4
Design, Construction and Operation of Different Components of Hydro-electric Power-stations

4.1. RESERVOIRS

The natural stream of water if used for hydro-electric project, may be unable to satisfy the demands of its consumers during extremely low flows. The quantity of water flow is extremely large during flood period whereas the quantity of water flow is very little during dry period of the year as mentioned earlier. Therefore, there is necessity to store the water during high flow of the river and supply the same to the power plant during low flow period. A storage used to retain such excess water from periods of high flow and supplies the retained water during low flow is commonly known as reservoir. The storage of water during high flow period (flood) may also reduce flood damage to the area below the reservoir in addition to conserving water for later use. The main function of the reservoir is to store and supply the water according to demand by regulating the quantity of water supplied.

Once the dam site is selected, the other important problem is to find out the most economical cost to provide the necessary storage volume. .

The increase in dam height produces increase in head and mean output. This gain in mean output requires an economic analysis because gain in output must counterbalance the increase in cost due to increased height. If the head of the power-plant is solely created by the dam then it may permit the increase in height to increase the installed capacity. However, when fairly high natural head is available, it does not usually pay to increase it beyond the point necessary to provide adequate storage.

The economic analysis of storage possibilities is not rigid and, therefore, the designer must take his own analysis of storage, cost balancing, the cost of increase in dam height against the advantage gained from extra firm output.

The cost of dam (cost of storage) roughly varies H^x where H is the height of dam and x lies between 2 and 3 depending upon the shape of the valley and type of construction. The high value of x is expected with an increase in height compared with increase in length of the dam.

Reservoir capacity. The capacity of the reservoir on natural sites is determined with the help of topographic surveys as its shape is always irregular.

The available storage capacity of the site is generally measured by surveying a series of water level counters. The desirable interval between the two counters may range from 3 m to 15 m depending upon the shape of the valley and the uniformity of its side slopes. The procedure of finding the storage capacity between two counters is illustrated in Fig. 4.1. In practice, to find out the reservoir capacity, an area

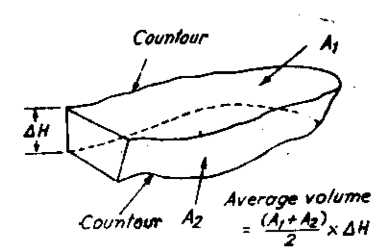


Fig. 4.1.

elevation curve is constructed. The integral of the area-elevation curve in the given range of heights gives the storage capacity of the reservoir. The increase of storage capacity between two elevations is calculated by multiplying the average of the areas at the two elevations and the height between two areas. The summation of these increments below any elevation is the storage volume below that level.

4.2. DAMS

The Dam is the most important and expensive structure in hydro-electric power plant. The dam can be constructed in several different forms and with different materials. The most suitable type for a particular site will depend on a large number of factors as topographical, geological, availability of materials, labour cost and many others. Whatever the type adopted, it must be permanently stable, watertight, low in maintenance costs, simple in construction and economic for its purpose.

Pioneering efforts of several engineers in many countries mostly in U.S.A., Italy, France, Portugal, Japan, Sweden and Switzerland are responsible for the recent advancements in the design of dams during the last few decades. Modern dams like arch, dome and hollow dams are more safe, aesthetic in design and also economical. Larger numbers of dams for higher capacity and for greater heights are being built for optimum utilization of water resources in several countries.

The dams which are commonly used in practice are classified as

(*a*) Masonry dams (*b*) Earth-fill dams.

The masonry dams are further sub-divided as per the shape and size of the dams as

(1) Gravity dams (2) Buttress dams (3) Arch dams.

The earth-fill dams are further sub-divided as

(1) Earth-fill dams and (2) Rockfill dams.

1. Solid Gravity Dams of Concrete and Masonry. This type of dam is built of masonry, mortar or concrete. This dam is solid through its length except for joints in the structure to allow for expansion due to temperature changes. The height of the dam is limited by the strength of the available foundation. The high dams can be built on rock foundations than the earth foundations. Gravity dams are the simplest in design but they carry massive volumes of materials. The solid gravity dams rely on weight for the stability of the dam. This weight is provided entirely by the concrete in the dam. The general structure is shown in Fig. 4.2.

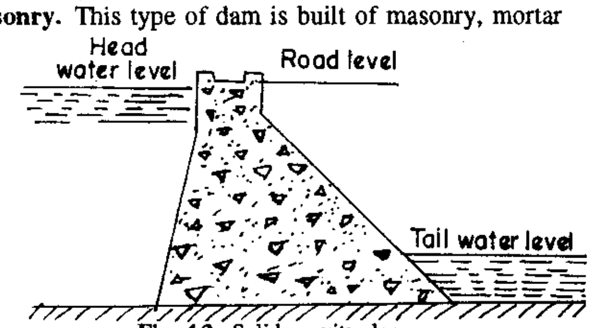


Fig. 4.2. Solid gravity dams.

Where dams have to be constructed across relatively narrow river valleys, the concrete dam is invariably more economical as the concrete dam requires much simpler arrangements for passing the flow of the river during construction. The solid gravity dam provides safe and economical spillway facilities whereas safe spillway provisions in an earth dam is often expensive.

2. Arch dams. An arch dam is a solid concrete structure, curved upstream in plan, which in addition to resisting part of pressure of the reservoir by its own weight obtains a large measure of stability by transmitting the remainder of water pressure load by arch action to the abutments. The most important developments in the design of dams have taken place in the case of arch and dome dams, affecting considerable economy in the construction costs. Arch dams are not only cheaper but also stronger than the massive gravity dams. Model tests have proved that the safety factor of arch dam is far greater than other types of dams. The general structure is shown in Fig. 4.3.

The arch dam is safe against earthquake when the reservoir is full but is not considered safe when the reservoir is empty. This can be rectified to some extent by providing an overhung on the downstream side of the arch dam.

The Vajont Reservoir disaster in Italy was caused by a major landslide near the Vajont arch dam. A mass of material of 230 million cubic metres suddenly plunged into reservoir causing a violent surge of water 100 metres high overtopping the dam. Despite the sudden impact and enormous amount of excess pressure, no damage was caused to the main dam. This showed the soundness of the design of arch dams.

Auburan dam at California 209 m in height and 1266 m in crest length is the world's longest arch dam ever built.

Idikki hydel power project fully instrumented, 555 feet high and 65 feet wide on a base is the highest arch dam on the continent and India's first arch dam. It has doubled the available electric power resources of the Kerala State. The cost of Idikki originally estimated at Rs. 68 crores has attained to Rs. 110 crores. This dam is almost five times stronger than it needs to be and it is one of the most beautifully made things.

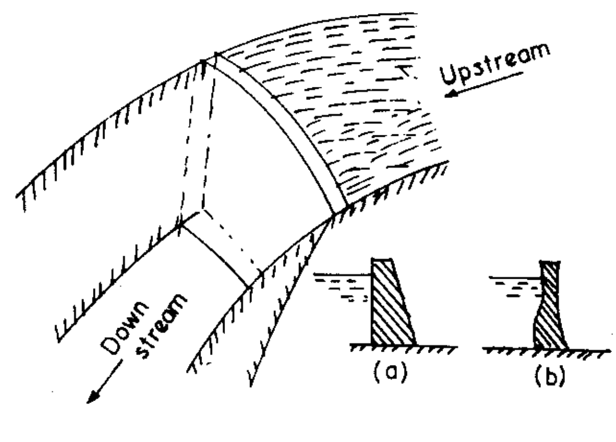


Fig. 4.3. Single arch dam.

3. **Buttress Dams.** The dams of buttress type have become more and more popular because of overall economy in their construction. They are suitable for weaker foundations where differential settlements are likely to occur. They are also more safe against earthquake effects, they have been built in very large number in Italy and Japan. In Japan, in spite of high seismic activity and limited river potential, hundreds of dams of various designs are being built. The arrangement is shown in Fig. 4.4.

(*B*) 1. **Earthfill dams.** The earth dams have become more popular in recent years owing to the development in soil mechanics and heavy earth moving machinery. The earth dams are more economical for sites where excavation of the foundation soil is considerable.

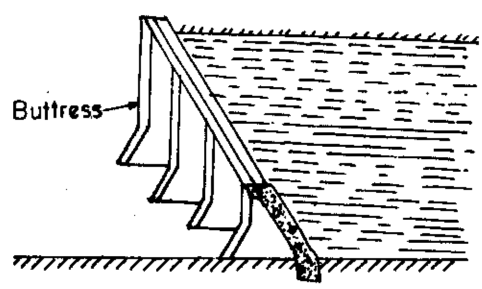


Fig. 4.4. (*a*) Buttress dam.

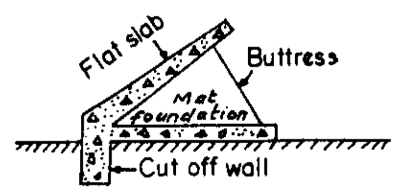
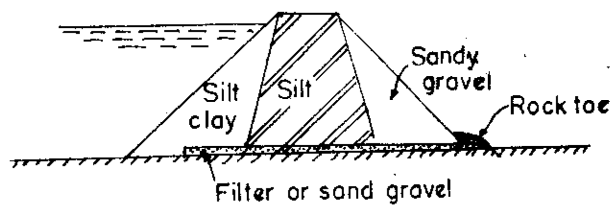
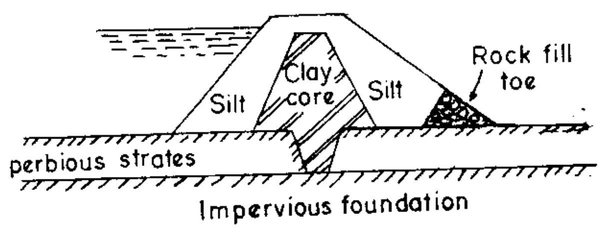


Fig. 4.4. (*b*) Section of buttress dam.

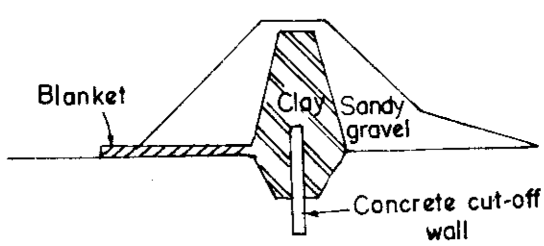
A safe earth dam can be built for almost any given site and foundation condition by utilizing a wide range of earth materials like loose rock, gravel, sands, silt, rock, flour and clay. Actually, in the interest of economy, the design of an earthen dam should be adopted for the utilization of materials available at or near the site. It can be built on weak or pervious foundation where the use of other type of dam would be impracticable. The special features of earth dam which permit its adoption are the ability of plastic earth fill to deform without rupture and secondly large base width which reduces the shear stresses in the foundation. Different arrangements of earthfill dams are shown in Fig. 4.5.



(*a*) Earth dam with simple zoned embankment on impervious foundation.



(*b*) Earth dam with core extending to impervious foundation.



(*c*) Earth dam on pervious material.

Fig. 4.5. Cross-sections of some typical earth dams.

2. Rockfill Dams. The rockfill dams have characteristics midway between gravity dams and earth fill dams. Rockfill dams are considered economical when adequate quantity of good rock is easily available near the dam site and when the transportation cost of foreign materials like cement, iron, machinery is costly or there is dearth of suitable earth material nearby. A rockfill dam is also most economical at the site where major fault lies in the foundation and its treatment is expensive. Two sections of this type of the dam are shown in Fig. 4.6.

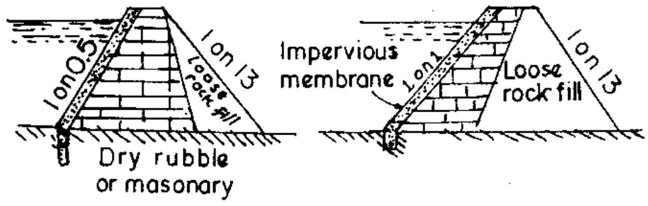


Fig. 4.6. Cross-section of some rockfill dams.

A rockfill dam has high resistance to earthquake because of its flexible character which permits considerable movement. Therefore, Japanese Engineers are building more of large size rockfill dams. The highest rockfill dam so far built is 300 m high and 1000 m long Nasekskaya dam in Russia.

Rockfill dams are subjected to considerable settlement, which may result in cracking the membrane. This is the greatest weakness of rockfill dams, although in many instances leakage is controlled by periodic repair of the membrane.

4.3. SPILLWAYS AND CONTROL GATES

The spillway is used to discharge the water during flood period without passing through the power house. It acts as a safety valve for the dam. They maintain the water level in the reservoir below a predetermined maximum level and safeguard the life of dam. The different types of spillways used are discussed below :

1. Overflow Spillway. The ideal overflow known as Ogee spillway is shown in Fig. 4.7. This is simple in design, low in cost and suitable for concrete dams.

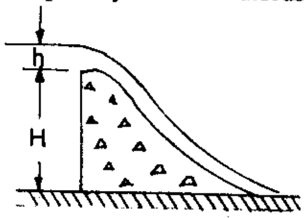


Fig. 4.7. Overflow spillway.

2. Chute Spillway. The chute spillway refers to an overflow spillway isolated from the dam. Its crest is normal to its centre line and it has a discharge channel to the river downstream in an excavated trench. The excavated trench is paved with concrete of 20 to 30 cm thickness. This is well adopted to earth or rockfill dams. The spillway is shown in Fig. 4.8.

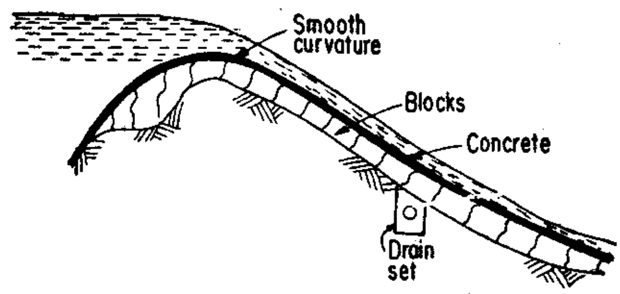


Fig. 4.8. Chute set spillway.

3. Shaft Spillway. The shaft spillway is shown in Fig. 4.9. In this type of spillway, the water drops through the vertical shaft and passes through a horizontal conduit which conveys the water to the downward side of the dam. It is preferred where there is inadequate space for other types of spillways. This is the preferred type for earthfill or rockfill dams as it is undesirable to carry a spillway over or through earth or rockfill dams.

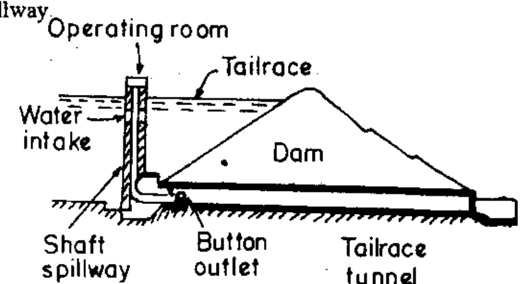


Fig. 4.9. Shaft Spillway.

4. Siphon Spillway. The water during the flood period is discharged by siphon action. Siphon spillway is a better selection when the space is limited and discharge capacity is less. Fig. 4.10 shows the cross-section of the siphon spillway. It has the advantage of automatically maintaining the water-level in the reservoir. If it is properly designed for flow, the dam is safer with siphon spillway than any other type.

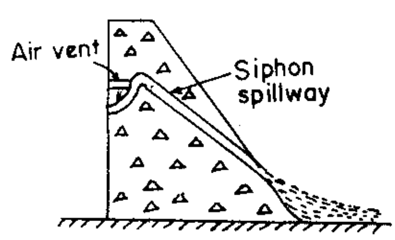


Fig. 4.10. Siphon spillway.

The storage capacity above the spillway crest can be increased by the installation of movable gates. Such increase in reservoir level is permissible during low run-off period. Full spillway capacity can be made available by removing the gates during floods. The different types of gates which are commonly used are discussed below.

1. Vertical Lift Gate. The cross-section of the vertical lift gate is shown in Fig. 4.10 (*a*). Steel gates which slide in vertical guides on piers on the crest of the dam are generally used for small power plants.

Because of high hydrostatic force on the gate ; the gate lifting mechanism must be able to overcome high frictional forces developed in the guides. A gate of 5 m^2 area weighs 150 tonnes and has to support 2000 tonnes of water load. The design of gate and its operating mechanism is a complicated structure and creates a mechanical problem of considerable magnitude.

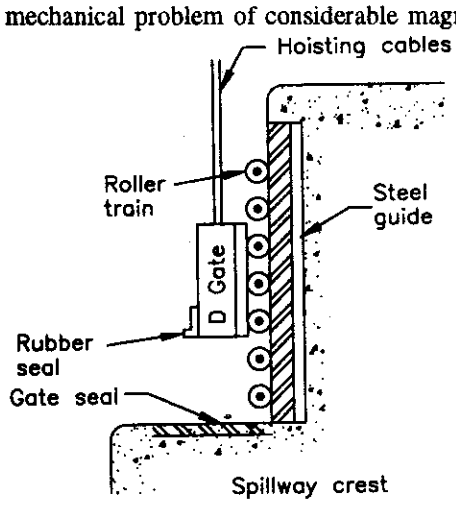


Fig. 4.10 (*a*). Vertical lift gate.

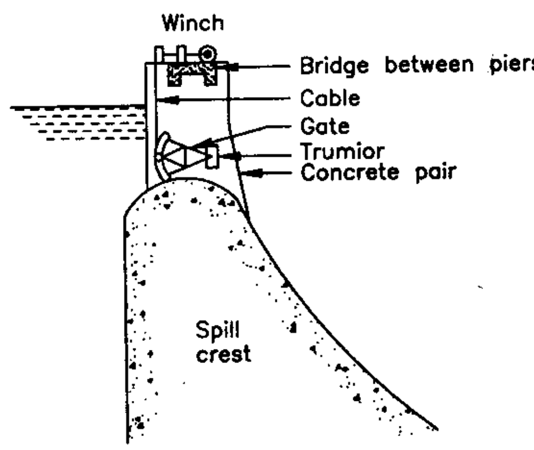


Fig. 4.11. Radial gate.

2. Radial Gate. The cross-section of radial gate is shown in Fig. 4.12. The gate is a segment of cylinder supported on a steel framework which is pivoted on trunnions as shown in Fig. 4.12. Hoisting cables are attached to the gate and other ends to the winches on the platform above the gate. The winches are motor driven. Each gate may have its own hoisting mechanism or a common unit may be moved from gate to gate.

Radial gates have several advantages over vertical lift gates. The friction is much less than for sliding gates and the hoist load is also much less than for vertical lift gates of the same size.

One of the largest gates of this type is at Clark Hill dam in Georgia.

3. Rolling Gate. The cross-section of the rolling gate is shown in Fig. 4.12. A rolling gate is moving cylinder mounted between two piers. A moving cylinder has teeth on its surface and works as a pinion. An inclined rack is provided on the pier. The rolling cylinder rolls on the rack provided with the help of hoist cable as shown in Fig. 4.12. The rolling gates are preferred for long spans and moderate height. One of the largest rolling gates (44.5 metre in length and 6.35 metre high) is installed on the Glommen River in Norway.

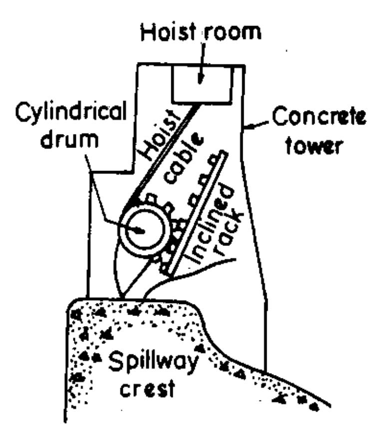


Fig. 4.12. Rolling gate.

4. Drum Gate. The cross-section of drum gate is shown in Fig. 4.13. This type of gate is also preferably adopted for long spans. This gate also consists of a segment of a hollow cylinder. This gate fits in a recess in the top of the spillway in open position. When the water is admitted under force to the recess, the hollow drum gate is forced upward to the closed position. The gate is generally hinged at the upstream edge so that the buoyant force aids in its lifting. When the gate is lowered, it conforms closely to the shape of Ogee crest. They are not adopted to small dams because of large recess required by the drum gates in the lowered position.

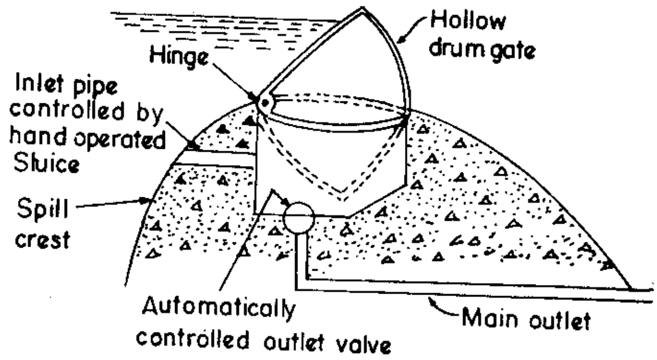


Fig. 4.13. Hollow drum gate.

5. **Tilting Flap Gate.** Fig. 4.14 shows a section of a tilting flap gate. The lower edge of the flap is hinged to the upstream part of the dam and the upper edge is held in position by chains or screwed rods supported by an overhead bridge.

The gate is lowered about the hinge and the water is allowed to flow over the crest of the gate to pass the flood water.

This gate is more suitable for small size openings. The tilting gate is not suitable for larger openings compared with other types of gates as the water load on the gate is appreciable.

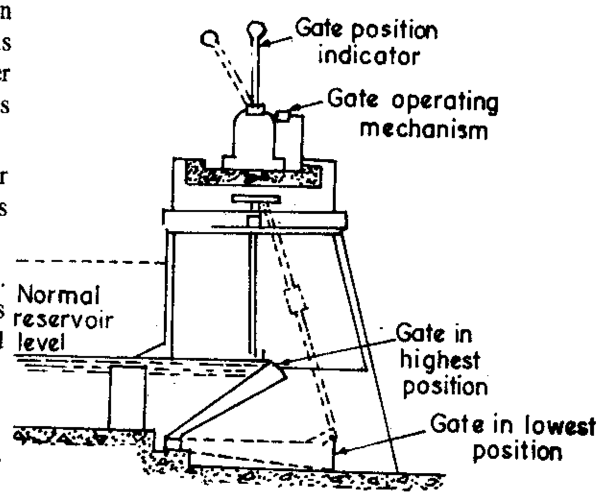


Fig. 4.14. Tilting flap gate.

4.4. INLET AND OUTLET WORKS

The intake arrangement as shown in Fig. 4.15 is provided in most of the power plants. The intake is taken sufficiently below the minimum reservoir level to prevent air being drawn into the inlet tunnel by vortex formation. There is a special advantage of locating the inlet sufficiently below the water level in countries where winter is severe as it will not be obstructed by the surface ice formation. Intake towers are often used when there are wide fluctuations of water level. The towers are generally provided with ports at various levels to regulate the flow. A typical intake tower is shown in Fig. 4.16.

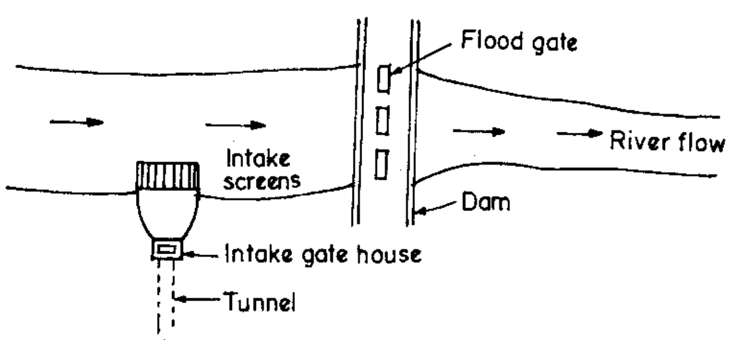


Fig. 4.15. Intake location so that river flow prevents the flow of ice and floating material through screen.

Interior Gate Valves. Gate valves are used to regulate the flow. Butterfly valves are preferred for moderate heads whereas needle valves and tube valves are used for high head plants.

Figure 4.17 shows the arrangement of needle valve. It consists of three chambers A, B and C as shown in the figure. Its opening and closing are controlled by varying the pressures in the chambers A, B and C. The valve is opened by increasing the pressure in chamber C and releasing the pressure in chambers A and B which are interconnected by forcing the needle to the left. For closing the valve, the pressure in the chamber C is released whereas the pressures in chamber A and B are increased which forces the needle valve towards the right.

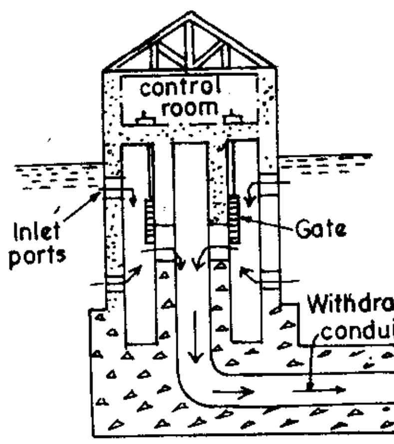


Fig. 4.16. Intake tower.

