HYDRAULIC MACHINE AND INDUSTRIAL FLUID POWER MECHANICAL ENGG(5TH)

HYDRO – ELECTRIC POWER STATIONS

Hydro – Electric power is a conventional renewable source of energy which is clean,free from pollution and has good environmental effect.

The following factors are major obstacles in utilization of Hydro-Electric power stations:

Large investment.

Long gestation period.

Increased cost of power transmission.

Next to thermal power, Hydro power is important in power generation. The Hydro-Electric power plants provide 30% of the total power. It is an independent power source and most effective with adequate storage capacity, otherwise the maximum load capacity of the station has to be based on minimum flow of stream and there is a great wastage of water over the dam for greater part of the year. This increases the per unit cost of installation. When the stream flow is lower than the maximum demand the Hydro-plants supplies the peak load.

Advantages and Disadvantages of Hydro-Electric Power Stations

Advantages

No fuel charge.

Highly reliable.

Maintenance and operation charges are very low.

4.The plant efficiency does not change with age.

It takes few minutes to run and synchronize the plant.

Less supervising staff.

No ash problem and atmosphere is not polluted since no smoke is produced.

In addition to power generation these plants are used for irrigation purposes.

The plant has a long life of 100-125 years as against 20-45 years for thermal plant.

The hydro electric plants are more robust and run at a speed of 300 to 400 RPM where as in thermal plants run at a speed of 3000 to 4000 RPM.

The cost of land is not a problem as the Hydro electric plants are situated away from the developed areas.

Disadvantages

1.Initial cost of the plant is very high.

It takes long time for erection of a hydro electric plant.

Plants are located away from the load centers and require long transmission lines to deliver power; subsequently the cost of transmission lines and losses in them will be more.

Power generation depends on the quantity of water available which is turn depends on the rains. If the rainfall is in time and proper, the plant will function satisfactorily, otherwise not.

Elements of Hydro – Electric Power Stations

The following are the essential elements of Hydro- Electric power stations:

Catchment area.

Reservoir

Dam

Spillways

Conduits

Surge tanks

Prime movers

Draft tubes

Pump house and equipment.

The description of various elements of Hydro- Electric power stations is as follows:

Catchment area: The whole area behind the dam, draining into a stream or river across which dam is built at a suitable place.

2. **Reservoir**: The water reservoir is the primary requirement of Hydro-Electric power station. It is used to store water to be utilized to generate power by running the hydraulic turbines.

A reservoir may be natural or artificial. A natural reservoir is a lake in high mountains. An artificial reservoir is built by erecting a dam across the river. Water held in upstream reservoir is called Storage and water behind the dam at the plant is called pondage.

3. **Dam**: A dam is a barrier to confine or raise water for storage or diversion to create a hydraulic head. A reservoir dam stores water by raising its level.

4. **Spillways**: When the water enters the reservoir basin, the level of water in the basin rises. This rise is arranged to be of temporary nature, because excess accumulation of water endangers the stability of dam structure. To relieve reservoir of this excess water, a structure is provided in the body of a dam to safe guard the structure is called a spillway.

A spillway should fulfill the following requirements:

It should provide structure stability to the dam under all conditions of floods.

It should be able to pass the designed flood without raising the reservoir level above H.F.L (High flood level)

It should have an efficient operation.

It should have an economical selection.

5. Conduits:

Open conduits - canals and flumes

Closed conduits – Tunnels, pipelines and pen stocks.

***Canal*: ** A canal is an open water way excavated in natural ground. It has to follow the contour of theground, with a slight gradient corresponding to the head loss.

***Flume* :** It is a open channel erected on the surface, supported above the ground on a trestle.It is used with canal to cross a ravine or where the slope of the ground is greater than the hydraulic gradient.

***Tunnel* :** It is a closed channel excavated through a natural obstruction such as a ridge of higher land between the dam and power house.

***Pipe line* :** A pipe line is a closed conduit usually supported on or above the surface of ground. When the pipe line is laid on the hydraulic gradient, it is called a flow line.

Pen stock **:** It is a closed conduit for supplying water under pressure to a turbine where the slope is too great.

Surge Tanks: A surge tank is a small reservoir or tank in which the water level rises or falls to reduce the pressure swings so that they are not transmitted in full to a closed circuit.

Prime movers : In hydraulic power plant, the prime mover converts the energy of water into mechanical energy and further into Electrical energy. These are classified on the basis of the action of water on moving blades as

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

Reaction turbine ***:*** Here the water pressure combined with velocity works on the runner. The power is developed from the combined action of pressure and velocity of water.

