example 6.35. *At a particular site the mean monthly discharge is as follows :*

Month	*Discharge, m³/s*	*Month*	*Discharge, m³/s*
January	*100*	*July*	*1000*
February	*225*	*August*	*1200*
March	*300*	*September*	*900*
April	*600*	*October*	*600*
May	*750*	*November*	*400*
June	*800*	*December*	*200*

Draw the following :

(i) Hydrograph *(ii) Flow duration curve.*

Solution. (*i*) The **hydrograph** is plotted between discharge (m³/sec) and time (months) as shown in Fig. 6.57.

(*ii*) **Flow duration curve :**

In order to draw *flow duration curve* it is essential to find the *length* of *time* during which certain flows are available, *e.g.* 100 m³/s is available for all 12 months, flow of 200 m³/s for 11 months, 225 m³/s for 10 months and so on. This information is indicated in the table.

Discharge, m³/s	Length of time, months	%age time
100 (and more)	12	100
200 (and more)	11	91.7
225 (and more)	10	83.3
300 (and more)	9	75.0
400 (and more)	8	66.7
600 (and more)	7	58.3
750 (and more)	5	41.7
800 (and more)	4	33.3
900 (and more)	3	25.0
1000 (and more)	2	16.7
1200 (and more)	1	8.3

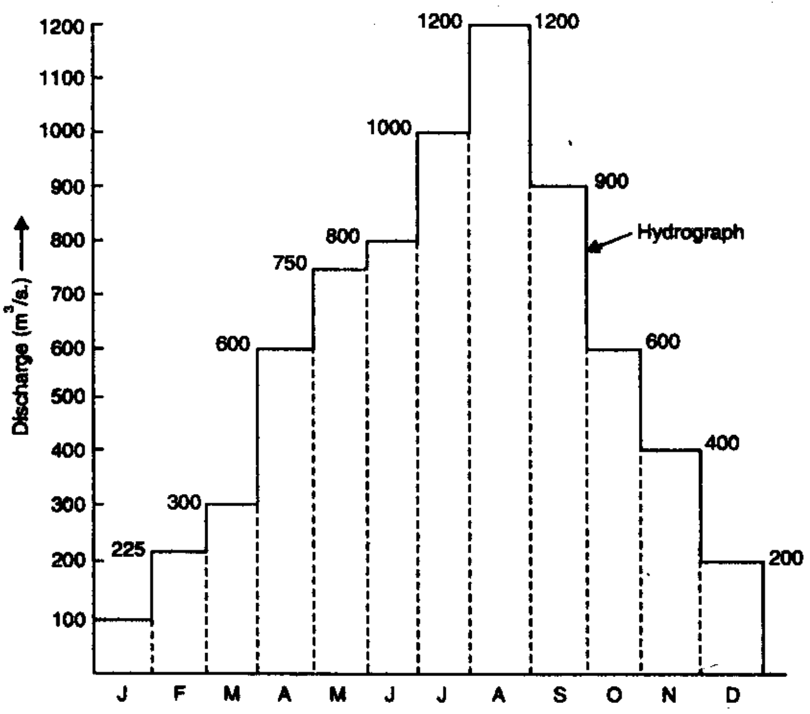


Fig. 6.57. Hydrograph.

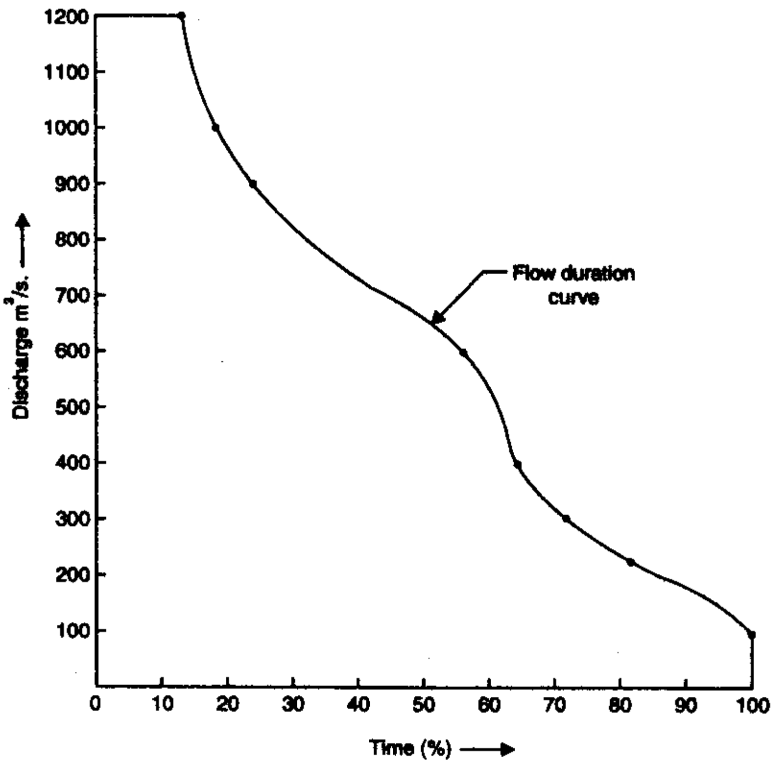


Fig. 6.58. Flow duration curve.