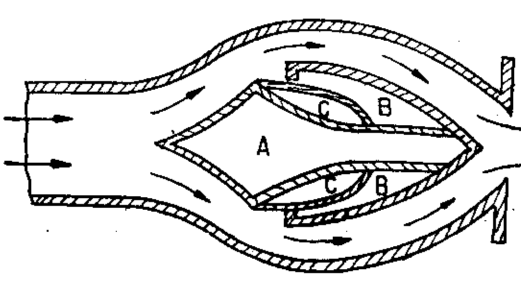


Fig. 4.17. Needle valve.

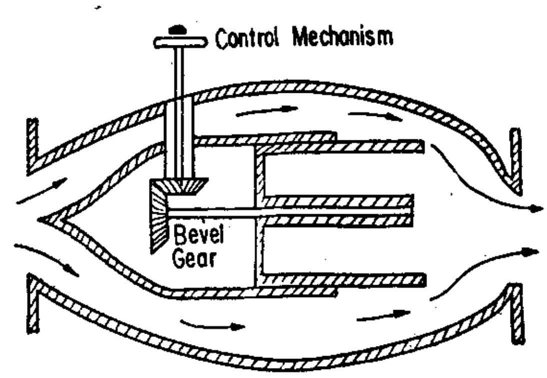
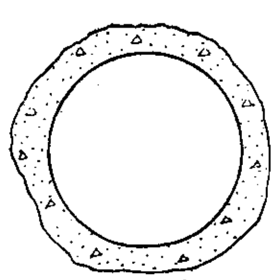


Fig. 4.18. Tube valve.

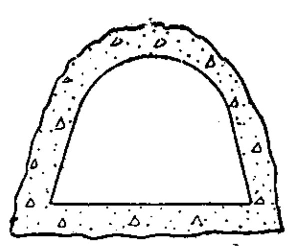
Figure 4.18 shows the arrangement of the tube valve. This valve is opened or closed by mechanical operation. The cylinder (tube) is moved towards or away from the valve seat with the help of screw stem operated by bevel gear to open or close the valve as required. This valve is lighter in weight and shorter in length and occupies less space compared with needle valve.

4.5. WATER TUNNELS

The tunnels which are used to carry water are either of circular sections as shown in Fig. 4.19 (*a*) or horse-shoe section as shown in Fig. 4.19 (*b*). The tunnels act as open channels when flowing partially full and act as pressure conduits when flowing full.



(*a*) Reinforced concrete tunnel.



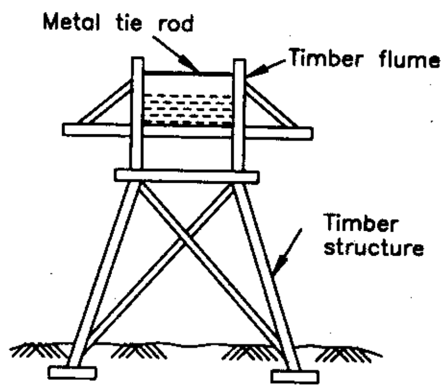
(*b*) Horse-shoe tunnel.

Fig. 4.19. Forms of tunnels.

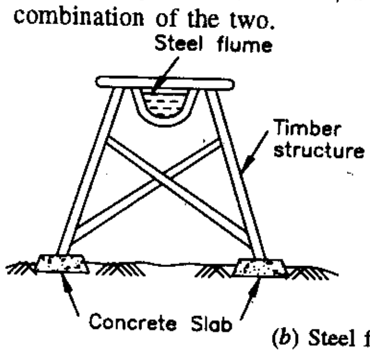
When it becomes difficult or expensive to construct canals to carry water, the water is generally conveyed using flumes. The flume is so designed that it is able to carry the weight of water and its own weight. The flumes may be made of wood, steel or concrete. The flumes made of wood, steel and concrete are shown in Fig. 4.20. The life of concrete flume is longer than that of the wooden flume as it deteriorates more rapidly when it is wet.

4.6. CANALS AND PENSTOCKS

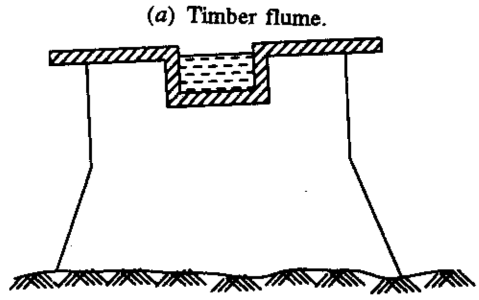
A water-channel is required to carry the water to the power house where additional head is developed over and above that created by the dam. The water-channel may consist of canal, a closed conduit or a combination of the two.



(*a*) Timber flume.



(*b*) Steel flume.



(*c*) Concrete flume.

Fig. 4.20. Different types of flumes.

The conduit system carrying the water from the reservoir to the power house is generally divided into two parts, namely "high-line" or non-pressure conduit (open channel, closed pipe or tunnel) and the "penstock". The high line and penstock are shown in Fig. 4.21.

Canal and closed conduits are used as non-pressure tunnels and made of concrete. Canals are generally used where the quantity of water carried is large because pipe would be too large and too costly. Sometimes, the topography of the river banks compels to use the closed conduit instead of open channels.

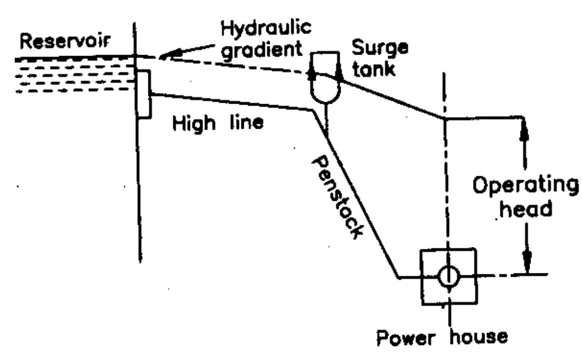


Fig. 4.21. Position of Penstock.

Tunnels. Many times it is cheaper to convey water by tunnel through a hill to the powerhouse than by canal or flume around the hill.

Tunnels are generally of horse-shoe section to take the advantage of arch action. A concrete or steel linear is necessary to prevent the collapse if the tunnel material is weak. The tunnels carried through the rock are not lined but smoothed to improve the hydraulic characteristics. The tunnels may flow full or partly. The steel lining is always necessary for the full running tunnels as they act as pressure conduit. The tunnels running partly full need not be lined as they act as open channel.

2. Penstocks. The term penstock is generally used to a relatively short length of pipe connecting the prime mover with the main water-way.

The design of penstock requires special consideration as it has to work under high pressures developed under part load conditions.

The economical shortest route is always desired in the location of a penstock as in the case of canal. It is further desirable to have the penstock always sloping towards the powerhouse but its grade may be varied as desired to fit the topography. On the other hand, the most economical location for the penstock is the flat grade for the greatest part of its length provided its position is below the hydraulic gradient.

The intake of the penstock at the dam or forebay must be at level low enough to provide an adequate water seal under all conditions. Low water seal will form whirlpools and carry air into the penstock, and to the prime movers, tending to reduce the power output.

Arrangements are made to cut off the supply of water at the inlet of the penstock under emergency conditions. Under the emergency conditions, when the inlet gates are closed and the water in the penstock is drawn through the wheels and the penstocks are subjected to sub-atmospheric pressures, some serious failures of penstock have been reported due to this reason alone. Therefore, it is desirable that close conduit system without surge tank be provided with a passage which admits air into the penstock and relieves it from the sub-atmospheric pressure. Care should be taken to see that the water in the air-vent pipe does not become frozen during operation, thus preventing the air entry.

The failure of penstock of Oigawa power station in Japan in 1950 is an example for the cause mentioned above.

Materials for Penstock. Steel pipes even upto 7 metres in diameter are commonly used as penstocks. Larger size penstocks are usually built by welding or riveting the steel plate. Welded pipes are much smoother than riveted pipes and are superior in strength also.

The open metal pipes are subjected to chemical corrosion when exposed to atmosphere. Therefore, it is always necessary to protect the outer surface of the pipe from corrosion by some form of painting. Corrosion of metal pipes may be reduced by protective coating of paint, galvanizing or bituminous compound linings. The life of steel pipe above ground can be prolonged indefinitely by frequent painting as no paint gives permanent protection to the steel.

The use of reinforced concrete pipe in hydro-electric work is limited for the power plant upto 30 metre head as its strength is limited. The advantages of reinforced concrete pipe are long life and freedom from maintenance. The average life of concrete pipe is nearly 30 to 50 years. The concrete pipes are undesirable in cold countries as alternate freezing and melting deteriorate the pipes earlier.

In cold climates, an ice sheet generally forms on the inside surface of the penstock. The formed ice-sheet affects the hydraulic properties of the pipe and during a thaw, enough ice may break and enter the turbine to plug the gates. The water hammer intensity may be considerably greater than that computed for normal operation in such cases. Therefore, it is always necessary to protect the pipes from freezing in cold climate countries.

The freezing troubles can be eliminated by burying the pipes or covering them with insulation. There is no freezing danger if the pipes are buried one metre below the earth surface.

Buried *Versus* Exposed Penstocks. The advantages of exposed penstocks are listed below :

(1) It provides more space for construction.

(2) It is less expensive to install.

(3) Exposed penstocks are more accessible for inspection, maintenance and repairs. This is the favourable feature of exposed penstock.

(4) The corrosion of buried penstocks is more rapid, therefore, the life of buried pipe is less than exposed one. The frequent inspection and painting are not possible in case of buried pipe.

The following conditions favour the underground penstocks.

(1) Penstock running on steep hillside on earth foundation, make supporting and anchoring very difficult and expensive. Such anchoring and supporting are not necessary if the pipe is buried.

(2) On steep hillside, there is frequent danger of landslide, snow slide and falling rock which may injure the exposed pipe. This can be completely eliminated if the pipe is buried.

(3) There is every danger of freezing the exposed pipe in cold climates particularly when the pipe is long and velocity is low. In such cases to bury the pipe is economical than to provide the protection against freezing.

(4) When the pipe passes through earth cut, it is often less expensive to bury it with excavated earth than to provide cradles and sills.

4.7. WATER HAMMER AND SURGE TANKS

Water-Hammer. When the gates supplying the water to the turbines are suddenly closed owing to the action of governor, when the load on the generator is suddenly reduced, there is sudden rise in pressure in the upstream of the pipe supplying the water to the turbine. This sudden change of pressure and its fluctuations in the pipeline during reduction of load on turbine is known as "Water Hammer". The turbine gate suddenly opens because turbine needs more water due to increased demand on generator and, therefore, during increased load conditions, water has to rush through the pipe (known as penstock) and there is tendency to cause a vacuum in the pipe supplying the water.

The pipe supplying the water must withstand the high pressures caused by sudden closing of turbine gate (known as positive water hammer) and there should not be any vacuum in the pipe line when the gate opens suddenly.

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 the prime mover. The water hammer occurs at all points in the penstock between the forebay or surge tank and the turbines because of sudden changes in the demand for water during load fluctuations.

Surge Tank. Surge tank is an open tank which is often used with the pressure conduit of considerable length. The main purpose of providing surge tank is to reduce the distance between the free water surface and turbine thereby reducing the water-hammer effect on penstock and also turbine thereby reducing the water-hammer effect on penstock and also protect upstream tunnel from high pressure rises. It also serves 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.

A simple surge tank is a vertical standpipe connected to the penstock as shown in Fig. 4.22.

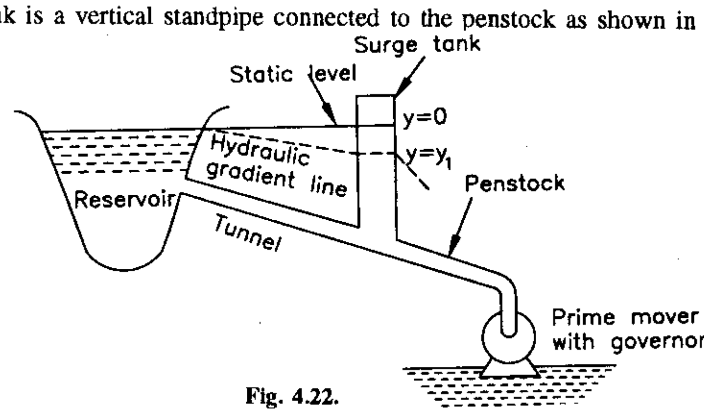


Fig. 4.22.

If the overflow in the surge tank is allowed, the pressure rise can be practically eliminated but overflow surge tank is seldom satisfactory and usually not economical. Surge tanks are built high enough so that the water cannot overflow even with a full load change on the turbine.

Location of the surge tank. A surge tank should be located as near to the power house as is feasible to reduce the length of the penstock thereby reducing water hammer effect. The ideal place for the surge tank is at the turbine inlet, but it is seldom possible in case of medium or high head plants because it will have to be made very high. It is generally located at the junction of tunnel and penstock in order to reduce its height.

Increase in the length of penstock will increase the intensity of water hammer while shortening will reduce its intensity. The location of the surge tank away from the powerhouse should be fixed on the basis of analysis done for the cost of tank against the cost of strengthening the pressure pipeline for the water hammer and requirements of speed regulation.

It is always desirable to place the surge tank on ground surface, above the penstock line ; at the point where the latter drops rapidly to the power-house as shown in Fig. 4.23 (*a*).

The height of the tank should be increased with the help of the support when the suitable sight for its location is not available as shown in Fig. 4.23 (*b*).

It is also more economical to provide underground surge tank in topographically suitable area as shown in Fig. 4.23 (*c*). The underground surge tank is often preferred for reasons of economy and appearance and because it is less subject to freezing in cold locations. Surge tank may be excavated in the rock above the tunnel if the geological conditions are favourable. The surge tank on Appalacchia project of the Tennessee valley authority is an example of underground surge tank.

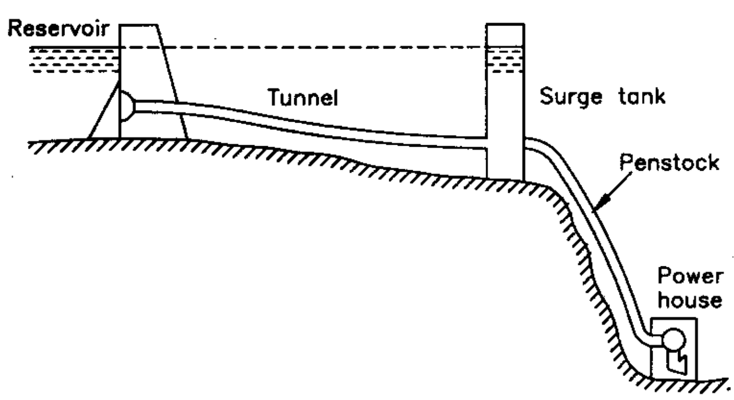
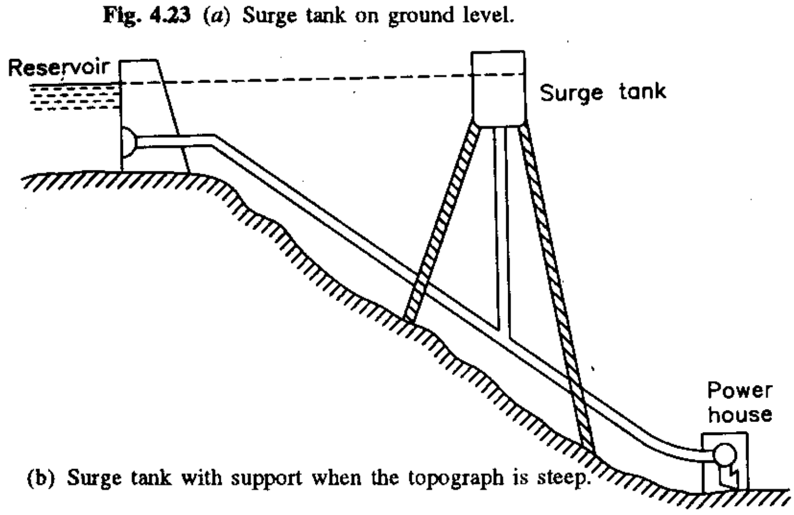


Fig. 4.23 (*a*) Surge tank on ground level.



(b) Surge tank with support when the topograph is steep.

Functions of Surge tank. The functions of surge tank are listed below :

1. It reduces the distance between the free water level of the reservoir and turbine and also reduces the intensity of water hammer that the surge chamber (towards the reservoir) to such an extent above the water hammer effect can be neglected in the design of tunnel. Only relatively short length of conduit (known as penstock) below the surge tank must be designed to withstand the water hammer effects.

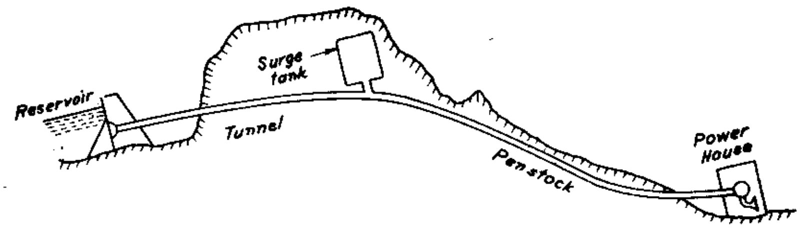


Fig. 4.23 (*c*) Underground surge tank with penstock partly underground.

2. The surge tank acts as a relief valve when the load on the turbine is reduced and pressure in the pipe suddenly increases by diverting the main conduit flow partly or wholly into this tank. The water level in the tank rises until it exceeds the level in the main reservoir thus retarding the main conduit flow and absorbing the surplus kinetic energy.

3. The tank acts as a temporary reservoir during increased load on turbine. It provides sufficient water to enable the turbine to pick up the new load quickly and safely and to keep it running at the increased load until the water level in the surge tank falls below its original level. Sufficient head is thereby created to accelerate the flow in the conduit until it is sufficient to meet the new demand.

Different Types of Surge Tanks

1. Simple surge tank. The most simple type of surge tank is a plain cylindrical tank. It is connected to the conduit by a short connecting shaft as shown in Fig. 4.24 (*a*). The diameter of the tank is governed by making the area sufficient to ensure stability and secondly by the necessity of keeping the surges within reasonable limit of amplitude as mentioned earlier.

This type of surge tank is uneconomical due to its large size and its action is also sluggish as compared with other types of tanks. It is most expensive and seldom used in preference to other types.

2. Inclined surge tank. If the surge tank of diameter 'd' is inclined at an angle θ to the horizontal as shown in Fig. 4.24 (*b*), its effective water surface area increases from $\pi/4\ d^2$ to $\pi/4\ d^2$ cosec θ. 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. No doubt, it is more costlier than ordinary type as construction is difficult and it is seldom used unless the topographical conditions are in favour. This type of surge tank is used at Caldas installation

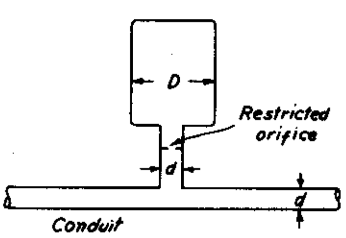
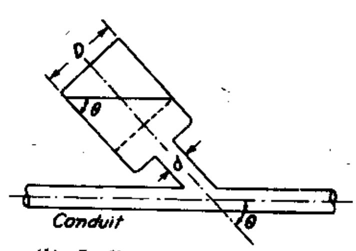


Fig. 4.24 (*a*). Simple surge tank.



(*b*). Inclined simple surge tank.

in Colombia. The surge tank was formed as sloping pipe laid on the surface of hillside following its natural slope as surge chamber above ground was impracticable due to the possibility of earthquake in that area.

3. The expansion chamber and gallery type surge tank. It is sometimes economical to have a surge tank of variable section. As shown in Fig. 4.24. (*c*), a surge tank with expansion tank at top and expansion gallery at the bottom are provided. These provided expansions limit the extreme surges.

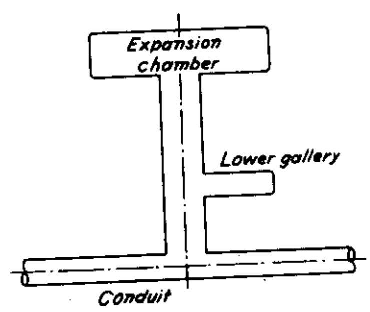


Fig. 4.24 (*c*). Expansion chambers tank.

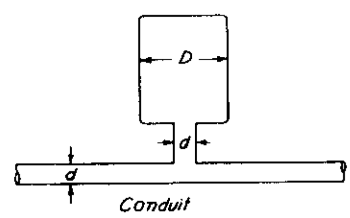


Fig. 4.24 (*d*). Restricted orifice surge tank.

The upper reservoir absorbs the rising surges, while the lower one provides reserve storage of water on starting the turbine or increasing the load on the turbine. 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. In addition, the intermediate shaft should have a stable minimum diameter. The Glenlee surge tank in Scotland is of this type.

4. The restricted orifice or throttled surge tank. The simple surge tanks are inadequate for medium and large head plants and, therefore, some modifications to improve the damping action and minimising the cost are essential.

In a simple surge tank, the cross-sectional area of the pipe connecting the tank and conduit is equal to or greater than the cross-sectional area of the conduit itself. Under these conditions, the losses in the connecting pipe can be neglected. The amplitude of the surge and tank height can be greatly reduced by introducing a throttle at the base of the tank as shown in Fig. 4.24 (*d*). The purpose of the 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 desired retarding head. If it is large enough (area equal to or greater than conduit area) then the tank becomes a simple tank and retarding head is negligible. If the throttle is infinitely small, the retarding head is equal to the water hammer in the conduit without surge tank. 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 (case of complete closure of gate valve). The effect of throttle is very limited except at large change of load because the additional frictional loss is proportional to the square of the velocity in the port. The change in velocity will not be considerable unless the change of load is not large. It is very rapid in its action, but the pressure rises are also equally rapid, therefore, it is less effective than simple surge tank in relieving water hammer.

The disadvantage of this surge tank is that, considerable portion of water hammer pressure is transmitted directly into the low pressure conduit. The advantage of this tank over simple one is, the storage function of the tank can be separated from accelerating and retarding functions. The accelerating heads are developed more quickly than simple tank. Tanks of this type are less popular than others.

5. Differential surge tank. The differential surge tank was first introduced by R.D. Johnson. This was designed to provide a compromise between the simple and restricted orifice tank.

The arrangement of differential surge tank is shown in Fig. 4.25. It consists of a cylindrical chamber with central riser whose area is equal to that of the conduit. The riser is connected to the outer chamber by ports at its base.

With the change of load, the water level in the riser rises or falls very rapidly thus producing a rapid deceleration or acceleration of the conduit flow. While the water level in the outer chamber moves slowly and thus lags behind that in the riser. Though rapid in action, the differential surge tank gives reasonably low pressure rises and surges of low amplitude.

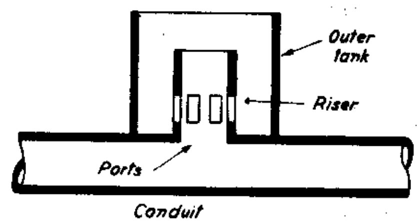


Fig. 4.25 Differential surge tank.

The riser also affords a relief overflow into the outer tank when the sudden shut-down occurs which causes the water to rise to the top of the riser and while spilling into the outer tank, the conduit receives the benefit of this back pressure and deaccelerates the velocity more rapidly, thus reducing the amount of water to be stored in the tank.

This type of surge tank can be built smaller than a simple tank for same results and has the advantage of preventing increasing surges under all conditions. Largest differential surge tank built till today is at Wallenpanpack (U.S.A.) which is 16.75 metre in diameter, 41.25 metre high with a storage capacity of nine million litres (2.4 million gallons).

Air Chamber. All the surge tanks described have free surface on the top of the tank. Sometimes a closed surge tank is provided which consists of air. The air is compressed during load reduction and opposes the rise of water. During increased load condition, compressed air pushes the water out. Enclosing the air at the top of the tank reduces the size of the tank required to perform the same function.

Pressure relief valve. The water-hammer can be reduced with the use of pressure relief valve, which is coupled to the governor such that it opens simultaneously at the closure of the water supply gate and closes at much slower speed over a period of 20 to 30 seconds thereby reducing excessive rise due to water hammer. This is effective only during load reduction period.

The pressure relief valve is not useful during increased load period and pressure rise due to counter blow is unavoidable.

Nowadays, it is general practice to provide a relief valve with a longer closing period (2 to 4 minutes). It is found that the pressure relief valve operating on a longer period slows down the acceleration and retardation of flowing water and allows a considerable reduction in the surge tank dimensions.

Heating of Surge Tank. In cold climates where there is danger of freezing tanks must be well lagged or they must be provided with heating arrangement. The use of electric heater floating in the riser pipe of a differential surge tank has been found more effective.

4.8. POWER HOUSE AND TURBINE SETTING

According to the location of the hydel power station, the power houses are classified as surface power house or underground power house. As the name implies, the underground power house is one which is built underground. A cavity is excavated inside earth surface where the sound lock is available to house the power station. A surface power house is one which is founded on earth's surface and its superstructure rests on the foundation member of the power house itself without taking any lateral support.

The surface power house has been broadly divided into three subdivisions which is separated from the intake as mentioned below :

(*a*) Substructure ; (*b*) Intermediate structure ; (*c*) Super-structure.