Draft tubes : The draft tube serves the following two purposes:

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

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

Power House and Equipment : A Power house should have a stable structure and its layout should have adequate space around the equipment (eg. Turbines, generators, valves, pumps etc) so that the dismantling and repairing may be easily carried out.

Classification of Hydro – Electric power Plants:

Hydro-electric power stations may be classified as follows:

A. According to availability of head

High head power plants. – 100M and above.
Medium head power plants – 30M to 100M
Low head power plants – 25M to 30M

B. According to the nature of load.

Base load plants.
Peak load plants.

Run- of- river plant without pondage.
Run-of- river plant with pondage.
Storage type plants.
Pump storage plants.
Mini and Micro–hydel plants.

A. According to availability of head

I. ***High head power plants*****:** This type of plants work under heads 100M and above. Water is stored up in lakes on high mountains during the rainy season. The rate of flow should be such that the water can lost throughout the year. The pelton wheel is the common prime mover used in high head power plants.

Medium head power plants: This type of plant work under the operating heads between 30M to 100M and they use Francis Turbines. The water is generally carried in open canals from the main reservoir to the fore bay and then to power house through penstock. The fore bay works as a surge tank in this type of plant.

III. ***Low-head power plants***: This type of plants usually consists of a dam across river. A side way stream diverges from the river at the dam. Over this stream the power house is constructed. Later this channel joins the river further down stream. This type of plants uses vertical shaft Francis turbine or Kaplan turbine.

B. According to the nature of load

I). Base load plants: The plants which caters for the base load of the system are called base load Plants. These plants supply constant power when connected to the grid.

II). Peak load plants: The plants which can supply the power during peak loads are known as peak load plants and they are required to work during peak load hours only.

C. According to quantity of water available:

1). Run-of-river plants without pondage: It does not store water and uses the water as it comes. These is no control on flow of water, during floods or low loads water is wasted, while during low run-off the plant capacity is considerably reduced. Due to non-uniformity of supply and lack of firm capacity, the utility of these plants is much less than those of other types.

2). Run-of-river plant with pondage: Pondage refers to collection of water behind a dam at the plant and storage means collection of water in the upstream reservoir which will last for several months. Storage plants work satisfactorily on base load and peak load plants. This type of plant is more reliable and its generating capacity is less dependent on the flow rate of the water available.

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

4). Pumped storage plants: Pumped storage plants are employed at the places where the quantity of water available for power generation is in adequate. The water passing through the turbines is stored in **"tail race pond".** During low load periods this water is pumped back to the head reservoir using the extra energy available. This water can be again used for generating power during peak load periods.

<u>Advantages :</u>

1.There is an increase in the peak load capacity of the plant at comparatively low capital lost.
2.The operating efficiency of the plant is high.
3.There is an improvement in the load factor of the plant.
4.The energy available during peak load period is higher than that of during off peak period.
5.Load on the Hydro-electric plants remains uniform.
6.The Hydro-Electric plant becomes partly independent of the stream flow conditions.

Under pump storage projects almost 70% power used in pumping the water can be recovered.These units can be used as turbine while generating power and as pump while pumping water to storage. The generator in this case works as motor during reverse operation. The efficiency in such case is high and almost same in both the operations. With the use of reversible turbine pump sets, additional capital investments on pump and motor can be saved and are more economical.

***5). Mini and Micro hydel plants*:** In order to meet the energy crisis partly is to develop (5M to 20M head) Mini and (less than 5M head) Micro hydel power plants. The low head hydro-potential is scattered and the estimated potential is 20,000 MW.

By proper planningand implementation, it is possible to commission small hydro-generating set up of 5MW.

To reduce the cost of Micro-hydel stations than that of the conventional installation the following considerations are:

The civil engineering works needs to be kept to a minimum.

The machines need to be manufactured in small range of sizes and design.

These installations must be automatically controlled to reduce personnel.

The equipment must be simple and robust

The units must be light

Micro- hydel plants make use of standardized sets with unit out put ranging from 100 to 1000 KW working under heads between 1.5 to 10 Meters.

<u>MASS CURVE</u>: The mass curve is obtained by plotting cumulative volume of flows as ordinate and time (days, weeks, months as abscissa. Cumulative daily flows, instead of monthly flows will give more accurate mass curve. The slope of the curve at any point gives the flow rate in second-meter. Let us join two points X and Y on the curve. The slope of this line gives the average rate of flow during the period between X and Y.

This will be =

If during a particular period, the slope of mass curve is greater than the demand line, it means more water is flowing into the reservoir than is being utilized, So the water level in the reservoir will be increasing during that period and vice-versa.