Substructure. The substructure of a power-house is defined as that part which extends from the top of the draft tube to the soil or rock. Its purpose is to house the passage for the water coming out of the turbine. In case of reaction turbines, the hydraulic function of the sub-structure is to provide a diverging passage (known as draft tube) where the velocity of the exit water is gradually reduced in order to reduce the loss in pushing out the water. In case of impulse turbine, such a draft tube is not required and only an exit gallery would serve the purpose.

The structural function of substructure is dual. The first function is to safely carry the superimposed loads of machines and other structures over the cavities. The second function is to act as transition foundation member which distributes heavy machine loads on the soil such that the obtainable ground pressures are within safe limits.

Intermediate structure. The intermediate structure of a power house may be defined as that part of the power house which extends from the top of the draft tube to top of the generator foundation. This structure contains two important elements of the power house, one is the scroll case which feeds water to the turbine. The generator foundation rests on the scroll-case which is embedded in the concrete. The other galleries, adits and chambers also rest on the same foundation. Scroll or spiral case is a part of the turbine and it distributes water coming from penstock uniformly and smoothly through guide vanes to the turbine. The scroll case is required only in case of reaction turbine. In case of impulse turbine, the place of scroll case is taken by the manifold supplying water to the jets:

The structural function of the concrete around scroll case would depend upon the type of scroll case used. If the scroll case is made of steel and strong enough to withstand internal loads including the water hammer effects, the surrounding concrete acts more or less as a space fill and a medium to distribute the generator loads to the sub-structure. If it is a concrete scroll case then this concrete should be strong enough to withstand the internal hydro-static and water hammer head as well as the external superimposed loads on account of the machine etc. Many times, the steel scroll case is used as water linear and in this case the surrounding concrete must be strong enough to withstand the internal hydraulic pressures in addition to the superimposed loads.

The structural function of the generator foundation is to support the generator. Arrangements may be made either to transmit the load directly to the substructure through steel barrel or through a column beam or slab arrangement.

Superstructure. The part of the power house above the generator floor right upto the roof is known as superstructure. This part provides walls and roofs to power station and also provides an overhead travelling crane for handling heavy machine parts.

The arrangement of the power house is shown in Fig. 4.26.

Arrangement of Reaction and Impulse Turbines. Factors affecting the choice between horizontal and vertical setting of machines are : relative cost of plant, foundations, building space and layout of the plant in general.

Vertical machines offer many advantages over horizontal especially when there are great variations in tail-race level. Horizontal machines turbine-house should be above the tail-race level or the lower part of the house must be made watertight. In vertical machines, the weight of rotating parts acts in the same direction as axial hydraulic thrust. This requires a thrust bearing capable of carrying considerable heavy load. The efficiency of the vertical arrangement is 1 to 2% higher than for a similar horizontal arrangement. This is due to the absence of a suction bend near the runner. As the alternator being mounted above the turbine, it is completely free from flooding.

With the horizontal machines, there may be two turbines driving one generator and turbines would operate at a higher speed bringing about a smaller and lighter generator. The horizontal machines would occupy a greater length than the vertical but the foundations need not be so deep as required for vertical machines. The horizontal shaft machines require higher settings to reduce or to eliminate the cost of sealing

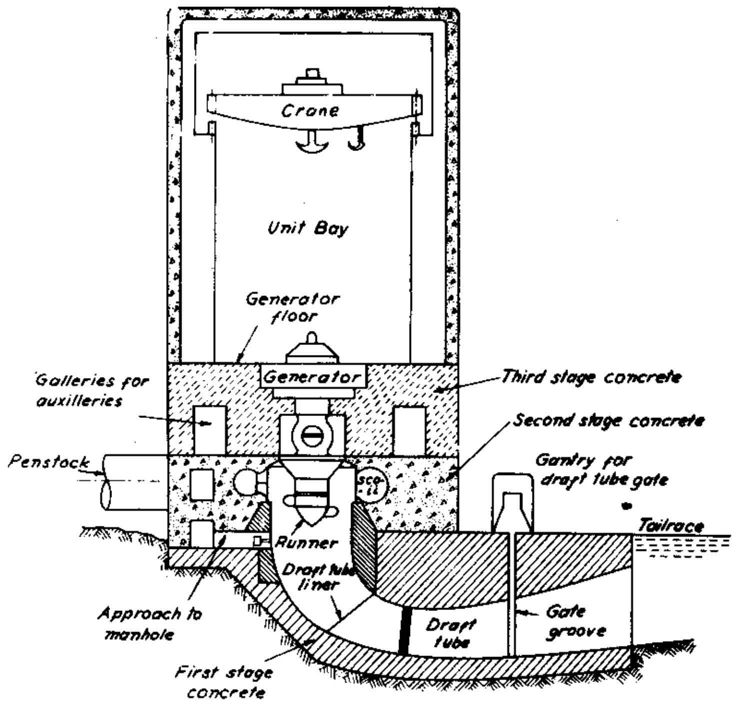


Fig. 4.26. Section of a Hydel Power Station showing sub-structure.

the generator, the auxiliary electrical equipment and cable ducts against water. In actual cases, the arrangement of the machine (vertical or horizontal) is so chosen which will give the lowest cost of the station. The majority of impulse turbines are of the horizontal shaft types. The horizontal arrangement is simpler than vertical from constructional and maintenance point of view. The overall height and width of the station will be relatively greater in case of vertical arrangement. The floor space occupied by horizontal shaft units is in general greater than that required for vertical shaft machines. Horizontal shaft arrangement is adopted in most cases for Pelton wheels, mainly because this type of setting lends itself readily to the use of multiple runner units and secondly, because the resulting hydraulic conditions are not favourable with vertical machines.

There are mainly two principal types of setting as :

(1) open flume and (2) cased turbines.

The open flume setting as shown in Fig. 4.27 and Fig. 4.28 (Rewalls power plant on black river at Watertown in U.S.A.) are chiefly used for low heads with concentrated falls or with a short canal. Open penstock setting is one where the entry to the runner has no casing but is placed in an open forebay. The runner should be placed at a convenient depth below the water surface such that eddies and suction of air through vertices will not take place. The turbine is completely submerged which results in a simple and comparatively cheap plant. The disadvantage of this

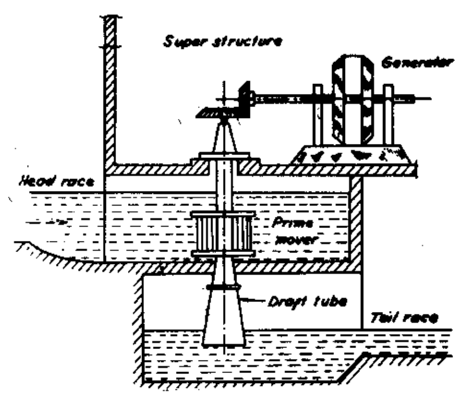


Fig. 4.27. Open flume with vertical setting of Francis Turbine (Gear system is not generally used as shown in present installations).

arrangement is that the pit must be drained to enable inspection and maintenance to be carried out on the turbine and guide vane mechanism. The turbine should have an adequate water head above it, otherwise a sudden increase in load may draw the water to a dangerous level and allow air to enter. Such condition would break the vacuum in the draft tube and stop the turbine.

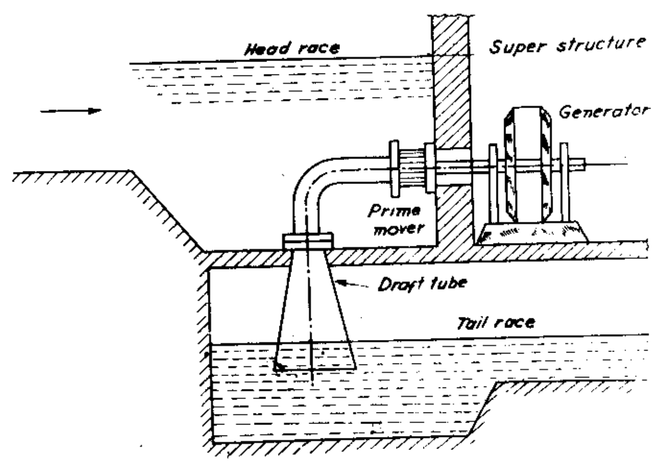


Fig. 4.28. Open flume with horizontal setting of Francis Turbine.

The cased turbines are further divided as concrete casing or steel plate casing as mentioned earlier.

The width of the concrete flume should be kept as small as possible as design permits because the concrete approach flume often fixes the machine spacing. The concrete scrolls are limited to low head installations upto 20-metre heights. The complicated form work and reinforcement required for a concrete flume makes it expensive so that other methods of construction have to be used.

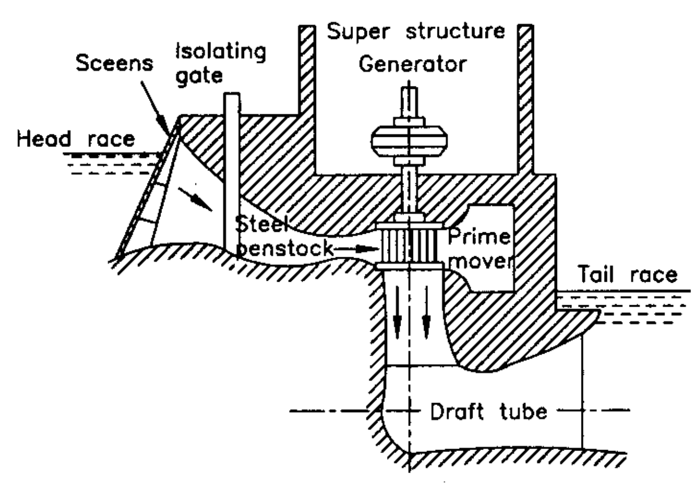


Fig. 4.29. Vertical setting of Francis turbine with steel penstock and scroll.

Steel plate scrolls are used for heads ranging from 10 m to 120 m. The arrangement of steel scroll is shown in Fig. 4.29.

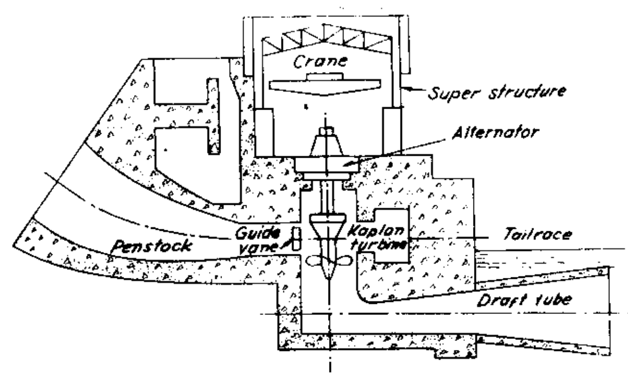


Fig. 4.30. Vertical setting of Kaplan turbine with steel penstock.

Underground Power House. The conventional hydro-electric power stations are usually located overground at the foot of a dam or a hill slope on the banks of a river. The first underground power station *Nerayaz* was built in 1897 in Switzerland. The high capacity underground power plants were built only after second world war. The idea of locating power-house underground was suggested not only with the intention of protecting them against air raids but also technical and economical considerations were mainly considered. After second world war, the immunity against air attacks was unquestionably regarded as an important advantage of underground power station. A large number of underground power stations have been installed in U.K., U.S.A., Russia, Canada, Japan after second world war and recently in India also. In all, there are about 300 such stations in service with a total installed capacity of 31 million kW upto the end of 1963.

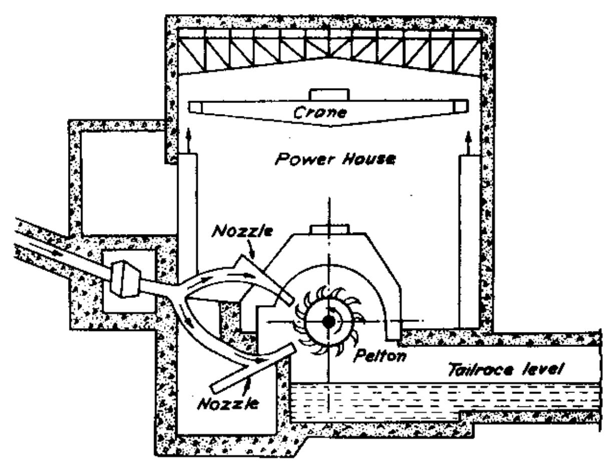


Fig. 4.31. Horizontal setting of Pelton wheel with penstock having two nozzles.

The considerations supporting the construction of underground power stations are stated below :

(1) Non-availability of a suitable site for a conventional surface station and good slope for penstock.

(2) 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 tail-race outlet.

(4) Possibility of elimination of surge tank required for surface station due to long pressure tunnel.

(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 tail-race system underground.

(6) Foundation costs for overground power house become excessive in case of poor quality surface layers. The construction of draft tube, spiral case and separating floors in loose weathered rock is again more expensive than the excavation of corresponding parts underground. The costs of underground machine hall are lower than those of the superstructure of a surface powerhouse of similar dimensions.

Advantages and Disadvantages of underground Power-House

Advantages. (1) Under suitable geological conditions, the underground conduit may prove the shortest and sometimes even straight. The power conduit may be much shorter than the length of power canal used for overground power house as the power canal usually built to follow the contours of the terrain. By locating the power house underground, the number of restrictions as safe topographical and geological conditions along the penstock and sufficient space at the foot of the hill for constructing the power house are completely eliminated.

(2) The construction of underground conduit instead of penstock results in considerable saving in steel as the internal pressure is carried partly by the rock if it is of good quality. In sound high quality rock, the penstock is replaced by an inclined or vertical pressure shaft excavated in rock and provided with a steel lining of greatly reduced thickness in comparison with exposed penstock. The purpose of lining in such cases is protection against the seepage losses.

(3) The reduced length of the pressure conduit reduces the pressures developed due to water-hammer. Therefore, smaller surge tank is also sufficient.

(4) For the economical arrangement, the ratio of the pressure conduit to the tail-race tunnel is also significant. The overall cost of the system is lower if the tail-race tunnel length is relatively large.

(5) The construction work at underground power station can continue uninterrupted even under severest winter conditions. The overall construction cost and period of construction is reduced due to continuity of work.

(6) Much care is devoted today in many countries to preserve landscape features such as picturesque rock walls, canyons, valleys and river banks in their original beauty against spoiling by exposed penstocks, canal basins and machine halls. There is less danger and disturbance to amenities with an underground power house and pipelines. The other advantages gained by constructing underground power house are listed below.

The six advantages mentioned above reduce the constructional difficulties and overall cost of the plant and preserve the original beauty of landscape. The overall cost is further reduced by the modern techniques in tunnel work and better excavation process.

(7) The shorter power conduit of underground power house reduces the head losses.

(8) The regular maintenance and repair costs are lower for underground stations as the maintenance required for rock tunnels is less.

(9) The power plant is free from landslides, avalanches, heavy snow and rainfall.

(10) The useful life of the structures excavated in rock is considerably longer than that of concrete and reinforced concrete structures.

(11) It is possible to improve the governing of the turbines with the construction of underground power house.

(12) The construction period is reduced mainly due to the possibility of full-scale construction work in winter.

(13) Underground power station is bomb-proof and may be preferred for military reasons. They are perfectly protected against air-raids. The military considerations became more predominant with the increased shadow of the war and the building of underground power stations underwent a rapid evolution after second world war.

Disadvantages. (1) The construction cost of the underground power house is more compared with the overground power house :

(*a*) The excavation of the caverns required for housing the turbine generator units and auxiliary equipments (machine hall of Koyna project is 800′ × 120′ × 60′ in dimensions) is very expensive.

(*b*) The costs of access tunnels are considerable.

(*c*) The separate gallery excavated for the inlet valves adds the extra cost.

(*d*) The construction of air ducts and bus galleries also adds in total construction costs.

(*e*) Special ventilation and air-conditioning equipment required for underground adds in the constructional costs.

(*f*) In some cases, the tailrace tunnel of an underground power house requires a more elaborate solution than a tailrace tunnel designed for the surface arrangement. The advantage gained by reducing the pressure conduit would be lost by extending the tailrace tunnel.

(*g*) The first cost is also increased by locating the transformer and high-voltage switchgear underground. The above-mentioned constructions increase the capital cost of the plant.

(2) The operational cost of the power plant increases due to following reasons :

(*a*) The lighting cost. (*b*) The running cost of air-conditioned plant. (*c*) The removal of water seeping may be more costly than for the surface arrangement.

Adequate lighting, proper ventilation, maintenance of uniform climatic conditions within the power houses, provision of the necessary safety equipments against flooding, maintenance of proper accoustical conditions, augmenting the feeling of safety by providing a sufficient number of well placed exits and finally artistic shaping and outfitting of machine hall increases the overall cost of the underground power house compared with ground surface power house.

The choice of the site for the power house either overground or underground requires a considerable economical analysis according to the available topography and no thumb rule can be applied for its selection.

Types of underground power stations. There are mainly five different types of underground power stations as per hydraulic characteristics.

1. Free level tailrace tunnel without a downstream surge tank. This arrangement, the long and steep tailrace tunnel is built to cope with the discharge without putting the tunnel under pressure, both under steady and unsteady flow conditions. This type is more suitable with Pelton-wheel because it does not interfere with the flow in tailrace tunnel. This arrangement is shown in Fig.4.32.

The underground Innertkirchen power house in Switzerland is the example of such construction. The head is 672.3 metres, length of pressure tunnel is 10 kilometres and tailrace tunnel is 1294 metre with a slope of 4 : 1.

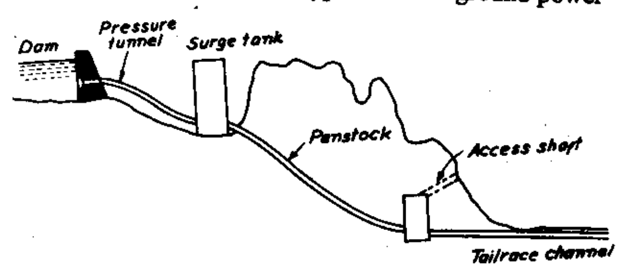


Fig. 4.32. Underground power-house with tail-race channel without downstream surge tank.

2. Upstream station arrangement or tailrace pressure tunnel with downstream surge or Swedish type. The arrangement is shown in Fig. 4.33. This arrangement is more suitable for continuously sloping and mildly rolling terrain because the construction of horizontal pressure tunnel is impossible and the internal pressures in the tunnel following the slope of terrain would be excessive. Therefore, vertical pressure shaft extending down directly from the intake to the power house is more perferable. Owing to the shortness of pressure shaft, no special valve chamber and conduit values are necessary before the units. The intake gate with automatic quick control mechanism connected to the governing system of turbine takes care of adequate safety of the power house.

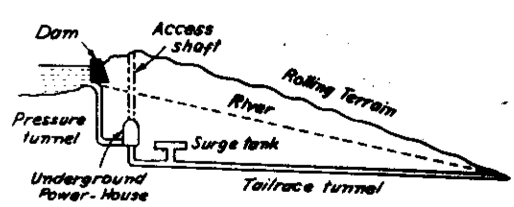


Fig. 4.33. Underground upstream station arrangement.

There is no upstream surge tank and tailrace pressure tunnel but downstream surge tank is provided. The distance between the surge tank and draft tube should be as short as possible because of negative water hammer waves developing in the draft tube.

The reaction type turbine is mostly preferred in most schemes using the downstream surge tank.

A vertical access draft is provided as shown in Fig. 4.33 for transporting machine and machine parts. The same shaft is used as entrance to the power house during operation.

Totladore power house near Nagpur falls under this class.

3. Downstream station arrangement or Alpine type. The arrangement is shown in Fig. 4.34. In this arrangement, the water is carried through a long horizontal pressure tunnel to the point of emergence to the surface, from where a step pressure shaft continues down to the power house as shown in figure. A surge tank is provided at the junction of pressure tunnel and pressure shaft as in the case of exposed penstock and surface power station.

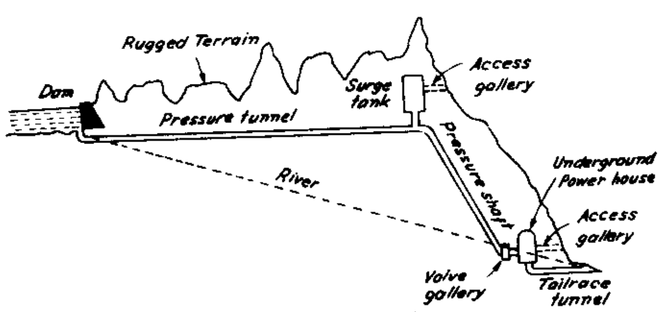


Fig. 4.34. Underground downstream station arrangement.

The valve chamber after the surge tank is also provided underground and the valves are also provided before the prime-mover. These valves may be located either in the main cavern or a separate valves gallery is excavated for this purpose. Access to both surge tank and power house is provided through horizontal tunnels as shown in Figure. The tailrace tunnel is considerably short in length. The arrangement is generally preferred in mountain regions. The downstream surge tank is also used if a tailrace tunnel is long and considerable surges are likely to occur in the tailwater.

4. Intermediate station arrangement. Fig. 4.35 shows the economic site of the power house at an intermediate section of the entire power conduit. The specific characteristic of this arrangement is long headrace tunnel and a long tailrace tunnel. Upstream and downstream surge tanks are necessary as shown in figure to deal with the pressure oscillations in both headrace and tailrace.

If the prime mover is impulse type, there is no interference between tailrace and headrace level and, therefore, the dimensions of both surge tanks can be calculated independently according to the usual surge theory. If the prime mover is reaction type, the oscillations in tailrace and headrace interfere with each other and, therefore, the larger areas of surge tanks are required than the areas required for surge tank used with impulsive type prime mover.

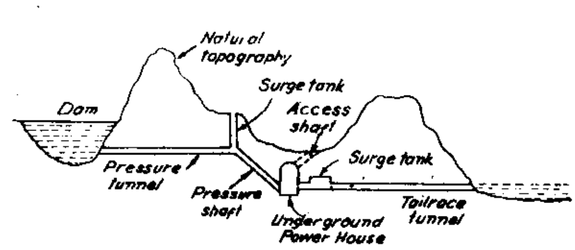


Fig. 4.35. Underground intermediate station arrangement.

The Santa Giustina power house in Italy is an example of this type of arrangement. Koyna power project also comes under this class except there is no surge tank to the downstream side as the tailrace tunnel is not very long.

5. Station arrangement without surge tank. If the pressure tunnel and tailrace tunnel are short in length, the upstream and downstream surge tanks can be eliminated from the system. The main points to be considered in this design are the maximum water hammer effect and danger of cavitation in the turbine. The latter can be eliminated by selecting the proper turbine axis level above the draft tube axis level.

A vertical or steep shafts (10 : 1) are provided to access the upstream or Swedish type power house whereas horizontal or mild sloping tunnels prove more favourable for downstream stations or Alpine type layout.

Generally fresh air as supplied to the power house through the main access tunnel and warmed up air is exhausted along the same tunnel through a separate duct. Sometimes separate air shafts are used to exhaust the warmed up air.

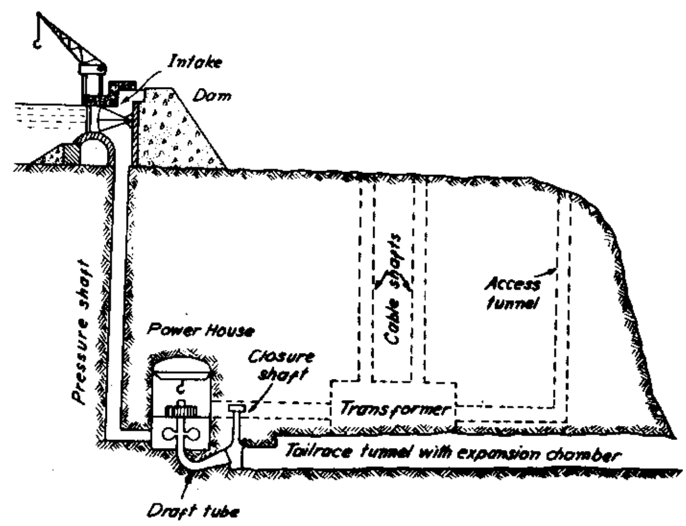


Fig. 4.36. Underground power station with transformer without surge tank.

The transformers and high voltage switching equipments were previously located outdoors almost without exception. In recent practice, transformers are also arranged underground in the transformer room excavated in the vicinity of power house. If the decision of the management is in the favour of underground power house against air-raids, no significant gain could be achieved by locating the transformer outdoor as it is one of the most sensitive and essential components of the power project. An underground location of the transformer is further supported by the fact that the location of the transformer near the power house involves hardly any excess cost.

4.7. PRIME-MOVERS

The prime-mover in the hydraulic power plant converts the kenetic 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 the action of water on the prime-mover, they are classified as impulse turbine and reaction turbine.

In impulse type turbine, the pressure energy of the 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.

In case of reaction turbine, 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.

The casing of the impulse turbine operates at atmospheric pressure whereas the casing of the reaction turbine operates under high pressure. The pressure acts on the rotor and vacuum underneath it. This is why the casing of reaction turbine is made completely leakproof.

The details of few turbines which are commonly used in hydro-electric power plants are given below.

Pelton Turbine. Figure 4.37 shows the layout of the Pelton turbine. This was discovered by Pelton in 1880. This is a special type of axial flow impulse turbine generally mounted on horizontal shaft as mentioned earlier. A number of buckets are mounted round the periphery of the wheel as shown in figure. The water is directed towards the wheel through a nozzle or nozzles. The flow of water through the nozzle is generally controlled by special regulating system. The water jet after impinging on the buckets is deflected through an angle of 160° and flows axially in both directions thus avoiding the axial thrust on the wheel. The hydraulic efficiency of Pelton wheel lies between 85 to 95%. Now-a-days, Pelton wheels are used for very high heads upto 2000 metres.

Arrangement of jets. In most of the Pelton wheel plants, single jet with horizontal shaft is used. The number of the jets adopted depends upon the specific speed required.

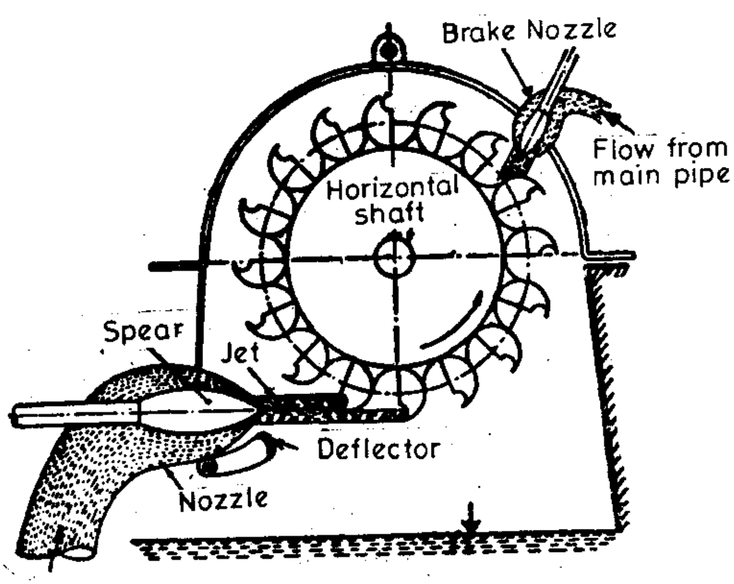


Fig. 4.37. Single jet, horizontal shaft Pelton turbine.

Any impulse turbine achieves its maximum efficiency when the velocity of the bucket at the centre line of the jet is slightly under half the jet velocity. Hence, for maximum speed of rotation, the mean diameter of the runner should be as small as possible. There is a limit to the size of the jet which can be applied to any impulse turbine runner without seriously reducing the efficiency. In early twenties, a normal ratio of *D/d* was about 10 : 1. In a modern Turgo impulse turbine, it is reduced upto 4.5 to 1. The basic advantage of Turgo-impulse turbine is that a much larger jet could be applied to a runner of a given mean diameter. The jet of Pelton turbine strikes the splitter edge of the bucket, bifurcates and is discharged at either side.

With the turgo impulse turbine, the jet is set at an angle to face the runner, strikes the buckets at the front and discharges at opposite side. The basic difference between the two is shown in Fig. 4.38.

The Turgo impulse turbine bridges the gap of specific speed between the Pelton wheel and Francis turbine. Two turgo impulse turbines are used in a power house at Poonch which is 320 km from Jammu.

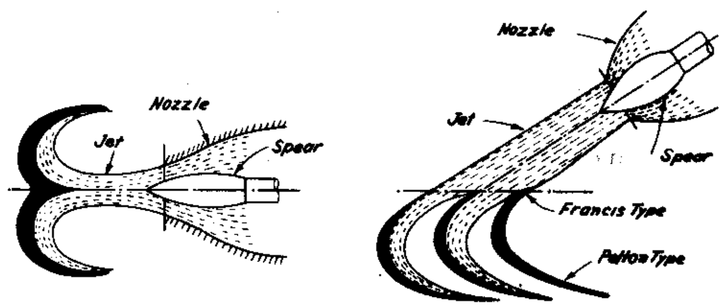


Fig. 4.38. Flow through Pelton and Turgo impulse turbines.

The reaction turbines are further divided into two general types as Francis and Propeller Type: The propeller turbines are further subdivided into fixed blade propeller type and the adjustable blade type known as Kaplan Turbine.

Francis Turbine. In Francis turbine, the water enters into a casing with a relatively low velocity, passes through guide vanes located around the circumference and flows through the runner and finally discharges into a draft tube sealed below the tailwater level. The water passage from the headrace to tailrace is completely filled with water which acts upon the whole circumference of the runner. A large part of the power is obtained from the difference in pressure acting on the front and back of the runner buckets, and only a part of total power is derived from the dynamic action of the water.

There are mainly two types of Francis turbines known as open flume type and closed type.

In open flume type, the turbine is immersed under water of the headrace in a concrete chamber and discharges into the tailrace through the draft tube. The main disadvantage of this type is that, runner and guide-vane mechanism is under the water and they are not open either for inspection or repair without draining the chamber.

In the closed type ; the water is led to the turbine through the penstock whose end is connected to the spiral casing of the turbine. The open flume type is used for the plants of 10 metres head whereas closed type is preferred above 30 metres head.

The guide vanes are provided around the runner to regulate the water flowing through the turbine. The guide vanes provide gradually decreasing area of flow for all gate openings, so that no eddies are formed and efficiency does not suffer much even at part load conditions.

The majority of the Francis turbines are inward radial flow type and most preferred for medium heads. The inward flow turbine has many advantages over outward flow turbine as listed below :

1. The chances of eddy formation and pressure loss are reduced as the area of flow becomes gradually convergent.

2. The runaway speed of the turbine is automatically checked as the centrifugal force acts outwards while the flow is inward.

3. The guide vanes can be located on the outer periphery of the runner, therefore, better regulation is possible.

4. The frictional losses are less as the water velocity over the vanes is reduced.

5. The inward flow turbine can be used for fairly high heads without increasing the speed of the turbine as centrifugal head supports considerable part of supply head.

A comparison of various types of reaction runners of the same power, but of different specific speed, is shown in Fig. 3.29. The first three show the sections of Francis runners and the fourth one is a section of propeller runner.

It is obvious from the figures that the flow through the runner changes from radially inward to nearly axial as the specific speed of the runner is increased. It is also obvious from the figure that the size of the runner decreases with an increase in specific speed for the same power.

Recent Developments in Francis Turbines. The last decade has seen considerable developments in the design of Francis turbines, and the modern trend is to go in for large sizes of machines with high speeds so as to economise in the cost of plant and civil work and at the same time improve the working characteristics (effeciency) of the Francis runner.

The largest Francis runner in operation until 1955 was of 147 MW capacity in Sweden. The recent move towards the higher capacities has resulted in sets of 580 MW (680,000 B.H.P.) capacity unit at Krasnoyarsk Power Station in Russia. This station has 10 such sets in operation under the head of 103 metres. The Canada Electricity Board has planned to manufacture 11 units of 485 MW capacity to be used at Churchill Falls plant. The 660 MW capacity unit has been designed in U.S.A. for the Grand Coulee power station and these are the largest Francis turbines in the world so far developed. The water turbines of 650 MW capacity are reported to be under design in Russia. for the Sayano-Shushenkaya station on the river Yenisei in Siberia. It is also said that 800 to 1000 MW hydro sets are also being planned for huge hydro-power station coming up in Siberia.

The largest Francis turbine of 172 MW capacity in India at present is used at Dehar project by Heavy Electrical Ltd., Bhopal. The manufacture of 200/250 MW capacity units which will be used in hydro-projects planned in the Himalayas is also undertaken by the same company.

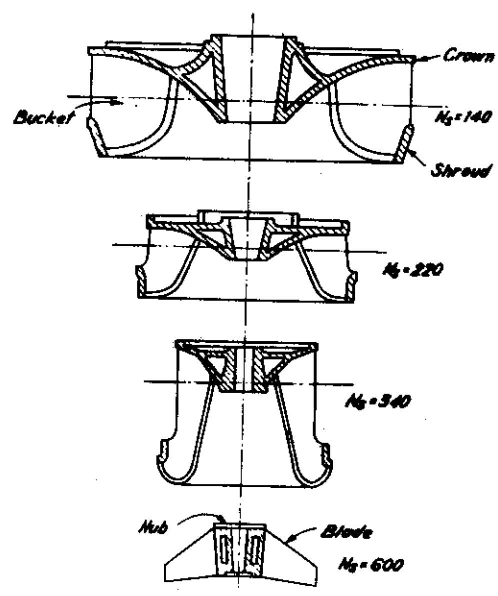


Fig. 4.39. Different types of reaction turbine runners.

Manufacture of high capacity units in India is largely limited by the lack of transport facilities, the small power grids and long transmission lines.

Propeller Turbine.. The propeller runner may be considered as a development of a Francis type in which the number of blades is greatly reduced and the lower band omitted. It is axial flow turbine having a small number of blades from three to six as shown in Fig. 4.40. The propeller turbine may be fixed blade type or movable blades type known as Kaplan Turbine.

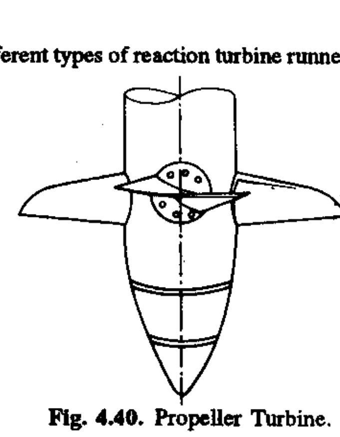


Fig. 4.40. Propeller Turbine.

The fixed blade propeller type turbine has high efficiency (88%) at full load but its efficiency rapidly drops with decrease in load. The efficiency of the unit is hardly 50% at 40% of full load at part load operation. The use of propeller turbine is limited to the installations where the units run at full load conditions at all times. The use of propeller turbine is further limited to low head installations of 5 to 10 metres.

Kaplan Turbine. Great strides are made in last few decades to improve the performance of propeller turbine at part load conditions. The Kaplan turbine is a propeller type having a movable blade instead of fixed one. This turbine was introduced by Dr. Vitkor Kaplan. This turbine has attained great popularity and great progress has been made in recent years in the design and construction of this turbine.

The rotor of the Kaplan turbine is shown in Fig. 4.41. The blades are rotated to the most efficient angle by a hydraulic servo-motor. A cam on the governor is used to change the blade angle with the gate position so that high efficiency is always obtained at almost any percentage of full load.

These turbines are constructed to run at speeds varying from 60 to 220 r.p.m. and to work under varying head from 2 to 60 metres. These are particularly suitable for variable heads and for variable flows and where the ample quantity of water is available.

The specific speed of Kaplan lies in the range of 400 to 1500 so that the speed of the rotor is much higher than that of Francis Turbine for the same output and head or Kaplan turbine having the same size as Francis develops more power under the same head and flow quantity.

The velocity of water flowing through Kaplan turbine is high as the flow is large and, therefore, the cavitation is more serious problem in Kaplan than Francis Turbine.

The propeller type turbines have an outstanding advantage of higher speed which results in lower cost of runner, generator and smaller power house substructure and superstructure.

The capital and maintenance cost of Kaplan turbine is much higher than fixed blade propeller type units operated at a point of maximum efficiency.

For a low head development with fairly constant head and requiring a number of units, it is always advisable to instal fixed blade propeller type runners for most of them and Kaplan type for only one or two units. With this combination, the fixed blade units could be operated at point of maximum efficiency and Kaplan units could take the required variations in load. Such combination is particularly suitable to a large power system containing a multiplicity of the units.

Francis *Versus* Pelton. The Francis turbines are used for all available heads on the other hand. Pelton wheels are used for very high heads only (200 m to 2000 m).

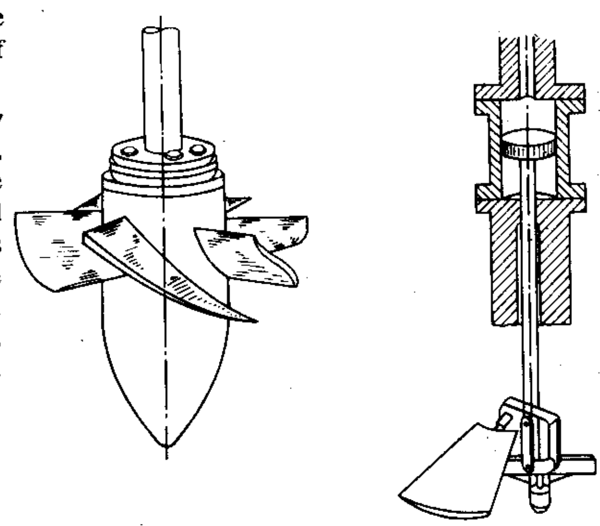


Fig. 4.41. Kaplan Turbine.

The Francis turbine is preferred over Pelton for the following reason :

1. The variation in the operating head can be more easily controlled in Francis than in Pelton.
2. The ratio of maximum and minimum operating head can be even two in case of Francis turbine.
3. The operating head can be utilised even when the variation in the tail water level is relatively large when compared to the total head.
4. The size of the runner, generator and power house required is small and economical if the Francis is used instead of Pelton for the same power generation.

5. The mechanical efficiency of Pelton decreases faster with wear than Francis.

The drawbacks of the Francis compared with Pelton are listed below :

1. Water which is not clean can cause very rapid wear in high head Francis turbine. In passing through the guide vanes and cover facings, it can quickly reduce overall efficiency of the turbine by several percent. The effect is much more serious in turbines of small diameter than in large ones.

Particles of solid matter in the water will wear the lip of the spear, the nozzle and after several years the runners also. The first two are easily removable, renewable and repairable. The runner repairing by welding can often be done without removing the runner from the shaft or casing.

2. The inspection and overhaul of a Francis is much more difficult job than that of the equivalent Pelton turbine. The badly worn-out parts will have to be replaced by new ones and it will take a considerable time.

3. Cavitation is an ever-present danger in Francis as well as in all reaction turbines. The raising of power house floor level to reduce the danger of flooding may be followed by endless cavitation troubles.

4. Usually below 60% load ; the Pelton is much better as it gives more efficiency than Francis of low specific speed. If there is possibility of running the prime-mover below 50% load for a long period, the Francis will not only lose its efficiency but the cavitation danger will become more serious.

5. The water hammer effect with the Francis is more troublesome than the Pelton turbine.

Kaplan *Versus* Francis Turbine. The advantages of Kaplan over Francis are listed below :

1. It is more compact in construction and smaller in size for the same power developed.

2. Its part-load efficiency is considerably high. The efficiency curve remains more or less flat over the whole load range.

3. The frictional losses passing through the blades are considerably lower due to small number of blades used.

4.10. SPECIFIC SPEED OF TURBINE

The specific speed of a turbine is defined as the speed at which the turbine runs developing one kW under a head of one metre.

The equation for the specific speed of a turbine can be obtained by using the principle of similarity.

(1) $$V = \frac{\pi DN}{60} \propto \sqrt{H}$$

$\therefore\ D \propto \frac{\sqrt{H}}{N}$ where D and N are diameter and speed of a turbine and H is the head acting on the turbine.

(2) $$Q = \pi DB.V_f \propto D^2\sqrt{H}.$$

where B is the height of the blade and V_f is the velocity of flow.

Substituting the value of D in the above equation,

$$\therefore \qquad Q \propto \frac{(H)^{3/2}}{N^2}.$$

(3) $$P = \frac{mgH}{1000}$$

where P is the power developed in kW and $m = Q\rho g$

Substituting the value of Q in the above equation we get

$$P \propto \frac{\rho g}{1000}\left[\frac{(H)^{3/2}}{N^2}\right) H \propto \frac{(H)^{5/2}}{N^2}$$

$$\therefore \qquad N^2 \propto \frac{(H)^{5/2}}{P}.$$

$$\therefore \qquad N \propto \frac{(H)^{5/4}}{\sqrt{P}} = C\frac{(H)^{5/4}}{\sqrt{P}}$$

where C is constant depending upon the type of the turbine.

If the turbine develops 1 kW under one metre head then

$$C = N = N_s$$

where N_s is the specific speed as per the definition.

Substituting the value of C in the above equation, we get

$$N_s = \frac{N\sqrt{P}}{(H)^{5/4}} \text{ when } P \text{ is in kW} \qquad \text{...(4.1)}$$

By definition, the specific speed is number of revolutions per minute at which a given runner would revolve if it were so reduced in proportions that it would develop one kW under one metre-head.

The specific speed of a single jet Pelton wheel in terms of diameter of runner and diameter of jet in metric units is given by

$$N_s \text{ (single jet petrol)} = 244.75\,\frac{d}{D} \qquad \text{...(4.2)}$$

In a multi-jet pelton wheel, the kW is directly proportional to the number of jet if the head remains constant. The specific speed of multi jet Pelton wheel is given by

$$N_s \text{ (}\propto \sqrt{n} \text{ as } N_s \propto \sqrt{P} \text{ and } P \propto n.$$

Therefore, the specific speed of multi jet unit can be calculated by multiplying the specific speed of single jet unit with a factor $\sqrt{n}$ where n is number of jets used.

It is necessary to know a characteristic of an imaginary machine identical in shape for comparing the characteristics of machines of different types. 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 same basis of head and power capacity.

The overall cost of installation (runner + generator + power house and auxiliary equipments) is lower if a runner of high specific speed is used for a given head and power output. 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 high 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 the turbine is more important in the selection of a turbine instead of maximum efficiency.

Experience has determined that there is a range of heads and specific speeds for each type of turbine. Special conditions may sometimes dictate departure from common practice.

The ranges of heads and specific speeds for different types of turbines are tabulated in Tables (*a*) and (*b*).

Table (a)

Type of Turbine	*Range of Head*	*Specific speed in metric units*
Pelton (1 nozzle) Pelton (2 nozzles) Pelton (4 nozzles)	200 metres to 2000 metres	10 – 20 20 – 40 40 – 50
Turgo impulse turbine Francis (low speed) Francis (medium speed) Francis (high speed) Francis (express)	as above 15 metres to 300 metres	50 – 100 80 – 120 120 – 220 220 – 350 350 – 420
Propeller	5 metres to 30 metres	310 – 1000

Table (b)

Type of Turbine		N_s *in MKS*	N_s *in SI*	N_s *in FPS*
Axial flow (Kaplan)	Slow Normal Fast	300 – 450 450 – 700 700 – 1200	14.8 – 22.2 22.2 – 34.6 34.6 – 59.3	67.5 – 101.2 101.2 – 157.4 157.4 – 270.0
Radial and Mixed flow (Francis and Deriaz)	Slow Normal Fast	60 – 150 150 – 250 250 – 400	2.9 – 7.4 7.3 – 12.4 12.4 – 19.8	5.5 – 33.7 33.7 – 56.2 56.2 – 90.0
Impulse (Pelton)	Slow Normal Fast	4 – 10 10 – 25 25 – 60	0.2 – 0.5 0.5 – 1.2 1.2 – 3.0	0.9 – 2.3 2.3 – 5.6 5.6 – 13.5

$$N_s \text{ (SI units)} = N_s \text{ (MKS Units)} \times 0.0494 = N_s \text{ (FPS Units)} \times 0.2203.$$

The following formulae are suggested for Francis and Propeller type turbines to determine the desirable specific speed if the heads available are known.

$$\text{(1) Francis Turbines } N_s \text{ (metric)} = \frac{6800}{(H+9.7)} + 84.5 \qquad \text{...(4.3)}$$

where H is head in metres.

$$\text{(2) Propeller Turbines } N_s \text{ (metric)} = \frac{9440}{(H+9.7)} + 156 \qquad \text{...(4.4)}$$

where H is head in metres.

To find out the specific speed of Kaplan turbine, the equation (4.4) is used multiplying by a factor 1.1.

4.11. DRAFT TUBES

Reaction turbines must be completely enclosed because a pressure difference exists between the working fluid (water) in the turbine and atmosphere. Therefore, it is necessary to connect the turbine outlet by means of a pipe known as draft tube upto tailrace level.

1. Output of reaction turbine when the tailrace level is above the turbine (submerged turbine.) The position of the turbine is shown in Fig. 4.42 and energies at all points are measured taking $x - y$ as reference line. Considering the energies of unit mass of water at all points, we can write

$$E_a = E_b = H_c + \frac{P_a}{\rho}$$

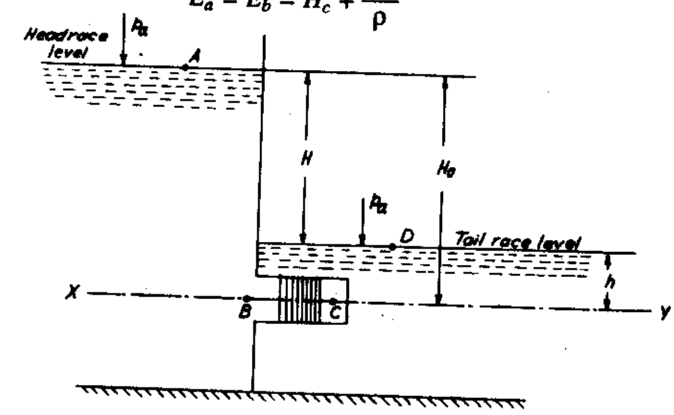


Fig. 4.42. Turbine below tailrace level.

W_1 (Work done per kg of water passing through the turbine)

$$= E_b - E_c = \left(H_o + \frac{p_a}{w}\right) - \left(\frac{p_c}{w} + \frac{V_c^2}{2g}\right) = \left(H_o + \frac{p_a}{w}\right) - \left(\frac{p_a}{w} + h + \frac{V_c^2}{2g}\right)$$

as $\frac{p_c}{w} = \frac{p_a}{w} + h$ for pressure equilibrium where w is weight density of water (N/m^3)

$$W_1 = H_o - h - \frac{V_c^2}{2g} = H - \frac{V_c^2}{2g} \qquad \text{...(4.5)}$$

where H is the net head between headrace and tailrace level and V_c is the velocity of water leaving the turbine.

2. Output of reaction turbine with draft tube. The arrangement of the turbine with draft tube is shown in Fig. 4.43 and energies at all points are measured taking $x - y$ as reference line as shown in Fig. 4.43.

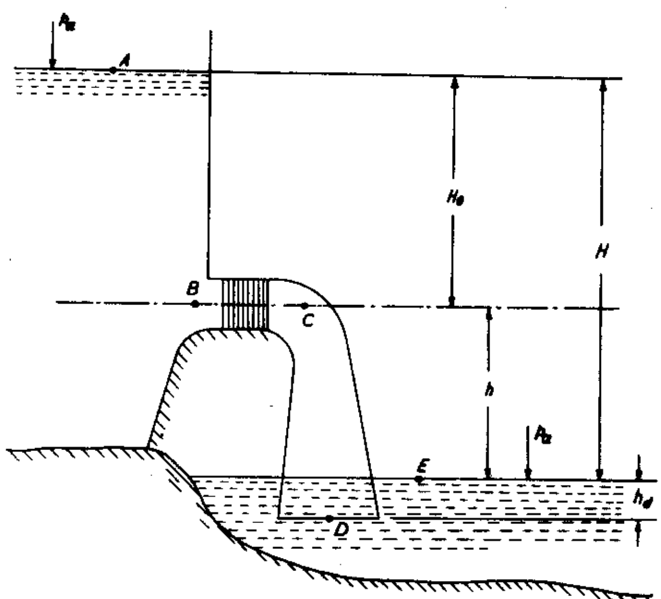


Fig. 4.43. Arrangement of reaction turbine with draft tube.

$$E_a = E_b = H + h_d + \frac{p_a}{w}$$

$$E_c = h + h_d + \frac{V_c^2}{2g} + \frac{p_c}{w}.$$

and
$$E_d = \frac{V_d^2}{2g} + \frac{p_d}{w}.$$

W_2 (work done per kg of water passing through the turbine) $= E_b - E_c$

$= E_b - (E_d + h_f)$ where $E_c = E_d + h_f$

where h_f is the head lost by water passing through the draft tube (friction and other losses).

$$= \left(H + h_d + \frac{p_a}{w}\right) - \left(\frac{V_d^2}{2g} + \frac{p_d}{w} + h_f\right).$$

$$= \left(H - \frac{V_d^2}{2g}\right) + \left(h_d + \frac{p_a}{w} - \frac{p_d}{w}\right) - h_f$$

The pressure at the point D and E must be same.

$$\therefore \quad \frac{p_d}{w} = \frac{p_a}{w} + h_d$$

Substituting this value in the above equation, we get

$$W_2 = \left(H - \frac{V_d^2}{2g}\right) h_f \qquad \text{...(4.6)}$$

$$= H - \frac{V_d^2}{2g} \text{ is } h_f \text{ is taken as zero} \qquad \text{...(4.7)}$$

Comparing the equations (4.7) and (4.5), the extra work done per kg of water due to draft tube is given by

$$\Delta W = W_2 - W_1 = \left[\left(H - \frac{V_d^2}{2g}\right) - h_f\right] - \left(H - \frac{V_c^2}{2g}\right) = \frac{V_c^2 - V_d^2}{2g} - h_f$$

$$= \frac{V_c^2 - V_d^2}{g} \text{ if } h_f = 0 \qquad \text{...(4.8)}$$

The head on the turbine (H) remains same as before, ΔW increases with the decrease in velocity V_d. The velocity V_d can be decreased by increasing the outlet diameter of the draft tube.