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

Mass curve can be used to solve the reserve problem of determining the maximum demand rate that can be maintained by a given storage volume.

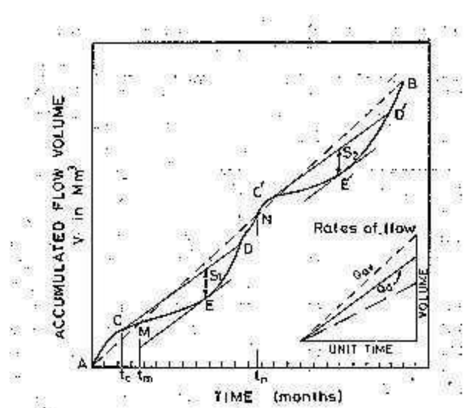


Fig. 5.9 Flow mass curve

RUN-OFF:

Rainfall is measured in terms of centimeters of water over a given area and over given a period.

The portion of the total rainfall that flows through the catchment area is known as Run-off. The catchment area of a hydro-site in the total area behind the dam, draining water in to the reservoir. Thus

Run-off = Total rainfall – Total evaporation.

Part of the rainfall is absorbed by the soil and seeps or percolates in to ground and will ultimately reach the catchment area through the underground.

Total Run-off = Direct run-off over the land surface + Run off through seepage The unit of run-off is M^3/sec or day-second meter.

Day-second meter = Discharge collected in the catchment area at the rate of 1M^3/sec for one day

= 1M^3/sec for one day = 1x24x3600M^3/day= 86400M^3/day

Factors affecting the Run-off:

***Nature of rainfall*:** Short showers produce little run-off. Rains lasting longer time results in larger run-off. The soils tend to become saturated results in increased runoff.

***Topography of catchment area*:** Steep and impervious areas will produce large % of runoff. The water flows quickly and absorption and evaporation losses will be small.

***Geology of the area*:** The run off is very much affected by the type of the surface soil, sub soil, type of rocks etc.

Meteorology: Evaporation varies with temp, wind velocity and relative humidity. Run-off increases with low temp, low wind velocity and high relative humidity.

***.Vegetation*:** Evaporation and seepage are increased by cultivation as it opens and roughens the hard, smooth surface and promotes seepage. Thick vegetation like forests consumes a portion of rainfall and also acts as an obstruction for run-off.

***Size and shape of the area*:** Large areas will give more Run-off. The flow along its width will give more Run-off than if the flow is along its length since in the former case seepage and evaporation will be less.

Measurement of Run-off: The flow can be determined with three methods.

***From rainfall records*:** The run-off can be estimated from the rainfall records by multiplying the rainfall with " **Run-off co-efficient**" for the drainage area. The run-off co-efficient takes in to account the various losses and will depend upon the nature of the catchment area.

Drainage Area	Run-off coefficient
1.Commercial and Industrial	0.90
2.Ashpalt or concrete pavement	0.85
3.Forests	0.05 to 0.30
4.Park and farm land	0.05 to 0.30

Run-off = Rainfall x Run-off Co-efficient

***Empirical Formulas*:** Empirical relations to determine the stream flow relate only to particular site and can't be realied upon for general use.

***Actual measurement*:** Direct measurement by stream gauging at a given site for a long period is the only precise method of evaluation of stream flow. The flow is measured by selecting a channel of fixed Cross - section and measuring the water velocity at regular intervals at enough points in the cross section for different water levels.

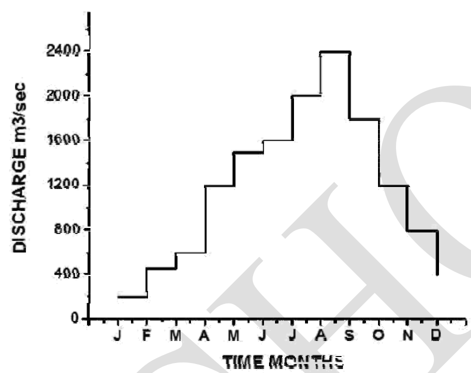
Hydro graph and flow duration curve:

A hydro graph indicates the variation of discharge or flow with time. It is plotted with flows as ordinates and time intervals as abscissa.

The flow is in M^3/Sec and the time may be in hours, days, weeks or months.

The flow duration curve can be plotted from a hydrograph

EX : The mean monthly discharge at a particular site is given in the table



From this it can be seen that a flow of 200 M^3/Sec is available for all the 12 Months and flow of 400 M^3/Sec for 11 months so an.

The use of Mass curve is to compute the capacity of the reservoir for a hydro-site. The Mass curve indicates, the total volume of run-off in second –meter-months during a given period. The Mass curve is obtained by plotting cumulative volume of flow as ordinate and time (days , weeks by months) as abscissa.

The Monthly flow is only the mean flow and is correct only at the beginning and end of the months. The variation of flow during the month is not considered. Cumulative daily flows, instead of monthly flows, will give more accurate mass curve. but this involves an excessive amount of work. The slope of the curve at any point gives the flow rate in second-meter. Let us joint two points X and Y on the curve. The slope of this line gives the average rate of flow during the period between X and Y.

This will be =

$$= \frac{36700 - 11560}{8.38} = 3000 \text{ second-metre}$$

Let the flow demand be 3000 Sec-meter. Then the line X-Y may be called as “Demand line”. If during the particular period, the slope of the mass curve is greater than that of the demand line it means more water is flowing into the reservoir, than is being utilized, so the level of water in the reservoir will be increasing during that period and vice-versa. Up to point X and beyond point Y the reservoir will be over flowing being full at X and Y.

The capacity of the reservoir is given by the max. ordinate between the Mass curve and the demand line. For the portion of Mass curve between point X and Y the storage capacity is about 4600sec-metre-months. However considering the entire Mass curve, storage capacity will be about 14500 sec-meter-months.

<u>Head and specific speed</u>: It has been found that there is a range of head and specific speed for which each type of turbine is most suitable.

***Specific Speed* :** It is defined as the speed of a turbine which is identical in shape, geometrical dimensions, blade angles, gate opening etc. with the actual turbine, but of such a size that it will develop unit power when working under unit head. It is denoted by symbol $\mathbf{N_S}$. The specific speed is used in comparing the different types of turbines as every type of turbine has different specific speed

The overall efficiency of turbine = $\frac{\text{Shaft power}}{\text{Water power}} = \frac{\text{Power developed}}{\frac{\rho g q H}{1000}}$

Power developed P = $\eta_o \times \frac{x\,x\,x}{1000}$

Specific speed $N_s = \frac{}{5/4}$

: FLUID MECHANICS AND HYDRAULIC MACHINERY UNIT-4

HYDRAULIC TURBINES

Turbines are defined as the hydraulic machines which converts hydraulic energy in to mechanical energy. This mechanical energy is used in running an electric generator which is directly coupled to the shaft of Turbine. Thus mechanical energy is converted in to electrical energy. The electric power which is obtained from the hydraulic energy is known as the Hydro-electric power.

Efficiency of a Turbine: The following are the important efficiencies of Turbine.

Hydraulic Efficiency, η_h

Mechanical Efficiency, η_m

Volumetric Efficiency, η_v

Overall Efficiency, η_0

Hydraulic Efficiency (η_h): it is defined as the ratio of power given by the water to the runner of a turbine (runner is a rotating part of a turbine and on the runner vanes are fixed) to the power supplied by the water at the inlet of the turbine. The power at the inlet of the turbine is more and this power goes on decreasing as the water flows over the vanes of the turbine due to hydraulic losses as the vanes are not smooth. Hence power delivered to the runner of the turbine will be less than the power available at the inlet of the turbine.

$$\eta_h = \frac{\text{Power delivered to the runner}}{\text{Power supplied at inlet}} = \frac{\text{R.P}}{\text{W.P}}$$

R.P = Power delivered to the runner kW----------- for Pelton Turbine

kW ----- Radial flow Turbine.

W.P = power supplied at inlet of turbine = $\frac{W \times H}{1000}$ kW

Where W = weight of water striking the vanes of the turbine per second = $\rho\ g\ Q$

= Volume of water per second

V_{w_1} =Velocity of whirl at inlet.

V_{w_2} = Velocity of whirl at outlet

u = Tangential velocity of vane

u_1 = Tangential velocity of vane at inlet of radial vane.

u_2 = Tangential velocity of vane at outlet of radial vane.

H = Net head on the Turbine.