The outlet diameter of the draft tube can be increased either by increasing the height of the draft tube or by increasing the angle of draft tube as shown in Fig. 4.44.

The increase in height for increasing the diameter without increase in angle is limited by the pressure at the outlet of the runner (at point C). This will be discussed later in detail.

An increase in draft tube angle (2α) for increasing the diameter without increase in height is limited by the losses in the draft tube. The flow in the draft tube is from low pressure region to high pressure region. In such flow, there is a danger of water particles separating out from main stream and trying to flow back resulting in formation of eddies which are carried away in main stream causing losses. The maximum value of α is limited to 4. The gain in work by increasing an angle α above 4 will be lost in eddy losses and separated flow.

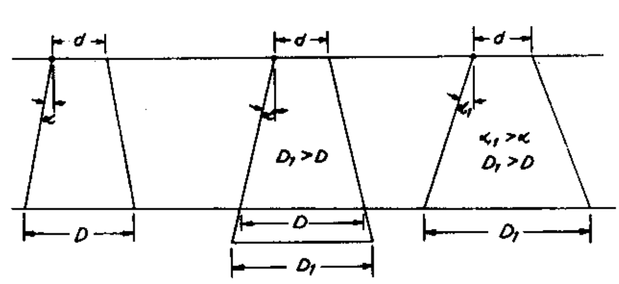


Fig. 4.44. Draft tubes.

Sometimes in order to decrease the length of draft tube, the diverging angle has to be made more than 4° and under such cases to reduce the losses due to separation, the air is sucked from the inside surface of the draft tube. Prof. Ackeret has shown that the efficiency of draft tube was raised from 50 to 80% by air sucking process. However, water equal to 5% of the total quantity is also withdrawn with the air.

The work done by the draft tube is further increased by decreasing h_f. This is generally done by proper lining the draft tube and by proper designing the shape and size of the draft tube.

The efficiency of the draft tube is given by

$$\eta = \frac{\Delta W}{V_c^2/2g} = \frac{V_c^2 - V_d^2}{V_c^2} = \left[1 - \left(\frac{V_d}{V_c}\right)^2\right] \qquad \text{...(4.9)}$$

The chief advantages of using draft tube are listed below :

(1) It allows the turbine to be set above the tailrace water level where it is more accessible and yet does not cause any sacrifice in the head of turbine. It also prevents the flooding of generator and other equipments during flood period when the tailrace water height goes up.

(2) It converts part of the velocity energy of the water leaving the turbine into the pressure energy and increases the overall efficiency of the plant.

Cavitation and Limitation of Turbine Height above Tailrace Level. The formation of water vapour and air bubbles on the water surface due to the reduction of pressure is known as "Cavitation". When the pressure on the water reduces below the saturation pressure corresponding to the temperature of the water, the rapid formation of water vapour and air bubbles starts. The bubbles suddenly collapse with the violent action and collapsing pressure will be very high. The rapid formation and collapsing of the bubbles causes the pitting of the metallic surface. It also reduces the efficiency of the hydraulic prime mover causing honey-combing of runner and blade contours which reduces the power output.

Referring to Fig. 4.43, we can write

$$E_c = E_d$$

$$\therefore \quad \left[\frac{V_c^2}{2g} + h + h_d + \frac{p_c}{w}\right] - h_f = \left[\frac{V_d^2}{2g} + \frac{p_d}{w}\right] \text{where } w \text{ is weight density (N/m}^3)$$

$$\therefore \quad \frac{V_c^2}{2g} + h + h_d + \frac{p_c}{w} - h_f = \frac{V_a^2}{2g} + \frac{p_a}{w} + h_d$$

$$\text{as } \frac{p_d}{w} = \frac{p_a}{w} + h_d \text{ for pressure equilibrium}$$

$$\therefore \quad \frac{V_c^2}{2g} + h + \frac{p_c}{w} - h_f = \frac{V_d^2}{2g} + \frac{p_a}{w}.$$

$$\therefore \quad \frac{p_c}{w} = \frac{p_a}{w} - \left[h + \left(\frac{V_c^2 - V_d^2}{2g}\right) - h_f\right] \qquad \text{...(4.10)}$$

or

$$h = \left(\frac{p_a - p_c}{w}\right) - \left(\frac{V_c^2 - V_d^2}{2g}\right) + h_f \qquad \text{...(4.11)}$$

$$= \left(\frac{p_a - p_c}{w}\right) - \frac{V_c^2}{2g} + \left(\frac{V_d^2}{2g} + h_f\right) \qquad \text{...(4.12)}$$

The equation (4.10) shows that the pressure at point c (at exit of the turbine) is below atmospheric pressure. The pressure p_c should not be below the cavitation pressure which is the saturation pressure of water at the water temperature to avoid the cavitation in turbine.

An increase in height of the draft tube also increases the height of the turbine (h) above tailrace level and reduces the pressure p_c and increases the danger of cavitation. The height of the turbine above tailrace level to avoid the flooding of superstructure is also controlled by the occurrence of cavitation danger.

Cavitation Factor. Prof. D. Thowa (Germany) suggested a cavitation factor to determine the zone where the turbine can work without any danger of cavitation.

The critical value of cavitation factor is given by

$$\sigma_c = \frac{(H_a - H_v) - h}{H} \quad \text{...(4.13)}$$

where H_a = Atmospheric pressure head in meter of water

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

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

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

The values of H_a with respect to the altitudes above sea level and the values of H_v with respect to the water temperatures are tabulated in the tables (4.1) and (4.2). The values of critical factor depend upon the specific speed of the turbine. The critical values of cavitation factors with respect to specific speed are tabulated in table (4.3).

Methods to Avoid Cavitation

1. **Installation of Turbine below Tailrace Level.** The danger of cavitation increases in case of low head and high speed propeller runner as the value of $(V_c^2 - V_d^2/2g$ is considerably large as mentioned earlier. In order to keep the value of p_c within the cavitation limit, the value of h is made negative keeping the runner below tailrace level. For such installations, the turbines remain always under water. 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 as mentioned earlier.

2. **Cavitation Free Runner.** The cavitation free runner can be designed to fulfil the given conditions with extensive research. The shape of the blade, the angle of the blade, the thickness of the blade can be changed and experiments can be conducted to find out the best dimensions of the blade (shape, size, angle, etc.)

3. **Use of Material.** The cavitation effect can be reduced 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. The pitting effect of cavitation on cast steel can be repaired more economically by ordinary welding. It has been observed that the welded parts are more resistant to cavitation than ordinary ones.

4. **Polishing.** The cavitation effect is less on polished surfaces than ordinary one. That is why the cast steel runners and blades are coated with stainless steel.

5. **Selection of Specific Speed.** By selecting a runner of proper specific speed for the given head from equation (4.12) and from tables (4.1) and (4.2), it is possible to avoid the cavitation.

Table 4.1

Altitude V_s Atmospheric Pressure

Altitude above sea level in metres		*0*	*1000*	*2000*	*3000*	*4000*
Barometric Pressure	mm of Hg.	760	676	595	528	463
	Metres of water	10.35	9.2	8.1	7.2	6.3

Table 4.2

Saturation Pressure as Function of Temperature

Temp.°C (1)	*Pressure in bar* (2)	*Pressure in mm of Hg.* (3)	*Pressure in metres of water* (4)
0	0.00122	4.60	0.062
2	0.00716	5.30	0.072
4	0.00829	6.30	0.083
6	0.00953	7.04	0.095

(1)	(2)	(3)	(4)
8	0.01093	8.05	0.1095
10	0.01251	9.23	0.1251
12	0.01429	10.50	0.1430
14	0.01629	12.05	0.1630
16	0.01853	13.70	0.1855
18	0.02103	15.50	0.2105
20	0.12383	17.60	0.2385
22	0.02700	19.95	0.2700
24	0.00040	22.40	0.3040
26	0.03430	25.30	0.3430
28	0.03850	28.40	0.3850
30	0.04330	32.00	0.4330
32	0.04850	35.80	0.4850
34	0.05420	40.00	0.5420
36	0.06050	44.70	0.6060
38	0.06760	50.70	0.6760
40	0.07520	55.50	0.7520
42	0.08360	61.70	0.8360
44	0.09280	68.50	0.9280
46	0.10280	76.00	1.0280
48	0.11380	84.00	1.1310
50	0.12580	93.00	1.2580

Table 4.3 $(N_s V_s \sigma_s)$

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 0.60
200	0.1	650 to 700	0.85
250	0.14	700 to 800	1.05
300	0.2	–	–
350	0.27	–	–

Types of Draft Tubes

(1) Conical Draft Tube. This is known as tapered draft tube and used in all reaction turbines where conditions permit. It is preferred for low specific speed and vertical shaft Francis turbine. The maximum cone angle of this draft tube is limited to 8° (α = 4°) for the cause mentioned earlier. The hydraulic efficiency of such type of draft tube is 90%.

In any event, the draft tube should be made as to secure a gradual reduction of velocity (uniform decrease towards the exit of draft tube) from the runner to the mouth. A form that is theoretically good is "Trumpet Shaped".

(2) Elbow Type Draft Tube. The elbow type draft tube is often preferred in most of the power plants where the setting of vertical draft tube does not permit enough room without excessive cost of excavation. This offers an advantage in the cost of excavation ; specially in the rock.

If the tube is large in diameter ; it may be necessary to make the horizontal portion of some other section than circular in order that the vertical dimension may not be too great. A common form of section used is oval or rectangle.

If some other section instead of circular is used, then the tube is so made that the area increases at a similar rate to what it would if it were circular. The other forms are generally used when the draft tubes are moulded in concrete.

If the cross-section is gradually changed from circular at wheel discharge to rectangular or elliptical at the mouth of the tube, there is considerable saving in the excavation cost. Such types of draft tubes give better hydraulic efficiency than conical elbow type. The efficiency of this tube lies between 60 to 70%.

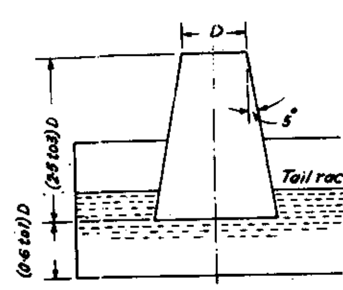
The horizontal portion of the elbow type draft tube is generally inclined upward to lead the water gradually to the tailrace level and prevent the entry of air from the exit end.

(3) **Hydracone or Moody Draft Tube.** This type of draft tube is also known as bell-mouth draft tube. The whirl component of the water is large when the turbine works at part load conditions. Turbine runs at high speed under low head conditions.

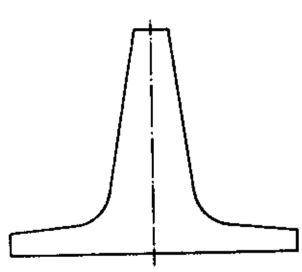
The high speed runner under low head has high whirling component. As water enters the draft tube from the high speed runner, it whirls in the direction in which the runner rotates. The axis of rotation is the vertical axis of the draft tube. The vortex tends to remain in the same plane because of its gyroscopic properties and therefore, will not follow the centre line of the tube. This causes eddies and whirls in the curved portion of the draft tube and only a portion of the discharged area at the exit may be effective. Actually water flows back into the part of the draft tube and causes serious eddies and losses.

The central cone arrangement of hydracone draft tube reduces the whirl action of the discharged water and increases the efficiency of this draft tube to 85%.

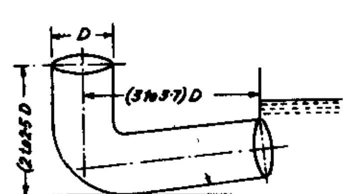
Two different hydracone type draft tubes are shown in Figs. 4.45 (*e*) and Fig. 4.45 (*f*). The flow coming out of the high speed runner is whirling flow and can be considered as free vortex flow. The pressure is minimum at the centre of the free vortex, therefore, the cavitation may start by the liberation of air and vaporization of water at the centre of the draft tube immediately underneath the runner if the velocity of whirl is large. To prevent the cavitation of runner under above-mentioned condition, the high speed runners are used in low head plants, and the central cone of draft tube has been extended right upto the tube as far as possible as shown in Fig. 4.45 (*g*). The tube shown in Fig. 4.45 (*e*) is used for low speed turbines where the whirl velocity is not high.



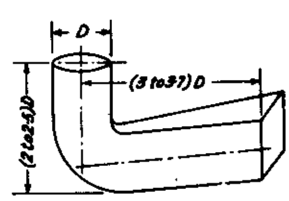
(*a*) Conical draft tube.



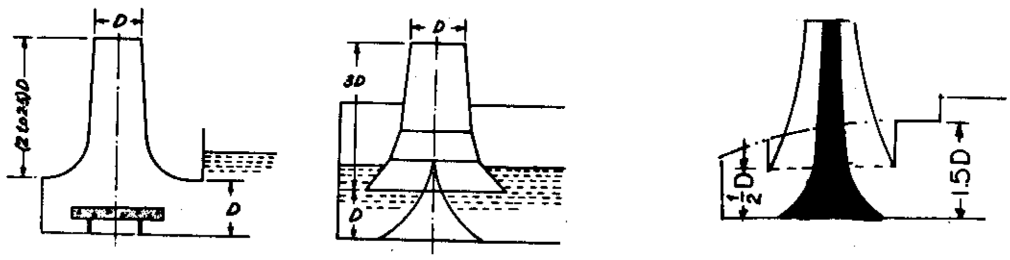
(*b*) Trumpet shaped draft tube.



(*c*) Elbow draft tube with circular section.



(*d*) Elbow draft tube with variable shape sections.



(*e*) **Hydracone** draft tube. (*f*) Moody draft tube with low cone. (*g*) Moody draft tube with high cone.

Fig. 4.45. Different types of draft tubes.

In another type of draft tube, a circular plate concentric with draft tube is put into the elbow section as shown in Fig. 4.45 (*e*) to improve the flow and efficiency of draft tube and for structural reasons in large units.

The draft tube plays more efficient role with the use of high specific speed runners like Express Francis and Kaplan. Because the value of velocity energy at the runner exit increases with an increase in specific speed and it will be nearly 45% in case of Kaplan turbine. Greater care is taken in the design and construction of the draft tube when used with a runner of high specific speed.

The different types of draft tubes described are shown in Fig. 4.45 (*a*) to (*g*).

Draft Tube Liners. The pitting of the turbine runner and in the upper part of draft tube has occurred in almost all types of runners and kinds of metals used. It is even reported that the runner blades of 5 cm thick have been eaten in less than two years. In avoiding the pitting, the draft head is of greatest importance. A poorly designed runner may be set with a low height above tailrace level and show no pitting, while a properly designed runner may be set high enough above tailrace level but pitting is unavoidable.

It is always desirable that atleast the upper portion of the draft tube should be lined with either a cast or plate steel liner to avoid the pitting on the surface of the tube. It has been reported that the unlined concrete draft tube has been eaten by pitting to a depth of 30 cm to 50 cm just below the runner.

In high head plants (using reaction turbine as prime mover), where the velocity in the draft tube may be considerably high, the upper part of the draft tube is usually made of steel plate.

4.12. MODELS AND MODEL TESTING

The size of the water turbines used in hydraulic power plant is usually very large (150,000 kW or more). The turbines are manufactured to fulfill the required specific conditions and, therefore, the mass production of hydraulic turbines used in power plants is not possible.

The cost of the turbine unit is considerably large, therefore, it is not economical to conduct the test on the proto-type units. The changes in dimensions, size and shape are not possible once the prototype is ready. The hydraulic limitations to conduct the test on prototype are listed below :

1. It is not possible to vary the head and speed of the unit as desired.
2. The load cannot be maintained constant on the turbine.

Due to the above-mentioned limitations for conducting the test on proto-type unit, it is always necessary to conduct the tests on the models of the turbines which is geometrically similar and can predict the behaviour of the prototype units.

The model and prototype should be identical in shape and the other parts like casing, guide mechanism and draft tubes must be also geometrically similar. It is always desirable to make a turbine model having an output of not less than 5 kW and not greater than 50 kW. Too small model may not give accurate result and too large model may not be economical.

To study the performance of the prototype using the models, certain characteristics of turbine as unit power, unit speed and unit quantity must be known.

1. Unit power. This is defined as the power developed by the turbine under a head of one meter.

$$P = \frac{\omega QH}{1000}$$

but $Q = AV$

where A is area through which water flows and V is the velocity of water.

$$\therefore \quad P = \frac{\omega AVH}{1000} = \frac{\omega AH}{1000}\sqrt{2gH}$$

as $V = \sqrt{2gH}$

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

or $P = K_1 H^{3/2}$

where K_1 is the coefficient which varies with the speed and gate opening

when $H = 1$, $P = K_1 = P_u$ (unit power by its definition)

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

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

2. Unit speed. This is defined as the speed of the turbine under a head of 1 metre

$$V = \frac{\pi DN}{60}$$

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

$$\therefore \quad N \propto \sqrt{H}$$

$$\therefore \quad N = K_2\sqrt{H}$$

where K_2 is the coefficient which varies with the conditions of running.

If $H = 1$ then $N = K_2 = N_u$ (unit speed by its definition)

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

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

3. Unit quantity. This is defined as the volume of water passing through the turbine under a head of 1 metre

$$Q = AV$$

$$Q \propto \sqrt{H} \qquad \text{as } V = \sqrt{2gH}$$

and A is constant for given turbine

$$\therefore \quad Q = K_3\sqrt{H}.$$

If $H = 1$ then $Q = K_3 = Q_u$ (unit quantity by its definition)

$$\therefore \quad Q = Q_u\sqrt{H}$$

$$\therefore \quad Q_u = \frac{Q}{\sqrt{H}}$$

If the question of reducing the performance of a turbine under head H to its performance under any other head H_o is required, then we can use the following equations.

$$\frac{P_o}{P} = \left(\frac{H_o}{H}\right)^{3/2}$$

$$\frac{N_o}{N} = \sqrt{\frac{H_o}{H}}$$

and

$$\frac{Q_o}{Q} = \sqrt{\frac{H_o}{H}}$$

The principle of similarity is applied to the turbines in order to predict the performance of actual prime movers from the tests on the model.

The vane angle at inlet and outlet will be same for model and prototype. The velocity triangles will also be identical for model and prototype when they are running under certain conditions.

The velocities are proportional to $\sqrt{H}$ for all similar turbines and hence :

(*a*) *Speed*

$$v = \frac{\pi dn}{60} \; \alpha \; \sqrt{h}. \text{ for model.}$$

and

$$V = \frac{\pi DN}{60}. \; \alpha \; \sqrt{H} \text{ for prototype.}$$

∴ From the above two equations, we can write

$$\frac{DN}{dn} = \sqrt{\frac{H}{h}}$$

or

$$\frac{N}{n} = \frac{d}{D}\sqrt{\frac{H}{h}} \qquad ...(4.14)$$

(*b*) *Quantity*

$$q = \pi db \, v_f \propto d^2 \sqrt{h} \text{ as } b \propto d \text{ and } v_f \propto \sqrt{h}$$

and

$$Q = \pi DBV_f \propto D^2 \sqrt{H}$$

∴

$$\frac{Q}{q} = \left(\frac{D}{d}\right)^2 \sqrt{\frac{H}{h}} = \left(\frac{D}{d}\right)^2 \cdot \frac{DN}{dn} = \left(\frac{D}{d}\right)^3 \cdot \frac{N}{n} \qquad ...(4.15)$$

(*c*) *Power*

$$p = \frac{\omega_m qh}{1000} \cdot \eta_m \propto \omega_m \, . \, d^2 \sqrt{h}. \, h \, . \, \eta_m$$

and

$$P = \frac{\omega_p QH}{1000} \cdot \eta_p \propto \omega_p \, . \, D^2 \sqrt{H}. \, H \, . \, \eta_p$$

∴

$$\frac{P}{p} = \frac{\omega_p}{\omega_m} \cdot \left(\frac{D}{d}\right)^2 \cdot \left(\frac{H}{h}\right)^{3/2} \cdot \frac{\eta_p}{\eta_m}$$

$$= \frac{\omega_p \eta_p}{\omega_m \eta_m} \cdot \left(\frac{D}{d}\right)^2 \cdot \left(\frac{H}{h}\right)^{3/2} = \frac{\omega_p \eta_p}{\omega_m \eta_m} \cdot \left(\frac{D}{d}\right)^2 \cdot \left(\frac{DN}{dn}\right)^3$$

$$= \frac{\omega_p \eta_p}{\omega_m \eta_m} \cdot \left(\frac{D}{d}\right)^5 \left(\frac{N}{n}\right)^3$$

If

$$\omega_p = \omega_m$$

∴

$$\frac{P}{p} = \frac{\eta_p}{\eta_m} \cdot \left(\frac{D}{d}\right)^5 \left(\frac{N}{n}\right)^3 \qquad ...(4.16)$$

If

$\eta_p = \eta_m$ which is not the general case

∴

$$\frac{P}{p} = \left(\frac{D}{d}\right)^2 \left(\frac{H}{h}\right)^{3/2} = \left(\frac{D}{d}\right)^5 \left(\frac{N}{n}\right)^3 \qquad ...(4.17)$$

(*d*) The specific speed for model and prototype should also be same

$$\therefore \quad N_s = n_s$$

$$\therefore \quad \frac{N\sqrt{P}}{(H)^{5/4}} = \frac{n\sqrt{P}}{(h)^{5/4}} \qquad ...(4.18)$$

The capital notations are used for prototype turbine whereas the small notations are used for model.

The above five equations are generally used for deciding the quantities required for model or the quantities for prototype if the test data of the model is available.

4.13. SELECTION OF TURBINE

The major problem confronting the engineering is to select the type of turbine which will give maximum economy. The hydraulic prime-mover is always selected to match the specific conditions under which it has to operate and attain maximum possible efficiency.

The choice of a suitable hydraulic prime-mover depends upon various considerations for the given head and discharge at a particular site of the power plant. The type of the turbine can be determined if the head available, power to be developed and speed at which it has to run are known to the engineer beforehand.

The following factors have the bearing on the selection of the right type of hydraulic turbine which will be discussed separately.

(1) Rotational Speed. (2) Specific Speed. (3) Maximum Efficiency. (4) Part Load Efficiency. (5) Head. (6) Type of Water. (7) Runaway Speed. (8) Cavitation. (9) Number of Units. (10) Overall Cost.

1. Rotational speed. In all modern hydraulic power plants, the turbines are directly coupled to the generator to reduce the transmission losses. This arrangement of coupling narrows down the range of the speed to be used for the prime-mover. The generator generates the power at constant voltage and frequency and, therefore, the generator has to operate at its synchronous speed. The synchronous speed of a generator is given by

$$N_{sync} = \frac{60f}{p}$$

where f = Frequency and p = Number of pairs of poles used. For the direct coupled turbines, the turbine has to run at synchronous speed only. There is less flexibility in the value of N_{sync} as f is more or less fixed (50 or 60 cycles/sec). It is always preferable to use high synchronous speed for generator because the number of the poles required would be reduced with an increase in N_{sync} and the generator size gets reduced. Therefore, the value of the specific speed adopted for the turbine should be such that it will give synchronous speed of the generator.

The problems associated with the high speed turbines are the danger of cavitation and centrifugal forces acting on the turbine parts which require robust construction. No doubt, the overall cost of the plant will be reduced adopting higher rotational speed as smaller turbine and smaller generator are required to generate the same power. The constructional cost of the power house is also reduced.

2. Specific speed. The equation (3) indicates that a low specific speed machine such as impulse turbine is required when the available head is high for the given speed and power output. On the other hand, propeller turbines with high specific speed are required for low-heads.

The specific speed can be calculated using the equations (4.18) and (4.19) if the available head is known. The specific speed versus head are shown in Fig. 4.46 for different turbines.

It is obvious from Fig. 4.46 that there is a considerable latitude in the specific speed of runners which can be used for given conditions of head and power provided that the height of the runner above tailrace level is such as to avoid the danger of cavitation as discussed earlier.

In all modern power plants, it is common practice to select a high specific speed runner because it is more economical as the size of the turbo-generator as well as that of power house will be smaller.

High specific speed is essential when the available head is low and power output is high because otherwise the rotational speed will be very low and it will increase the cost of turbo-generator and the power house as the sizes of turbine, generator and power house required at low speed will be large. On the other hand, there is no need of choosing high specific speed runner when the available head is sufficiently large because even with low specific speed, high rotational speeds can be attained.

Now it has been shown with the above discussion that if the speed and power under a given head are fixed (N_s is fixed), the type of the runner required is also fixed.

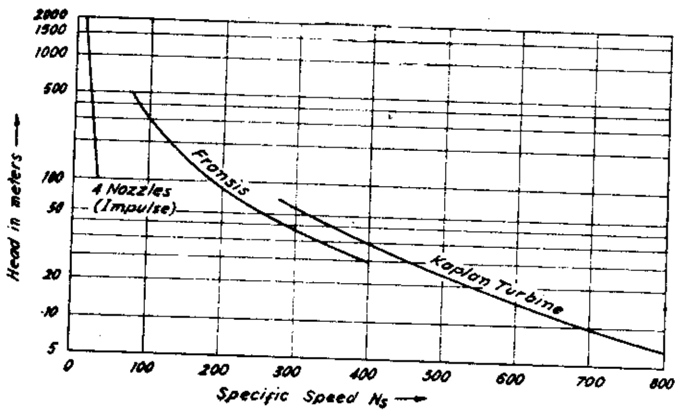


Fig. 4.46. Head *vs.* Specific speed of Turbines.

In practice, it may be possible to vary the specific speed through a considerable range of values. The speed and power required may be varied for a single runner and the choice is made wider.

Suppose turbine of a given power runs at 120 r.p.m. or at 900 r.p.m. and say available head is 200 metres, if the power is developed in a single unit at 120 r.p.m. is 18000 H.P. the required specific speed of the runner is given by

$$N_s = \frac{120\sqrt{18000}}{(200)^{5/4}} = \frac{120 \times 189.6}{750} = 30.4$$

Now if the same power is developed at 900 r.p.m. in two runners, the required specific speed of the runner is given by

$$N_s = \frac{900\sqrt{18000}}{(200)^{5/4}} = \frac{900 \times 134}{750} = 161$$

The above calculations show that the required power can be developed either with one impulse turbine (Pelton) or two reaction turbines (Francis).

It is customary to choose a speed between certain limits, as neither a very low nor a very high r.p.m. is desirable. The number of units into which a given power is divided is also limited. Nevertheless considerable latitude is left concerning the choice of the prime-mover and number of units used. Ultimately the choice of prime-mover is a matter of extensive experience instead of paper calculation.

3. Maximum Efficiency. The maximum efficiency, the turbine can develop, depends upon the type of the runner used.

In case of impulse turbine, low specific speed is not conducive to efficiency, since the diameter of the wheel becomes relatively large in proportion to the power developed so that the bearing friction and windage losses tend to become too large in percentage value. The value of N_s for highest efficiency is nearly 20.

The low specific speed of reaction turbine is also not conducive to efficiency. The large dimensions of the wheel at low specific speed contribute disc friction losses. In addition to this the leakage loss is more as the leakage area through the clearance spaces becomes greater and the hydraulic friction through small bracket passages is larger. These factors tend to reduce the efficiency as small values of specific speed are approached.

The high specific speed reaction turbines are associated with large discharge losses ($V_c^2/2g$) as mentioned earlier. The friction and leakage losses are reduced with an increase in specific speed but the discharged losses increase rapidly and the net effect of increase in specific speed is to decrease the efficiency. Total loss (friction, leakage and discharge) is minimum at medium specific speed. Therefore, it is always preferable to select the reaction turbines of medium specific speed if they operate at constant load conditions.

The effect of specific speed on the maximum efficiency is shown in Fig. 4.47.

Higher efficiencies have been attained with reaction turbines than with Pelton wheels. The maximum recorded efficiency till now for reaction turbine is 93.7% but quite a large units have shown efficiencies over 90%. The highest recorded value of efficiency for impulse turbine is 89% but usual maximum is 82%.

The efficiency of the Pelton wheel is not dependent on its size-like reaction turbine. Hence the Pelton wheel may have higher maximum efficiency than the reaction turbine for smaller powers.

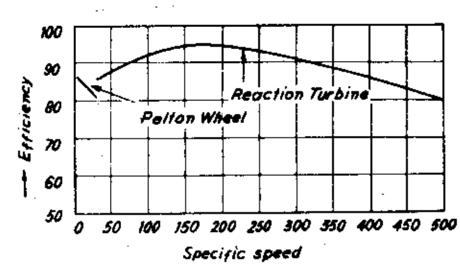


Fig. 4.47. Effect of specific speed on the efficiency of the turbines.

4. Part Load Efficiency. Full load is defined as the load under which a turbine develops its maximum efficiency. Anything above that is known as overload and anything below that is known as part load.

The part load effciency differs greatly for different specific speed and types of turbines. Fig. 4.48 shows the variations in part load efficiencies with different types of wheels.

In case of Pelton wheel, only the jet diameter through which the water flows is reduced by the governing mechanism when the load on the turbine is reduced below full load. The velocity diagrams at inlet and outlet remain practically unaltered in shape at all loads except for very low and very high loads. Thus the absolute velocity at inlet does not change and discharge loss remains same. Therefore, the part load efficiency curve is more flat in case of Pelton turbine.

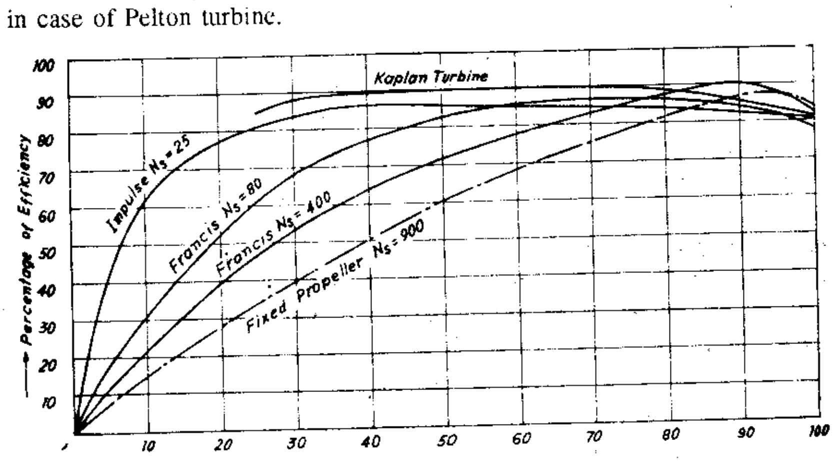


Fig. 4.48. Effect of load on the efficiency of turbine (Different Turbines).

In case of reaction turbine, the water completely fills the bucket passage and a reduced rate of discharge (required at part load) requires a proportionate reduction in the relative velocity at outlet. Thus the absolute velocity at outlet and discharge loss are inevitably increased. Therefore, the efficiency decreases with decrease in load on the turbine.

The higher the specific speed of the turbine, the greater the discharge loss at the normal gate opening and hence greater the effect produced upon the efficiency as shown in Fig. 4.48.

The part load characteristics of Francis turbines may affect the choice of the type of the wheel to be used. For a plant with variable load, the advantages of the higher specific speed wheel may be offset by lower part load efficiencies. If a constant speed is selected which is best for full load, there will be sacrifice of efficiency at part load conditions and this sacrifice will be greater as the specific speed of the turbine is higher. The high specific speed Francis turbines are suitable for low head plants but are unsuitable when required to operate under part load conditions.

The efficiency versus load curve remains constant for Kaplan turbine as the blade angle is adjusted according to the load on the turbine, therefore, this turbine is more suitable than Pelton when the load on the turbines changes from minimum to maximum.

5. Head. The choice of the turbine is a function of power and speed desired as well as the head also. Head plays a predominating influence, therefore, the choice of the turbine depends upon the available head. The relationship between the two is given by the equations (4.3) and (4.4).

The Pelton wheels are preferred generally in the range of 200 m to 2000 m head. The example of high head plant is Reisseck plant in Austria where the head is 5800 ft. (1800 m) and another example is Dixence Station in Switzerland where the head is 1740 metres. The Pelton wheel is not well adopted where the tailrace level varies appreciably and if adopted, must be installed above the highest tail water level with some sacrifice of head.

The reaction turbine is generally used for the heads between 15 metres and 250 metres. The reaction turbine can be used with variable head as it tends itself readily to the use of draft tube and it may be drowned without any loss of efficiency. The efficiency of reaction turbine is not much sensitive to the changes of head as that of Pelton turbine. The percentage variation in head is usually greater in low head plants and this is the reason for not adopting the Pelton turbines for low head plants. The maximum head for the reaction turbine is limited to 1000 ft. (330 m) because of possible danger of cavitation and difficulty of building casings, to withstand such high pressures. By using high speed reaction turbine (high N_s), the runner size and overall cost of the power plant is reduced. However, there is some loss of efficiency at high specific speed. The present trend is to use a runner of high specific speed sacrificing some efficiency.

The propeller turbines are used in the range of 5 m to 30 m head. The maximum head utilised for Kaplan is 230 ft. (70 m) in Bort Rhuet power plant in France with a rating of 31800 H P. Propeller turbines are commonly used upon 15 m head but only when there are practically no load variations.

6. Types of water available. The reaction turbines are not suitable for high head plants when the water carries undue amount of dirt and sand, because its runner cannot withstand the erosive action of the water. Its use is further restricted because the water ways are of very small sectional area and easily become choked by floating debris and fluid frictional losses become relatively high.

The greater simplicity and accessibility of the parts requiring replacement due to normal wear and tear or due to the chemical action of water renders Pelton wheel more suitable when the supply is taken from a stream carrying an appreciable amount of grit or silt in suspension or the water from chemical industries are discharged in the river and carried in the prime movers.

7. Runaway speed. In selecting a runner, consideration must be given to the relation between the characteristics of the turbine and generator as mentioned earlier.

The speed of the turbine increases with increase in head. The percentage change in head in low head plants is much more than in high head plants and, therefore, the turbine speed shoots up when the acting head increases. Therefore, the generator must be designed to stand the full runaway speed of turbine to which it is connected under maximum head conditions.

The reaction turbine will reach about 193% of its normal speed if the head on the turbine reaches 15% above normal. For fix blade propellers, the maximum runaway speed is as high as 250% of its normal speed. Higher the runaway speed of the turbine, the greater will be the cost of the machines as they should be designed to withstand abnormal stresses which occur hardly for a small period of the year.

The percentage runaway speed and percentage increase in power versus percentage rated head are shown in Fig. 4.49. The propeller runaway speed is 20% greater than the Francis runaway speed as can be seen from the figure.

Presently the operation of hydraulic turbines frequently involves the injection of air into the centre of the water stream before or after the runner. The purpose of air injection is to reduce the dynamic forces during times of runaway operation. The air injection can result in an increase in runaway speeds of upto 20%. In most cases, air injection has beneficial effects but under normal operating conditions, the air while suppressing pressure pulsations and vibration can also reduce the power output by as much as 1 to 3%.

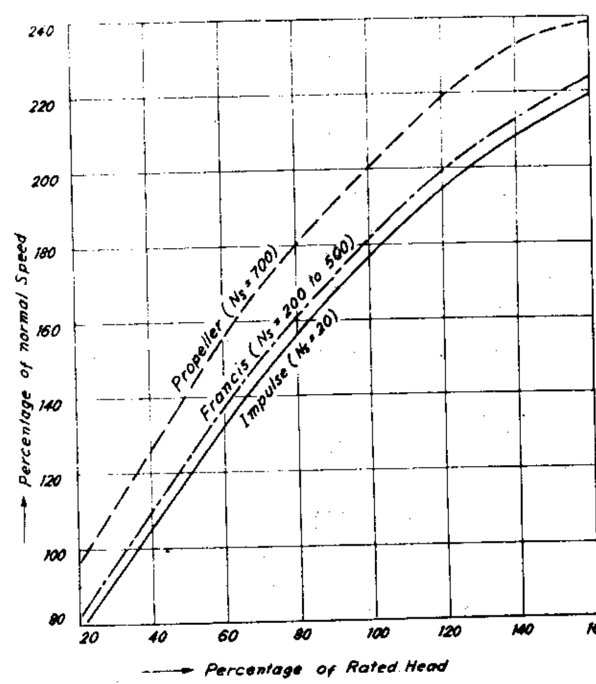


Fig. 4.49. Effect of head on runaway speed.

8. Cavitation. The use of runner having higher specific speed greater than the recommended values may result in cavitation. This may be avoided by setting the runner at a lower elevation from the tailrace.

If the cavitation occurs, the runner blades of 2.5 cm thick may be corroded within a year's operation. The usual method to repair is welding of corroded parts. The dense metals like cast steel and stainless steel resist better to cavitation than porous materials like cast iron.

The safe height of setting the runner above tailrace level varies with head and specific speed. Many times, the runner must be located under tailrace level (high speed Kaplan or Francis turbine used in low head plant) to avoid the cavitation. It is always desirable and economical to repair, once in a year, by welding the damages done by cavitation than to prevent cavitation.

9. Number of units. The average overall efficiency of large plant is influenced by the number of units installed. A plant with two similar units would have better value of average efficiency than with one unit of double the size of single unit. The plant containing three or more units would have still better average efficiency though an improvement is not as marked as when one unit is replaced by two.

Multiunit plant can meet large variations of load more economically as more units work at full load and only one unit works under variable load to take the fluctuating load.

The present trend is to use a single unit of big size instead of two or more units to reduce the capital cost and running expenses. The selection of number of units to be installed is left as a management and economic problem rather than a design problem.

The effect of increasing the number of units for the same generation of power on efficiency is shown in Fig. 4.50.

10. Overall cost of the plant. The plant should be designed for the minimum cost as cost is the prime consideration in designing a plant. The total cost consideration should include the capital cost and running cost. The design should generate the power with minimum cost.

4.14. GOVERNING OF TURBINES

Modern hydraulic turbines are directly coupled with generators which are designed to run at constant speed. The speed of the generator is fixed by number of pair of poles and required frequency as mentioned earlier. The frequency of the generation cannot be allowed to vary for electrical reasons. Therefore, the speed of the generator for the given number of pair of poles must remain constant at all loads. This requirement calls for governor to maintain the constant speed of turbine generator unit at all loads. This is done by supplying the water to the turbine in proportion to the load on generator.

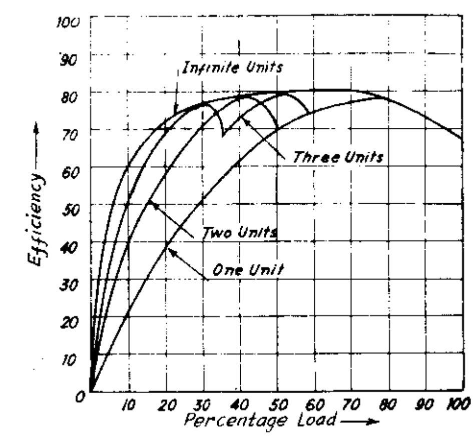


Fig. 4.50. Effect of load on the efficiency of a turbine taking number or units as parameter.

In Pelton turbines, the governor opens or closes partly the needle valve to vary the supply quantity of water to the turbine according to the load. In Francis Turbine, the governor closes or opens the guide vanes allowing the quantity of water flow according to the load. In case of Kaplan turbine, the governor controls the opening of the guide vanes and in addition to that, the blade movement is also changed.

The governor should be designed in such a way to keep the speed rise of runner and pressure rise in the penstock within the safe limits.

In order to save the pipe line from water hammer effects, the turbines are equipped with a safety device operated by the governor. A deflector in Pelton turbine and pressure relief valve in Reaction turbine are commonly used for the purpose mentioned above.

Like other governors, the governor used for hydraulic turbines also uses the centrifugal force of rotating balls to actuate the governing mechanism. But the force required for the operation of gates in reaction turbine and needle valve in Pelton wheel is considerably large. The energy required to operate the governor of small hydraulic turbine is of the order of 40000 Nm per stroke of piston while in large turbines it is of the order of 30,0000 Nm.

The centrifugal force of the flyball is used only to operate the relay which will further operate the regulating mechanism. The regulating mechanism used in hydraulic turbines is known as Servomotors.

1. Governing of Pelton Turbine. The line diagram of the governing system is shown in Fig. 4.51. This system known as "Servo-mechanism" consists of a needle having a streamlined head sliding axially within the nozzle. The space between the nozzle and needle valve through which water is supplied to the turbine is reduced as the needle valve moves forward. It cannot be moved to close the nozzles rapidly without loss of energy, therefore, the governing system is always supplemented with a deflector. The movement of the needle in the nozzle according to the load is controlled by the piston which is actuated by high pressure oil.

A servo-motor consists of a piston operating in a cylinder as shown in figure. The motion of the piston in the cylinder is controlled by oil pressure supplied from gear-pump and the piston's motion is further transmitted to the needle valve to control the supply of water to the Pelton wheel according to the load on the turbine.

The function of the governor is to control the motion of piston in a control valve. The function of the control valve is to control the supply of high pressure oil to either direction of the servo-motor cylinder.

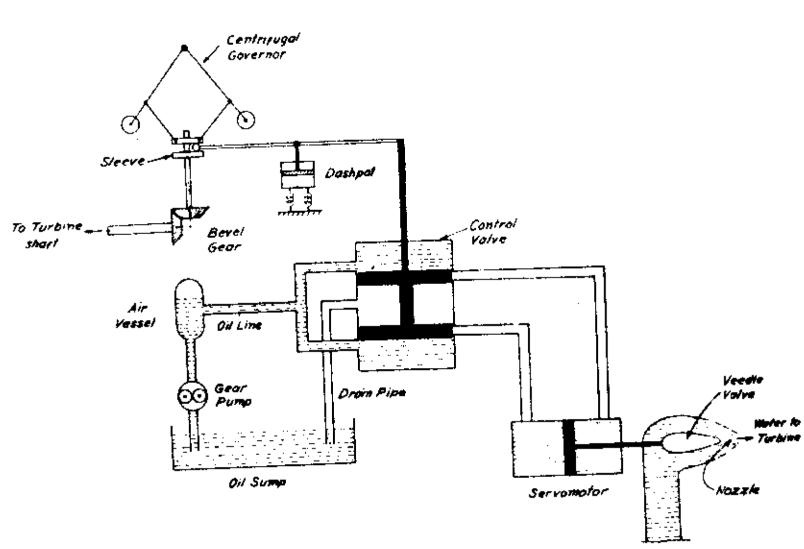


Fig. 4.51. Servo-Motor Mechanism for controlling the speed of Pelton Wheel. (Normal Position of the Mechanism is shown when the Pelton wheel runs at designed speed and designed load.)

The function of gear pump and air vessel is to supply the oil at high pressure without fluctuations to the control valve.

The function of the dash pot is to prevent sudden opening-out or closing-in of flyballs and thus acts as a damping device.

The working of the system is explained as follows.

Figure 4.52 shows the normal position of the Servo-motor mecnanism when the Pelton wheel runs at designed speed and designed load.

When the load on the turbine decreases, the speed of the turbine will start increasing and this also increases the speed of the governor which is directly connected to the turbine shaft. The balls of the governor fly outward due to the increase in governor speed and lift the piston upwards. This motion of piston allows the high pressure oil to flow to the left-side of the servo-motor piston as shown in Fig. 4.52 (*a*) and it pushes the piston towards the right and closes the nozzle partly which helps to restore the normal speed of the Pelton wheel.

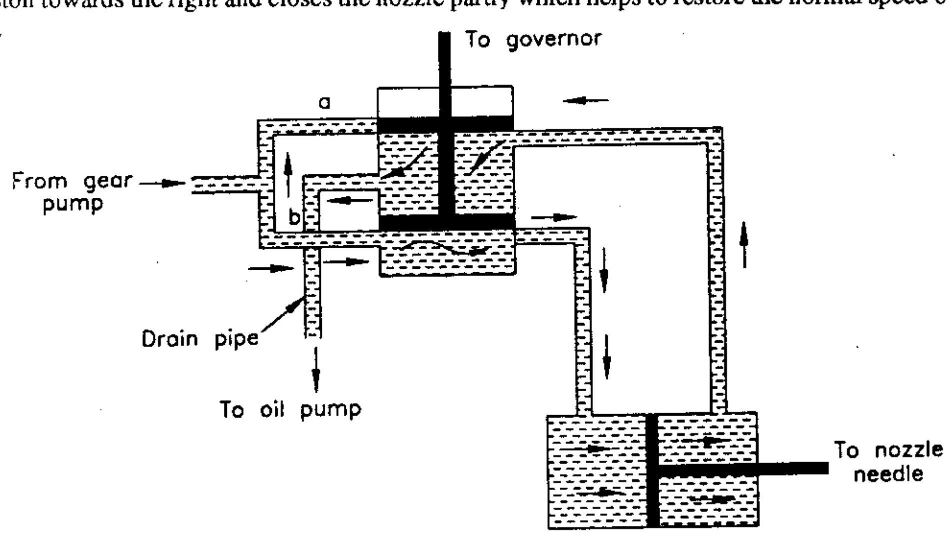


Fig. 4.52 (*a*). Motion of control valve and Servo-motor when load on the Generator increases. (Nozzle is partly closed).

When the load on the turbine increases, the speed of the turbine will start decreasing and this also decreases the speed of the governor. The balls of the governor fly inward due to the decrease in governor speed and push the piston valve downward. This motion of piston in the control valve allows the high pressure oil to flow to the right side of the servo-motor piston as shown in Fig. 4.52 (*b*) and it pushes the piston towards the left and opens the nozzle partly which helps to restore the normal speed of the Pelton wheel. As the piston in servo-motor moves towards the left, the liquid which was present already in left portion of the servo-motor cylinder is pushed to the oil sump through the drain pipe as shown in Fig. 4.52 (*b*).

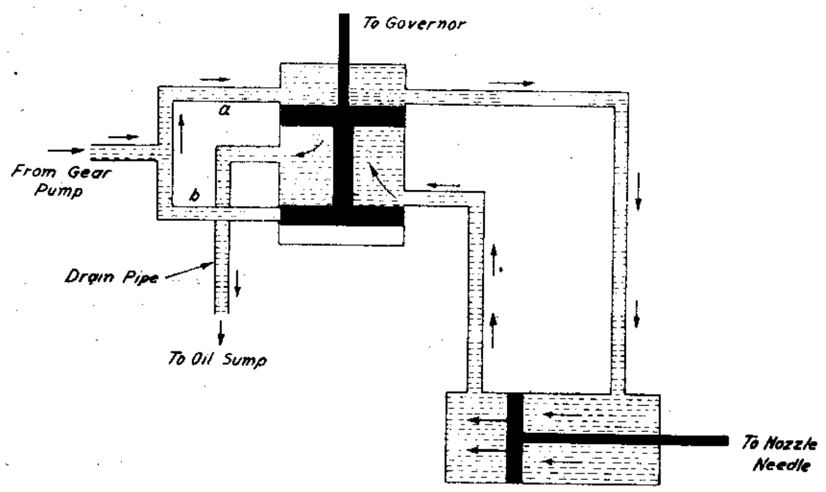


Fig. 4.52 (*b*). Motion of control valve and Servo-motor when the load on the Generators (Nozzle) is decreases.

The needle valve regulation described is used only for small load fluctuations and small capacity turbines. When there is sudden fall of load, the needle valve has to move rapidly to close the nozzle and rapid closing may result in water hammer as mentioned earlier. This is more serious in large capacity plants with long penstocks.

To avoid the water hammer effects due to rapid closing of nozzle during sudden fall of load, A deflector is introduced in the system (not shown in figure). The function of the deflector is to deflect the jet from the turbine runner when the load on turbine suddenly decreases. In this case, the quantity of water passing through the nozzle remains same but the part of water coming out from the nozzle is deflected and is not allowed to strike the bucket. The deflected water goes waste into the tailrace level.

The deflector comes into operation first with the decrease in load and prevents the rise in speed of the turbine. The needle valve closes the opening of the nozzle gradually and avoids the undue rise of pressure. This combined operation of nozzle and deflector reduces the danger of heavy water hammer and minimises the wastage of water.

The combined system is most commonly adopted in all modern power plants.

Governing of Francis Turbine. The governing of Francies turbine is exactly similar to the governing of Pelton wheel except the motion of the piston in servo-motor is used to close or open partly the guide vanes gate through which the water is supplied to the turbine instead of needle valve in the nozzle of Pelton turbine.

The working of the governor is shown in Fig. 4.53. The position of the control valve and servo-motor corresponds to the designed load on the turbine.

The working of the servo-motor and control valve is exactly same as described in the governing of Pelton wheel.

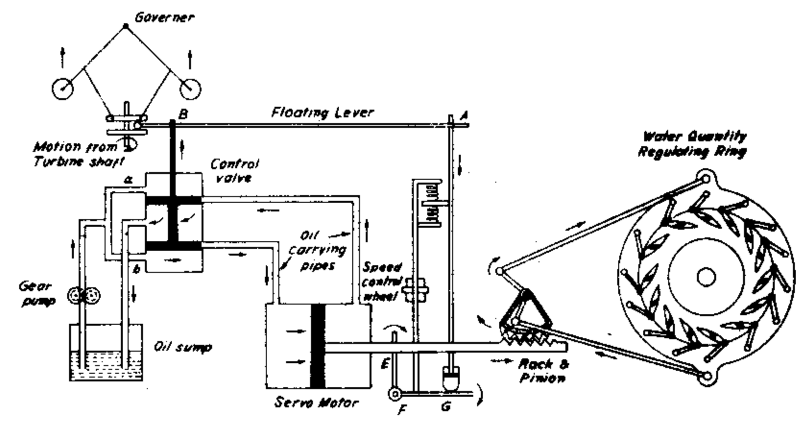


Fig. 4.53. The governing of Francis Turbine. The position of components is shown when the turbine runs at designed load and design speed. The arrows show the flow of oil and motion of different parts of the governing system when the load on the turbine decreases.

A compensating device which is not shown in the governing of Pelton wheel is shown in the governing of Francis turbine.

When the Servo-motor piston moves right as shown in Fig. 4.52 (*a*), the bell-crank level *EFG* as shown in Fig. 4.53 which is attached to the piston rod of Servo motor at *E* is rotated downward about *F* and the arm *G* is lowered. This pulls down the pivot *A* and causes the fulcrum *B* to be lowered. Thus the relay port '*b*' is again closed and stops the motion. This action prevents the governor from overtravelling. The device which prevents the overtravelling of the governor is known as compensating device. Without the compensating device, the Servo-motor piston would continue to move in the same direction and would advance beyond the required point. Finally when the flow conditions become readjusted for the new load, the governor would then move back to other side of the proper place and remains steady.

The compensating device described with the governing of Francis turbine is also necessary required for Pelton wheel.

The wheel *W* shown in Fig. 4.53 has right-hand and left-hand threads in it. By turning it, the length of rod can be changed and hence the relay valve is raised or lowered varying the turbine speed.

4.15. ADVANTAGES OF HYDRO-ELECTRIC POWER PLANTS

Hydroelectric power plants offer some inherent advantages over other types of power plants which make them attractive. Few of these advantages are listed below :

1. It is a renewable source of energy. The water, operating fluid, is neither consumed nor is converted into something else. It is lifted from low level to high level naturally by the use of solar energy. Therefore the generating and operating cost of the plant is considerably lower.

2. It does not pose the problem of air pollution as in the case of thermal plant and radiation hazards and waste disposal as in the case of nuclear plants.

3. It is well suited for use as peak load plant as it responds quickly to changing loads and as its part load efficiency is considerably higher compared with other power plants.

The efficiency *vs.* load curve for different plants is shown in Fig. 4.54. Reduction in part load efficiency of hydro-plant is considerably less whereas there is a rapid fall of efficiency with reduction in load for all types of thermal power plants.

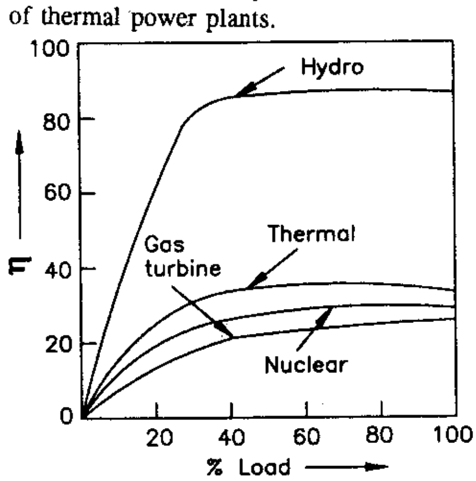


Fig. 4.54. Effect of load on efficiency for different power plants.

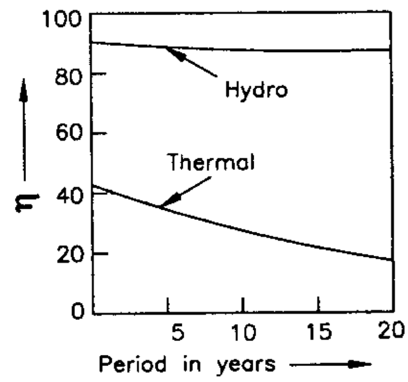


Fig. 4.55. Effect of period on efficiency of power plants.

Where peaking power is to be met for a fraction of day, there is nothing like hydro power. The extraordinary facility of switching on and off almost instantly of hydro-power plant is great asset in the combined power grid.

4. The life of hydro-plant is very long (few centuries) compared with thermal plants (few decades). This is because, the hydroplants operate at atmospheric temperature whereas thermal plants operate at considerably high temperatures (500—800°C).

5. There are no standby losses which are unavoidable for thermal and nuclear plants.

6. The efficiency of the hydel plant does not fall rapidly with respect to time as shown in Fig. 4.55 as the deterioration of hydro-equipments is less compared with thermal plant equipments.

7. Hydro-power projects also provide additional benefits like recreation, fishery, irrigation and flood control.

8. The water storage of the hydro-plant can also be used for domestic water supply and to provide cooling water needed for steam or nuclear power plants.

In all, hydel power plants include simplicity in design, low maintenance cost, absence of pollution, and zero fuel cost.

Some of the disadvantages are listed below :

1. It requires huge capital and long period for its *completion* (10-15 years) compared with the period required for thermal plants (3-5 years).

2. Power generation capacity is totally dependent on the quantity of water available which depends on the natural phenomena. The dry year affects the hydro-power generation considerably.

3. The sites of hydro-power plants are generally away from load centres. Therefore, transmission of power to the load centres requires large investment in transmission line and it causes loss of power during transmission.

Comparing the hydro-plants with other power plants, it should be considered as a complement to the thermal plants and not as a competitor as it plays the important role of providing peak power with minimum generation cost in the common national grid.

Water being a perennial source of energy, it is absolutely necessary for the country's prosperity to develop and use this source to the maximum extent.

SOLVED PROBLEMS

The following formulae are used for solving problems.

(1) $$N_s = \frac{N\sqrt{P}}{(H)^{5/4}} = 265\frac{d}{D}\sqrt{\eta} \text{ (for single jet Pelton) where } P \text{ is in kW}$$

(2) $$N_s = \frac{6800}{H+9.7} + 84.5 \text{ (for Francis)}$$

$$N_s = \frac{9440}{H+9.7} + 156 \text{ (for Propeller)}$$

$$N_s = 1.1\left[\frac{9440}{H+9.7} + 156\right] \text{ (for Kaplan).}$$

(3) $$\frac{p_c}{w} = \frac{p_a}{w} - \left[h + \left(\frac{V_c^2 - V_a^2}{2g}\right) - h_f\right]$$

or $$h = \frac{(p_a - p_c)}{w} - \frac{V_c^2 - V_a^2}{2g} + h_f$$

$$= \left(\frac{p_a - p_c}{w}\right) - \frac{V_c^2}{2g} + \left(\frac{V_a^2}{2g} + h_f\right).$$

(4) $$P_u = \frac{P}{H\sqrt{H}}$$

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

$$Q_u = \frac{Q}{\sqrt{H}}$$

(5) $$\frac{N}{n} = \frac{d}{D}\sqrt{\frac{H}{h}}$$

$$\frac{Q}{q} = \left(\frac{D}{d}\right)^2 \cdot \sqrt{\frac{H}{h}} = \left(\frac{D}{d}\right)^3 \cdot \left(\frac{N}{n}\right)$$

$$\frac{P}{p} = \frac{\eta_p}{\eta_m} \cdot \left(\frac{D}{d}\right)^2 \left(\frac{H}{h}\right)^{3/2} = \frac{\eta_p}{\eta_m}\left(\frac{D}{d}\right)^5 \left(\frac{N}{n}\right)^3 \text{ where } P \text{ and } p \text{ stand for power}$$

(6) $$\text{Power} = \frac{w_p Q H}{1000} \times \eta_p \text{ (for prototype)} = \frac{w_m q h}{1000} \times \eta_m \text{ (for model).}$$

(7) $$\text{Speed ratio} = \frac{\pi D N}{\sqrt{2gH}}$$

Problem 4.1. *A model of a water turbine develops 25 kW when working under a head of 5 m and running at 480 r.p.m. Find the power and r.p.m. of the actual turbine if working under a head of 40 metres. The model is 1/10th of prototype. Assume the efficiency of the model is equal to the efficiency of the prototype. Mention the type of turbine used for model.*

Sol. The following data is given

$$p = 25 \text{ kW},\ n = 480 \text{ r.p.m.},\ h = 5\ m,\ D/d = 10$$
$$H = 40\ m,\ P = ? \text{ and } N = ?$$

$$\frac{N}{n} = \frac{d}{D}\sqrt{\frac{H}{h}}$$

$$N = 480 \times \frac{1}{10} \cdot \sqrt{\frac{40}{5}} = \mathbf{136\ r.p.m.}$$

$$\frac{P}{p} = \left(\frac{D}{d}\right)^2 \cdot \left(\frac{H}{h}\right)^{3/2}$$

$$\therefore \quad P = 25(10)^2\left(\frac{40}{5}\right)^{3/2} = \mathbf{56600\ kW}$$

$$n_s = \frac{n\sqrt{p}}{(h)^{5/4}} = \frac{480\sqrt{25}}{(5)^{1.26}} = \frac{480 \times 5}{7.45} = \mathbf{322}$$

The runner is of propeller type.

As the model runner is same as prototype, therefore, the specific speed of prototype must be same as model.

$$\therefore \quad N_s = \frac{N\sqrt{P}}{(H)^{5/4}} = \frac{136\sqrt{56600}}{(40)^{1.25}} = \frac{136 \times 238}{100} = \mathbf{322}$$

Problem 4.2. *A model of Francis turbine developed 4.1 kW at a speed of 360 r.p.m. under a head of 1.8 m. Find the speed and power of a prototype machine when working under a head of 6 m. Also find the ratio of quantities of water flowing through the turbine. The model is 1/5th of prototype.*

Sol. The following data is given.

$$p = 4.1 \text{ kW},\ n = 360 \text{ r.p.m.},\ h = 1.8\ m,\ H = 6\ m,\ D/d = 5$$

Find out N and P.

$$\frac{N}{n} = \frac{d}{D}\sqrt{\frac{H}{h}}.$$

$$\therefore \quad N = 360 \times \frac{1}{5}\sqrt{\frac{6}{1.8}} = \mathbf{131\ r.p.m.}$$

$$\frac{P}{p} = \left(\frac{D}{d}\right)^2\left(\frac{H}{h}\right)^{3/2}$$

$$\therefore \quad P = 4.1(5)^2\left(\frac{6}{1.8}\right)^{3/2} = \mathbf{620\ kW}$$

$$\frac{Q}{q} = \left(\frac{D}{d}\right)^2 \cdot \sqrt{\frac{H}{h}} = (5)^2\sqrt{\frac{6}{1.8}} = \mathbf{45.5}$$

$N_s = n_s$ (required for model tested)

$$\therefore \quad \frac{N\sqrt{P}}{(H)^{5/4}} = \frac{n\sqrt{p}}{(h)^{5/4}}$$

$$\frac{131\sqrt{620}}{(6)^{5/4}} = \frac{360\sqrt{41}}{(1.8)^{5/4}}$$

$$\frac{131 \times 24.9}{94} = \frac{360 \times 2.02}{2.08}$$

349 = 349 (the turbine must be of propeller type).

Problem 4.3. *A model 1/10th of prototype in dimensions is to be constructed to determine the best design of a Kaplan turbine to devolop 10000 kW brake power under a head of 12 m. when running at 100 r.p.m. If the available head in the laboratory is 8 m find a) the running speed of the model and (b) B.P.*

Also find the flow quantity required if the model efficiency is 80% and specific speed of the runner.

Sol. The given data is

$$P = 10{,}000 \text{ kW}, H = 12 \; m, N = 100 \text{ r.p.m.},$$

$$\frac{D}{d} = 10 \text{ and } h = 8 \text{ m}, \eta_m = 80\%$$

Find out n, p and q

$$\frac{N}{n} = \frac{d}{D}\sqrt{\frac{H}{h}}$$

$$\therefore \quad n = 100 \times 10\sqrt{\frac{8}{12}} = \mathbf{815 \text{ r.p.m.}}$$

$$\frac{P}{p} = \left(\frac{D}{d}\right)^2\left(\frac{H}{h}\right)^{3/2}$$

$$\therefore \quad p = \frac{10{,}000}{100}\left(\frac{8}{12}\right)^{3/2} = \frac{100}{1.838} = \mathbf{54.5 \text{ kW}}$$

$$p = \frac{q \cdot wh}{1000} \times \eta_m$$

$$q = \frac{54.5 \times 1000}{1000 \times 9.81 \times 8 \times 0.8} = \mathbf{0.87 \text{ m}^3/\text{sec}}$$

$$N_s = n_s$$

$$\frac{N\sqrt{P}}{H^{5/4}} = \frac{n\sqrt{p}}{(h)^{5/4}}$$

$$\frac{100\sqrt{10{,}000}}{(12)^{1.25}} = \frac{815\sqrt{54{,}5}}{(8)^{1.25}}$$

$$\frac{100 \times 100}{22.4} = \frac{815 \times 7.37}{13.5} = \mathbf{445}$$

Problem 4.4. *A model testing is to be carried out to find the best design speed for a Francis turbine of 40,000 kW under a head of 240 m when running at 500 r.p.m. if the available head in the laboratory is 30 m and discharge is 150 litres/sec. Assuming the overall efficiency of 88%, find the scale ratio, running speed and power of the model. What is the type of the runner used for testing ? Take specific gravity of water = 1.1.*

Sol. The data given is

$$P = 40{,}000 \text{ kW}, N = 500 \text{ r.p.m.}, H = 240 \text{ m},$$

$$h = 30 \text{ m}, q = 150 \text{ litres/sec} = 150 \times 1.1 = 165 \text{ kg/sec} = \eta_m = 88\%$$

$$p = \frac{qwh}{1000}\eta_m = \frac{165 \times (1000 \times 9.81) \times 30}{1000 \times 1000} \times 0.88 = \mathbf{48.6 \text{ kW}}$$

$$\frac{P}{p} = \left(\frac{D}{d}\right)^2\left(\frac{H}{h}\right)^{3/2}$$

$$\therefore \quad \frac{D}{d} = \sqrt{\frac{40{,}000}{48.6}}\left(\frac{30}{240}\right)^{0.75} = 6$$

$$\frac{N}{n} = \frac{d}{D}\sqrt{\frac{H}{h}}$$

$$\therefore \quad n = 500 \times 6\sqrt{\frac{30}{240}} = \mathbf{1060\ r.p.m.}$$

$$N_s = n_s.$$

$$\frac{N\sqrt{P}}{H^{5/4}} = \frac{n\sqrt{p}}{h^{5/4}}$$

$$\frac{500\sqrt{40,000}}{(240)^{1.25}} = \frac{1030\sqrt{48.6}}{(30)^{1.25}}$$

$$\frac{500 \times 200}{940} = \frac{1030 \times 7.26}{70}$$

$$106.3 = 106.3$$

The runner is of Francis type.

Problem 4.5. *A model is to be designed to find the performance of a prototype Francis runner. The prototype turbine has to develop 50,000 kW under a head of 225 metres. The available head and flow in the laboratory for model testing are 36 m and 170 litres/sec. The prototype runner runs at 600 r.p.m. and assuming overall efficiency of 90%, calculate (a) suitable scale ratio for the model (b) power developed by the model (c) model runner speed.*

Sol. The given data is

$$P = 50,000 \text{ kW}, H = 225 \text{ m}, N = 600 \text{ r.p.m.},$$

$$h = 36 \text{ m}, q = 170 \text{ litres/sec}, \eta_p = \eta_m = 90\%$$

$$P = \frac{QwH}{1000}\eta_m$$

$$50,000 = \frac{Q \times 1000 \times 9.81 \times 225}{1000} \times 0.9$$

$$\therefore \quad Q = \frac{50,000 \times 1000}{1000 \times 9.81 \times 225 \times 0.9} = \mathbf{25.17\ m^3/sec}$$

$$\frac{Q}{q} = \left(\frac{D}{d}\right)^2\sqrt{\frac{H}{h}}$$

$$\because \quad \frac{25.17}{0.17} = \left(\frac{D}{d}\right)^2\sqrt{\frac{225}{36}}$$

$$\therefore \quad \left(\frac{d}{D}\right)^2 = \sqrt{\frac{225}{36}} \times \frac{0.17}{25.17} = \frac{1}{43.5}$$

$$\therefore \quad \frac{d}{D} = \frac{1}{4.86}$$

$\therefore$ The model size is $(1/4.86)^{th}$ of prototype

$$\frac{P}{p} = \left(\frac{D}{d}\right)^2\left(\frac{H}{h}\right)^{3/2}$$

$$\therefore \quad p = 50,000 \times \left(\frac{1}{4.86}\right)^2 \times \left(\frac{36}{225}\right)^{1.5} = \mathbf{135.7\ kW}$$

$$\frac{N}{n} = \frac{d}{D}\sqrt{\frac{H}{h}}$$

$$\therefore \qquad n = 600 \times 4.86\sqrt{\frac{36}{225}} = \mathbf{1167\ r.p.m.}$$

Problem 4.6. *The quantity of water available for hydroelectric station is 260 m³/sec under a head of 1.7 m. Assuming the speed of the turbine 50 r.p.m. and its efficiency of 82.5%, determine the number of turbine units required. Assume the specific speed of 890.*

Sol. Total power to be developed can be calculated using the following equation.

$$P = \frac{QwH}{1000} \times \eta_p = \frac{1000 \times 9.81 \times 260 \times 1.7}{1000} \times 0.825 = \mathbf{4336\ kW}$$

The power developed by each turbine unit can be calculated by using the following equation.

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

$$890 = \frac{50\sqrt{P}}{(1.7)^{1.25}}$$

$$\therefore \qquad \sqrt{P} = \frac{890 \times (1.7)^{1.25}}{50} = 34.5$$

$$\therefore \qquad P = \mathbf{1192\ kW}$$

$\therefore$ Number of Kaplan turbines required

$$= \frac{4336}{1192} = 3.63 \approx \mathbf{4.}$$

Problem 4.7. *A run-off rate of 400 m³/sec and head of 45 m is available at a site proposed for hydro electric power plant. Assuming the turbine efficiency of 90% and speed of 250 r.p.m., find the least number of machines, all of equal size required if (a) Francis turbine not greater than 200 specific speed or (b) Kaplan turbine not greater than 600 specific speed is used.*

Sol. $$\text{Power} = \frac{wQH}{1000} \times \eta = \frac{1000 \times 9.81 \times 400 \times 45}{1000} \times 0.9 = \mathbf{159 \times 10^3\ kW}$$

(*a*) $$N_s = \frac{N\sqrt{P}}{H^{5/4}} \qquad ...(1)$$

Consider Francis turbine and substituting the values in the equation (1).

$$200 = \frac{250\sqrt{P}}{(45)^{1.25}}$$

$$\therefore \qquad \sqrt{P} = \frac{200}{250} \times (45)^{1.25} = 118$$

$$\therefore \qquad P = \mathbf{13950\ kW}$$

$\therefore$ Number of Francis turbines required $= \dfrac{159 \times 10^3}{13950} = 11.4 \approx \mathbf{12}$

Now considering the Kaplan turbine and substituting the values in the equation (1).

$$600 = \frac{250\sqrt{P}}{(45)^{1.25}}$$

$$\therefore \quad \sqrt{P} = \frac{600}{250} \times (45)^{1.25} = \frac{600}{250} \times 118 = 285$$

$$\therefore \quad P = 80 \times 10^3$$

$$\therefore \text{ Number of Kaplan runners used} = \frac{159 \times 10^3}{80 \times 10^3} = 1.99 = \mathbf{2}$$

The installation of Kaplan turbine is more economical than Francis turbine as number of units required is less.

Problem 4.8. *The available discharge and head at a proposed site of hydro-electric power plant is 340 m³/sec and 30 m respectively. The turbine efficiency is 88%. The generator is directly connected to the turbine. The frequency of generation is 50 cycles/sec and number of poles used are 24. Find least number of machines required if (a) A Francis turbine with a specific speed of 300 is used (b) A Kaplan turbine with a specific speed of 800 is used.*

Solution. As the generator is directly coupled to the turbine, the speed of turbine used must be equal to the synchronous speed of the generator.

$$\therefore \quad N = \frac{120f}{\text{No. of Poles}} = \frac{120 \times 50}{24} = \mathbf{250 \ r.p.m.}$$

$$P = \frac{wQH}{1000} \times \eta = \frac{1000 \times 9.81 \times 340 \times 30}{1000} \times 0.88 = \mathbf{100 \times 10^3 \ kW}$$

The power capacity of each Francis turbine can be calculated by using the following formula

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

$$300 = \frac{250\sqrt{P}}{(30)^{1.25}}$$

$$\therefore \quad \sqrt{P} = \frac{300}{250} \times (30)^{1.25} = \frac{300}{250} \times \frac{70}{1} = 84$$

$$\therefore \quad P = \mathbf{7056 \ kW}$$

$$\therefore \text{ Number of Francis turbines required} = \frac{100 \times 10^3}{7056} = 14.2 = \mathbf{15}$$

The power capacity of each Kaplan turbine can be calculated by using the following formula.

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

$$800 = \frac{250\sqrt{P}}{(30)^{1.25}}$$

$$\therefore \quad \sqrt{P} = \frac{800}{250} \times (30)^{1.25} = \mathbf{244}$$

$$\therefore \quad P = \mathbf{5.98 \times 10^4 \ kW}$$

$$\therefore \text{ Number of Kaplan turbines required} = \frac{100 \times 10^3}{5.98 \times 10^4} = 1.67 = \mathbf{2}$$

Problem 4.9. *A run-off of 30 m³/sec is available at 7.5 m head for generating the power. The turbine efficiency is 85% (a) Is it feasible to develop this power by two turbines with r.p.m of 50 and the specific speed of turbine not greater than 340 ? (b) What type of runner will be used ? (c) What is the diameter of the runner if the ratio is 0.85.*

Solution.

$$P = \frac{wQH}{1000} \times \eta = \frac{1000 \times 9.81 \times 30 \times 75}{1000} \times 0.85 = \mathbf{1876 \ kW}$$

The actual specific speed of runner if it is allowed to run at 50 r.p.m. is given by

$$N_s = \frac{50\sqrt{1876}}{(7.5)^{1.25}} = \frac{50 \times 43.3}{12.4} = \mathbf{174.6}$$

(*a*) As $N_s = 340$, two turbine units can be used.

(*b*) The runner is Francis type.

(*c*) The speed ratio is given by

$$0.85 = \frac{v}{\sqrt{2gH}} = \frac{\pi DN}{\sqrt{2gH}} \times \frac{1}{60}$$

where v is the mean velocity of runner in m/sec.

$$D = 0.85 \times 60\sqrt{2gH} \times \frac{1}{\pi N} = 51\sqrt{2 \times 9.81 \times 7.5} \times \frac{1}{\pi \times 50}$$

$$= \frac{51}{50\pi} \times \frac{12.1}{1} = \mathbf{3.93\ metres.}$$

Problem 4.10. *A test is conducted on a model of $\frac{1}{4}$ size of prototype under the head of 36 m to find the performance of prototype. The head available for the prototype is 100 m and it has to run at 428 r.p.m. Find the power developed by the prototype. The power developed by the model is 135 kW when the water supplied is 0.44 m³/sec. Assume the efficiency of prototype is 3% greater than the efficiency of the model. State the type of the runner used.*

Solution. The given data is,

$h = 36$ m, $p = 135$ kW., $q = 0.44$ m³/sec, $H = 100$ m,

$N = 428$ r.p.m., $D/d = 4$ and $\eta_p = \eta_m + 0.03$

Find P

$$\frac{N}{n} = \frac{d}{D}\sqrt{\frac{H}{h}}$$

$$n = \frac{428}{1} \times \frac{4}{1} \times \sqrt{\frac{36}{100}} = \mathbf{1050\ r.p.m.}$$

$$p = \frac{wqh}{1000} \cdot \eta_m$$

$$\therefore \quad \eta_m = \frac{135 \times 1000}{1000 \times 9.81 \times 0.44 \times 36} = \mathbf{0.87.}$$

$$\therefore \quad \eta_p = 0.87 + 0.03 = 0.90$$

$$\frac{P}{p} = \frac{\eta_p}{\eta_m}\left(\frac{D}{d}\right)^2\left(\frac{H}{h}\right)^{3/2}$$

$$P = 135 \times \frac{0.90}{0.87}(4)^2\left(\frac{100}{36}\right)^{1.5} = 135 \times \frac{0.90}{0.87} \times \frac{16}{1} \times \frac{4.64}{1} = \mathbf{10350\ kW}$$

$$N_s = n_s$$

$$\therefore \quad \frac{N\sqrt{P}}{H^{5/4}} = \frac{n\sqrt{p}}{h^{5/4}}$$

$$\therefore \quad \frac{428\sqrt{10350}}{(100)^{1.25}} = \frac{1050\sqrt{135}}{(36)^{1.25}}$$

$$\frac{428 \times 101.4}{318} = \frac{1050 \times 11.6}{8} = 137.5$$

The runner is a Francis type.

Problem 4.11. *A power plant is proposed on a river where the available average flow is 70 m³/sec and head is 15 m. The runner has to run at constant speed of 200 r.p.m. The efficiency of the turbine is 50%. The best specific speed of the runner at the site is 340. Selection of the turbine is to be made from the following data given for the required specific speed and calculated for unit head.*

$N_s = 340. \quad H = 1$ m.

Diameter of runner in cm.	143	151	158.5	165	172.5
kW (Unit)	66.7	74	82.5	87	92
R.P.M. (Unit)	53	51	48.5	45.4	42.5

Find (a) type of the runner ; (b) the number of turbines required and (c) diameter of the runner selected from the above data by interpolation.

Solution. The given data is as follows.

$Q = 70$ m³/sec, $H = 15$ m, $N = 200$ r.p.m., $N_s = 340$, $\eta = 90\%$.

(*a*) The type of the runner is Kaplan as the specific speed is 340.

(*b*) The total power available at the site is given by

$$P = \frac{wQH}{1000} \times \eta$$

$$= \frac{1000 \times 9.81 \times 70 \times 15}{1000} \times 0.9 = \mathbf{9270\ kW}$$

The power output per turbine is given by

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

$$340 = \frac{200\sqrt{P}}{(15)^{1.25}}$$

$$\sqrt{P} = \frac{340 \times 29.5}{200} = 50$$

$$\therefore \quad P = \mathbf{2500\ kW}$$

$\therefore$ Number of turbine units required $= \dfrac{9270}{2500} = 3.7 = \mathbf{4}$

(*c*) The unit power and unit speed are given by,

$$P_u = \frac{P}{(H)^{3/2}} = \frac{2500}{(15)^{1.5}} = 86.2 \text{ kW}$$

$$N_u = \frac{N}{(H)^{1/2}} = \frac{200}{(15)^{0.5}} = \frac{200}{3.87} = 51.7 \text{ r.p.m. m}^{-1/2}$$

For unit power of 86.2 and unit speed of 51.7, the required diameter can be calculated by interpolation from the given data as

$$= 158.5 + \frac{(86.2 - 82.5)}{(87 - 82.5)} \times (165 - 158.5) = 158.5 = \frac{3.7}{4.5} \times 6.5 = \mathbf{163.85\ cm.}$$

Problem 4.12. *Find the maximum height of the Francis turbine above the tailrace from the following data :*

Atmospheric pressure = 1.03 bar

Pressure at the exit of the runner = 0.5 bar.

Velocity of water leaving the runner = 5 m/sec
Velocity of water leaving the draft tube = 2 m/sec
Head of water lost passing through the draft tube due to friction = 0.2 m of water head.

Solution. The given data is as follows :

$p_a = 1.03$ bar, $p_c = 0.5$ bar, $V_c = 5$ m/sec, $V_d = 2$ m/sec, $h_f = 0.2$ m.

The maximum height of the turbine above tailrace level can be calculated by using the following formula

$$h = \frac{p_a - p_c}{w} - \frac{V_c^2}{2g} + \left\{ \frac{V_d^2}{2g} + h_f \right\}$$

Substituting the given values in the above equation, we get

$$h = \frac{10^5}{1000 \times 9.81}(1.03 - 0.5) - \frac{5^2}{2 \times 9.81} + \left(\frac{2^2}{2 \times 9.81} + 0.2 \right)$$

$= 5.4 - 1.28 + 0.204 + 0.2 =$ **4.524 metres above tailrace level.**

Problem 4.13. *Find the position of the Kaplan turbine with respect to tailrace level from the following data if there is no cavitation in the runner.*

Atmospheric pressure = 750 mm of Hg.
Vacuum at the exit of runner = 400 mm of Hg.
Velocity of water leaving the runner = 13 m/sec.
Friction loss and exit velocity of water head = 1.5 m of water head.
Show the arrangement of turbine.

Solution. The given data is as follows :

$p_a = 750$ mm of Hg, $p_d = 750 - 400 = 350$ mm of Hg, $V_c = 13$ m/sec.

and $$\frac{V_d^2}{2g} + h_f = 1.5 \text{ m.}$$

We can use the following formula for finding out the height of turbine above tailrace level

$$h = \frac{p_a - p_d}{w} - \frac{V_c^2}{2g} + \left(\frac{V_d^2}{2g} + h_f \right) = \frac{(750 - 350)}{1000 \times 9.81 \times 760} \times 1.03 \times 10^5 - \frac{169}{19.62} + (1.5)$$

$= 5.55 - 8.62 + 1.5 = -$ **1.77 m.**

The negative sign indicates that the turbine is below the tailrace level as shown in Fig. Prob. 4.13.

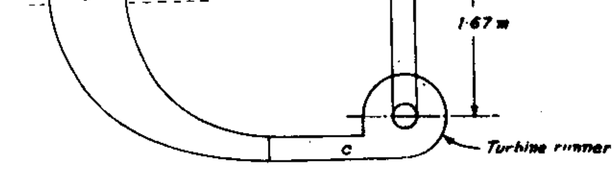


Fig. Prob. 4.13.

Problem 4.14. *The temperature of water flowing through a Francis turbine is 20°C. The atmospheric pressure is equivalent to 755 mm of Hg. The velocities of water leaving the turbine and draft tube are 8 m/sec and 3 m/sec respectively. Neglecting the friction loss through the draft tube, find the maximum possible height of the turbine from the tailrace level.*

Solution. As the height of the turbine above tailrace level increases, the risk of cavitation also increases, therefore, the maximum height of turbine above tailrace level should not create the danger of cavitation.

The given data is

$$p_a = 755 \text{ mm of Hg}$$

$$V_c = 8 \text{ m/sec}, V_d = 3 \text{ m/sec}, T_a = 20°\text{C}.$$

The maximum possible height of turbine above tailrace level without causing the cavitation is given by

$$h = \left(\frac{p_a - p_c}{w}\right) - \frac{V_c^2}{2g} + \left(\frac{V_d^2}{2g} + h_f\right)$$

The minimum value of p_c corresponds to the saturation pressure of water vapour at 20°C.

$\therefore$ p_c (from steam table) = 17.6 mm of Hg.

Substituting the given values in the above equation, we get

$$h = \frac{(755 - 17.6)}{760} \times 13.6 - \frac{8^2}{2 \times 9.81} + \frac{3^2}{2 \times 9.81}$$

$= 13.20 - 3.26 + 0.46 =$ **10.4 meters above tailrace level**

In the following examples, the N_s is defined as dimensionless

* $N_s = \dfrac{N\sqrt{Q}}{(gH)^{3/4}} \sqrt{\eta}$ (for turbines) where N is in Radians/sec.

The value of N_s is around 0.10 for single jet impulse and about 0.2 for multi-jet impulse turbines. For Francis turbines, the range is 0.2 to 2.0 and for axial flow machines above 2.0 and upto 20. The advantage of this definition is that this is dimensionless when N is given in radians/second.

$$\text{Unit speed} = \frac{N}{\sqrt{H}}, \text{ Unit power} = \frac{P}{H^{3/2}} \text{ and Unit discharge} = \frac{Q}{\sqrt{H}}.$$

Problem 4.15. *A turbine is to run at 200 rpm under the available head of 25 m. The flow rate available is 9 m³/sec. If the turbine efficiency is 90%, calculate (i) the specific speed. (ii) power generated. (iii) speed and power if the head is reduced to 15 m, and (iv) the type of turbine.*

Solution. (*i*)

$$N_s = \frac{N\sqrt{Q}}{(gH)^{3/4}} \cdot \sqrt{\eta} = \frac{2\pi \times 200 \times \sqrt{9}}{60 \times (9.81 \times 25)^{0.75}} \times \sqrt{0.9} = \mathbf{0.962.}$$

(*ii*) Power generated

$$= \frac{\rho g H Q \eta}{1000} \text{ kW} = \frac{1000 \times 9.81 \times 25 \times 9 \times 0.9}{1000} = \mathbf{1986.5 \text{ kW}}$$

(*iii*) When the head is 15 m,

$$N_2 = N_1 \sqrt{\frac{H_2}{H_1}} = 200 \sqrt{\frac{15}{25}} = \mathbf{154.9 \text{ rpm.}}$$

$$P_2 = P_1 \left[\frac{H_2}{H_1}\right]^{3/2} 1986.5 \times \left(\frac{15}{25}\right)^{1.5} = \mathbf{923 \text{ kW}}$$

(*iv*) From the range of specific speed it is seen that the turbine to be selected is Francis type.

Problem 4.16. *A turbine develops 5400 kW at 200 rpm under a head 240 m at an efficiency of 82%. The wheel diameter is 3 m. (a) Compute the flow rate, unit speed, unit power, unit flow and specific speed. (b) For this turbine, what would be the speed, power and flow under a head of 160 m. (c) If a similar unit is to develop 2850 kW under a head of 183 m, find its diameter, speed and rate of flow.*

* The proof of this is left as exercise to the students.

Solution. (*a*) Power :

$$= \frac{\rho g Q H \eta}{1000} = 5400$$

$$\therefore \quad Q = \frac{5400 \times 1000}{9.81 \times 1000 \times 240 \times 0.87} = \mathbf{2.7\ m^3/sec.}$$

$$\text{Unit speed} = \frac{N.D}{\sqrt{H}} = \frac{200 \times 3}{\sqrt{240}} = \mathbf{38.7}$$

$$\text{Unit Power} = \frac{P}{D^2 H^{3/2}} = \frac{5400}{3^2 \times (240)^{3/2}} = \mathbf{0.161}$$

$$\text{Unit flow} = \frac{Q}{D^2.\sqrt{H}} = \frac{2.8}{3^2\sqrt{240}} = \mathbf{0.02}$$

$$\text{Specific speed} = \frac{N\sqrt{Q}}{(gH)^{3/4}}\sqrt{\eta} = \frac{2\pi \times 200}{60} \times \sqrt{0.82} \times \frac{\sqrt{0.82}}{(9.81 \times 240)^{0.75}} = \mathbf{0.094.}$$

(*b*) When the head is changed to 160 m, the diameter remains the same.

$$N = \frac{N_u\sqrt{H}}{D} = \frac{38.7 \times \sqrt{160}}{3} = \mathbf{163\ rpm.}$$

$$P = P_u D^2 . H^{3/2} = 0.161 \times 3^3 \times 160^{3/2} = \mathbf{2930\ kW}$$

$$Q = Q_u D^2 \sqrt{H} = 0.02 \times 3^2 \times \sqrt{160} = \mathbf{2.28\ m^3/sec.}$$

(*c*) $P = P_u . D_1{}^2 H^{3/2} = 0.161 \times D_1{}^2 \times 183^{3/2} = \mathbf{2850 \times 10^3}$

Solving, the diameter required $D_1 = \mathbf{2.67\ m.}$

Speed $\quad N = \frac{N_u\sqrt{H}}{D_1} = \frac{38.7\sqrt{183}}{2.67} = \mathbf{196\ rpm.}$

Flow rate $\quad Q = Q_u D_1{}^2 . \sqrt{H} = 0.02\,(7.15)\sqrt{183} = \mathbf{1.93\ m^3/sec.}$

Problem 4.17. *An impulse turbine at its best speed produces 93 kW under a head of 64 m. (i) Determine the percentage by which the speed is to be increased for a head of 88 m. (ii) Assuming that the efficiency does not charge, compute the power developed.*

Sol. (*i*) For the same size, the speed is proportional to the square root of head and so

$$\frac{N_1}{\sqrt{H_1}} = \frac{N_2}{\sqrt{H_2}}$$

$$\therefore \quad N_2 = N_1\sqrt{\frac{H_2}{H_1}} = N\sqrt{\frac{88}{64}} = \mathbf{1.173\ N_1}$$

The speed increases by **17.3%**

(*ii*) For the same wheel, power varies as $H^{3/2}$ and so

$$P_2 = P_1\left(\frac{H_2}{H_1}\right)^{3/2} = 93\left(\frac{88}{64}\right)^{3/2} = \mathbf{150\ kW.}$$

Problem 4.18. *A large hydraulic turbine has a capacity of 86000 kW at 180 rpm under a head of 148 m. The diameter of the rotor is 3.4 m and the flow rate is 66.5 m³/s.*

Evaluate the unit speed, unit discharge, unit power and the specific speed. Indicate type of turbine that may be used.

Sol. $\quad N_u = \frac{D.N}{\sqrt{H}} = \frac{3.4 \times 180}{\sqrt{148}} = \mathbf{50\ rpm.}$

$$P_u = \frac{P}{D^2.H^{3/2}} = \frac{86000}{3.4^2 \times 148^{3/2}} = \mathbf{4.13\ kW.}$$

$$Q_u = \frac{Q}{D^2.\sqrt{H}} = \frac{66.5}{(3.4)^2.\sqrt{148}} = \mathbf{0.473\ m^3/s.}$$

$$N_s = \frac{N.\sqrt{Q}}{(gH)^{3/4}}\sqrt{\eta}$$

$$\eta = \frac{86000 \times 10^3}{9.81 \times 148 \times 66.5 \times 1000} = \mathbf{89\%}$$

$$\therefore \quad N_s = \frac{\pi \times 3.4 \times 180}{60} \cdot \frac{\sqrt{66.5}}{(9.81 \times 148)^{0.75}} \sqrt{0.89} = \mathbf{1.048.}$$

For this range of specific speed in the SI system (dimensionless) turbine used must be Francis type.

Problem 4.19. *A propeller type turbine is rated at 36000 kW at 81.8 rpm under a head of 13 m. The diameter is 7.82 m. For a geometrically similar unit to develop 27000 kW under a head of 11 m, what speed and diameter should be used ? What will be the flow rate to be expected ?*

Sol. As the specific speeds are the same, using the definition of specific speed in terms of power,

$$\frac{N_1\sqrt{P_1}}{H_1^{5/4}} = \frac{N_2\sqrt{P_2}}{H_2^{5/4}}$$

$$\frac{81.8\sqrt{36000}}{(13)^{5/4}} = \frac{N_2\sqrt{27000}}{(11)^{5/4}}$$

$$\therefore \quad N_2 = \mathbf{76.7\ rpm.}$$

As the unit speeds are same,

$$N_u = \frac{D_1N_1}{\sqrt{H_1}} = \frac{D_2N_2}{\sqrt{H_2}}$$

$$\therefore \quad D_2 = \mathbf{7.27\ m.}$$

As the unit flow is same

$$\frac{Q_1}{D_1^2H_1^{1/2}} = \frac{Q_2}{D_2^2H_2^{1/2}} \quad \therefore \quad Q_2 = \mathbf{0.883\ Q_1}$$

There is a reduction in flow by about **12%.**

EXERCISES

4.1. How the dams are classified ? What factors are considered in selecting a type of dam ?

4.2. What are the different types of spillways used in practice ? Discuss the advantages of one over the others ?

4.3. What topographical features compel to use shaft spill-way ? What are its advantages and disadvantages over other types ?

4.4. Where the siphon spillway is used ? What are its different features ? Explain its advantages and disadvantages over the other.

4.5. What different methods are used to dissipate the energy of water passing over the overflow spillways ? Why it is necessary ?

4.6. Differentiate between a conduit and penstock. How the length of penstock is decided in the hydraulic power plant ? What are the advantages and disadvantages of exposed penstock over buried penstock ?

4.7. Draw a neat sketch of a power house and describe the main features of sub-structure and superstructure.

4.8. What topographical features are in favour of underground power house ? What are the different types of underground power stations ? Draw neeat layout of each.

4.9. Describe the advantages and disadvantages of underground power stations compared with overground power stations.

4.10. What topographical and other conditions decide the setting of turbine either vertical or horizontal (*a*) in case of reaction turbine (*b*) in case of Pelton wheel.

4.11. What do you understand by open flume setting ? Draw the neat sketches of horizontal and vertical open flume setting for reaction turbines. When the open flume setting is more preferable ? What are its disadvantages ?

4.12. Which factors are considered in deciding the setting of Pelton wheel (*a*) in horizontal plane (*b*) in vertical plane. Discuss the advantages of one over the other.

4.13. Discuss the differences between Pelton, Francis and Kaplan turbines and types of power plants they are suitable for.

4.14. Why the inward flow reaction turbines have supersheded the outward flow turbines ?

4.15. What do you understand by the term specific speed of a water turbine ?
What information does it give and how it is made use in practice ?
Indicate how the form of a reaction turbine depends upon "specific speed".

4.16. Find out the expression for the specific speed of a water turbine in terms of power developed, the speed and the head available.
Further show that the specific speed of a Pelton wheel is 2450 d/D where d and D are the diameter of jet and diameter of mean circle bucket of Pelton wheel in metres respectively.
Assume that mean bucket speed = $0.46 \sqrt{2gH}$.
Maximum efficiency = 0.88% and coefficient of velocity of jet = 1.

4.17. Explain why the discharge conditions for a high specific speed runner are less favourable than those for a low specific speed runner both being assumed to be running at their points of maximum efficiency.

4.18. Explain why the discharge conditions at part load are less favourable for the high specific speed runner than for the low specific speed runner.

4.19. For a given head and stream flow available at a certain power plant, what quantities may be changed so as to permit the use of various types of turbines ? Which type of turbine will give the smallest number of units in the plant ? Which type will run at the lowest speed ?

4.20. How does the maximum efficiency of a reaction turbine vary with the type of the turbine ? For what type it is the highest ? Why ? For what type it is lowest ? Why ?

4.21. What are the disadvantages of a very low specific speed reaction turbine ? What are its advantages ?

4.22. How does the efficiency of the Pelton wheel vary with its speed ? Why ?

4.23. What effects the efficiency of a reaction turbine on part-load ? Is the part load efficiency is a function of specific speed ?

4.24. What are the advantages and disadvantages of very high specific speed turbine runners ?

4.25. What are the advantages of a high speed runner under very low heads. What are the advantages of medium speed runner under the same conditions ?

4.26. What are the advantages of Pelton for very high head ? What are the disadvantages of low speed reaction turbine for the same conditions ?

4.27. For the same power under the given head, compare impulse wheels and reaction turbines with respect to efficiency, speed, space occupied, freedom from breakdown, ease of repairs and durability with silt laden water.

4.28. Describe the characteristics of various types of turbines used in hydro-electric power stations with reference to (*a*) head (*b*) part load efficiency and maximum efficiency and (*c*) specific speed, and, state how these factors help in the choice of the turbine.

4.29. What factors are considered in selecting a prime-mover for a hydro-electric power plant ?

4.30. What ~~factors~~ are mainly considered in selecting a prime-mover for (*a*) run-off riveer plant (*b*) storage plant (*c*) pump-storage plant.
When the supply is drawn direect from the river instead of storage reservoir, would you go in for Pelton turbine or a reaction turbine ? State the reason for your choice. The head and flow are same in both cases.

4.31. How do the rotational speed and cavitation effect the selection of a water turbine for hydro-electric power plants ?

4.32. What are the advantages of reaction turbine over the Pelton wheel in respect of efficiency, size, cost and maintenance ?

4.33. What type of turbine will you select for head of (*a*) 200 m (*b*) 60 m (*c*) 10 m.

4.34. State briefly the type of water turbines you would prefer for the following head with reasons for your choice :
(*a*) Minimum head = 20 m. (*b*) Maximum head = 55 m. (*c*) Average head = 40 m.
B. (*a*) Minimum head = 12 m. (*b*) Maximum head = 28 m. (*c*) Average head = 22 m.
C. Net head = 900 m. (*D*) Net head = 300 m.

4.35. Explain with sketches the governing of a reaction turbine showing in detail the part played by the floating fulcrum.

4.36. Describe with sketches the satisfactory method of governing a large Pelton wheel.
Show how a sudden increase in pressure in the supply line may be prevented.

4.37. Describe the working of governing method used for Kaplan turbine with neat sketch.

4.38. What are the functions of a draft tube in a hydro-electric power plant ? Prove that a draft-tube prevents the loss of head of a reaction turbine.

4.39. What are the different types of draft tubes ? Sketch the different types of draft tubes and state which one of them gives maximum efficiency.

4.40. What is meant by "Cavitation" ? How and where does it occur in water turbines ? Find an expression for the lowest head required by a reaction turbine. Why does it become necessary to instal a water turbine below tailrace level ?

4.41. Derive thee expression for the maximum allowable height of a turbine runner above tailrace level and discuss the factors that affect this value ?

4.42. Explain how do the losses in the draft tube affect the pressure at runner exit and setting of the runner above tailrace level.

4.43. Describe the principle of "setting a turbine" with reference to the tailrace level. What is the effect of speed on the setting of a turbine ?

4.44. Describe the methods used to avoid the cavitation in water turbines. Why the upper part of the draft tube is lined with metal plate ?

4.45. Explain why the angle of taper of draft tube is limited and how air suction from the surface of draft tube helps in increasing the angle of taper.

4.46. What do you understand by water hammer and what are its effects on the power plant design ?

4.47. What are the functions of surge tank and Forebay ?
Describe different types of surge tanks. How will you differentiate differential type with that of simple or restricted orifice type.

4.48. A model turbine runner of 37.5 cm. diameter is tested under a head of 6 m and supply of water is 400 litres/sec. The model develops 30 kW when running at 350 r.p.m. (*a*) Find the specific speed, unit speed, unit power and unit discharge for the model. Also find the η of the model. (*b*) if the actual runner of 87.5 cm diameter is to be used under a head of 36 m, find the speed, discharged and power developed by this runner. Assume the efficiency in both cases is same.

4.49. A discharge of 850 litres/sec is available for power generation under a head of 152.5 m. Find the power of the turbine if its efficiency is 90% and it runs at 375 r.p.m. What type of turbine is suitable for this power plant ? Also find the diameter of runner and diameter of the nozzle.

4.50. A model of 1/8th full size develops 5 kW at 300 r.p.m. when the head supplied is 1.83 m. Find the speed and power developed by the prototype when running under a head of 6.1 m. Assume the same efficiency for both model and prototype.

4.51. A model 1/10th of full size turbine is tested at a head of 6.1 m. The power developed by the prototype is 10140 kW under a head of 9.15 m when running at 100 r.p.m. Find the flow required and brake power developed by the model if its efficiency is 88%. What type of runner is used for testing the model ?

4.52. A turbine model 1/4th of prototype develops 137 kW under a head of 11 m when water supplied is 1.64 m^3/sec. The actual turbine has to run at 428 r.p.m. under a head of 30.5 metres. Find the power developed by prototype and the speed of the model. Assume the efficiency of prototype is 3% greater than that of model.

4.53. A hydro-electric power plant site is capable of developing 101400 kW. If the turbine has to work under a head of 29.85 m and at a speed of 166.7 r.p.m. find the number of turbine units required if the specific speed of the turbine is not to exceed 445.

4.54. A run-off of 839.85 m^3/sec is available under a head of 27.45 metres at a proposed power plant site. The turbine has to turn at 166.7 r.p.m., find the number of units used (*a*) If the turbine used is Francis type whose specific speed should not exceed 267 (*b*) if the turbine used is Kaplan type whose specific speed should not exceed above 800.
Assume 88% efficiency in both cases.

4.55. The discharge of 354 m^3/sec. is available under a head of 30 m at the proposed site of hydro-electric power plant. The turbine has to run at 166.7 r.p.m. Find the least number of machines, all of them of same size, if
(*a*) Francis runner is used of $N_s = 222.5$
(*b*) Kaplan runner is used of $N_s = 890$.
Assume the efficiency in both cases is 90%.

4.56. A hydraulic turbine is designed to utilise 1.5 m^3/sec. flow under a head of 60 m. The generator is directly coupled to the turbine. The frequency of the generation is 50 cycles/sec. The turbine is placed 3 m above the tailrace level. Select the suitable type of the turbine and find (*a*) the power of the turbine (*b*) the rotational speed of the turbine and (*c*) the leading dimensions of the runner for cavitation free operation.
Assume the overall efficiency of the generation is 92%. Take the water temperature as 20°C.

4.57. In a certain hydro-electric power plant, the turbines are required to work for 6 hours at full load and rest of the day on 60% of full load.
Compare the quantities of water required per day under equal conditions of head and output by (*a*) Francis turbines (*b*) Propeller turbines and (*c*) Kaplan turbines.
Assume full load efficiency of each turbine as 90% and efficiency at 60% load is 75% for Francis, 60% for Propeller and 80% for Kaplan.

4.58. A hydro-electric power plant develops 5680 kW under a head of 23.4 metres. The number of prime-movers used are two and each is running at a speed of 250 r.p.m. Find
(*a*) specific speed of a turbine.
(*b*) state a suitable type of turbine.
(*c*) the inlet diameter of the runner if the speed ratio is 0.8.

4.59. Each turbine at Pathri hydro-electric Power station develops 9640 kW under a head of 9.76 m and flow of 83.5 m^3/sec when running at 125 r.p.m. Find
(*a*) overall efficiency of each turbine.
(*b*) specific speed of each turbine.
(*c*) speed ratio if the diameter of the runner is 3.88 m.
Draw the outline of the turbine showing the type of draft tube.

4.60. A turbine runner has an exit velocity of 9.6 m/sec. The loss of head due to friction and other causes in the draft tube and the exit velocity head at the tailrace should not exceed 1.5 m together. What maximum height of setting the turbine runner will you recommend for the turbine if cavitation is to be avoided. The cavitation commences when the pressure is 2.4 m of water head. The atmospheric pressure is 760 mm. of Hg.

4.61. The following data refer to an elbow type draft tube.
Area of circular inlet = 25 m^2.
Area of rectangular outlet = 116 m^2,
Velocity of water at inlet to draft tube = 20 m/sec.
Efficiency of draft tube = 70%
Elevation of inlet plane of dra. tube above tailrace level = 60 cm.
Find (*a*) vacuum or negative head at inlet of draft tube (*b*) power wasted in draft tube and (*c*) power thrown away in tailrace level.

4.62. A conical draft tube fitted to a Francis turbine has inlet and outlet diameter of 3 m and 5.05 m respectively. The velocity of water at the inlet of draft tube is 5 m/sec. The turbine runner is 5 metres above tailrace level. Assuming the loss in draft tube is 50% of velocity head at outlet, find (*a*) pressure head at the inlet of the draft tube (*b*) power thrown away in the tailrace level (*c*) power lost in draft tube.

4.63. A Kaplan turbine has a vertical conical draft tube. The diameters of the draft tube at inlet and outlet are 60 cm. and 90 cm. respectively. The draft tube is 6 m long with 1.5 m of its bottom length in tailwater. The velocity of water at the inlet of draft tube is 6 m/sec. and the frictional loss in the draft tube in 15% of the velocity head at the inlet of the draft tube. Find the water pressure at the inlet of the draft tube in bar and in metres of water head.

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