Power supplied at the inlet of the turbine in S I Units is known as Water Power.

$$W.P = \frac{\rho \times g \times Q \times H}{1000} \text{ K.W} \qquad (\text{For water } \rho = 1000 Kg/m^3)$$

$$= \frac{1000 \times g \times Q \times H}{1000} = g \times Q \times H \text{ kW}$$

Mechanical Efficiency (η_m): The power delivered by the water to the runner of a turbine is transmitted to the shaft of the turbine. Due to mechanical losses, the power available at the shaft of the turbine is less than the power delivered to the runner of the turbine. The ratio of power available at the shaft of the turbine (Known as S.P or B.P) to the power delivered to the runner is defined as Mechanical efficiency.

$$\eta_m = \frac{\text{Power at the shaft of the turbine}}{\text{Power delivered by the water to the runner}} = \frac{S.P}{R.P}$$

Volumetric Efficiency (η_v): The volume of the water striking the runner of the turbine is slightly less than the volume of water supplied to the turbine. Some of the volume of the water is discharged to the tailrace without striking the runner of the turbine. Thus the ratio of the volume of the water supplied to the turbine is defined as Volumetric Efficiency.

$$\eta_v = \frac{\text{Volume of water actually striking the Runner}}{\text{Volume of water supplied to the Turbine}}$$

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

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

$$= \frac{S.P}{W.P} = \frac{S.P}{W.P} \times \frac{R.P}{R.P}$$

$$= \frac{S.P}{R.P} \times \frac{R.P}{W.P}$$

$$\boldsymbol{\eta_0 = \eta_m \times \eta_h}$$

If shaft power (S.P) is taken in kW, Then water power should also be taken in kW. Shaft power is represented by P.

Water power in $kW = \frac{\rho \times g \times Q \times H}{1000}$ Where ρ = 1000Kg/m^3

$$\eta_0 = \frac{\text{Shaft Power in kW}}{\text{Water Power in kW}} = \frac{P}{\frac{\rho \times g \times Q \times H}{1000}}$$ Where P = Shaft Power

CLASSIFICATION OF HYDRAULIC TURBINES:

The Hydraulic turbines are classified according to the type of energy available at the inlet of the turbine, direction of flow through the vanes, head at the inlet of the turbine and specific speed of the turbine. The following are the important classification of the turbines.

According to the type of energy at inlet:

- Impulse turbine and
- Reaction turbine

According to the direction of flow through the runner:

- Tangential flow turbine
- Radial flow turbine.
- Axial flow turbine
- Mixed flow turbine.

According to the head at inlet of the turbine:

- High head turbine
- Medium head turbine and
- Low head turbines.

According to the specific speed of the turbine:

- Low specific speed turbine
- Medium specific speed turbine
- High specific speed turbine.

If at the inlet of turbine, the energy available is only kinetic energy, the turbine is known as **Impulse turbine**. As the water flows over the vanes, the pressure is atmospheric from inlet to outlet of the turbine. If at the inlet of the turbine, the water possesses kinetic energy as well as pressure energy, the turbine is known as **Reaction turbine**. As the water flows through runner, the water is under pressure and the pressure energy goes on changing in to kinetic energy. The runner is completely enclosed in an air-tight casing and the runner and casing is completely full of water.

If the water flows along the tangent of runner, the turbine is known as **Tangential flow turbine**. If the water flows in the radial direction through the runner, the turbine is called **Radial flow turbine.** If the water flows from outward to inwards radially, the turbine is known as **Inward** radial flow turbine, on the other hand, if the water flows radially from inward to outwards, the turbine is known as **outward** radial flow turbine. If the water flows through the runner along the direction parallel to the axis of rotation of the runner, the turbine is called **axial flow** turbine. If the water flows through the runner in the radial direction but leaves in the direction parallel to the axis of rotation of the runner, the turbine is called **mixed flow** turbine.

PELTON WHEEL (Turbine)

It is a tangential flow impulse turbine. The water strikes the bucket along the tangent of the runner. The energy available at the inlet of the turbine is only kinetic energy. The pressure at the inlet and out let of turbine is atmospheric. This turbine is used for high heads and is named after L.A.Pelton an American engineer.

The water from the reservoir flows through the penstocks at the out let of which a nozzle is fitted. The nozzle increases the kinetic energy of the water flowing through the penstock. At the outlet of the nozzle, the water comes out in the form of a jet and strikes the buckets (vanes) of the runner. The main parts of the Pelton turbine are:

Nozzle and flow regulating arrangement (spear)
Runner and Buckets.
Casing and
Breaking jet

Nozzle and flow regulating arrangement: The amount of water striking the buckets (vanes) of the runner is controlled by providing a spear in the nozzle. The spear is a conical needle which is operated either by hand wheel or automatically in an axial direction depending upon the size of the unit. When the spear is pushed forward in to the nozzle, the amount of water striking the runner is reduced. On the other hand, if the spear is pushed back, the amount of water striking the runner increases.

Runner with buckets: It consists of a circular disc on the periphery of which a number of buckets evenly spaced are fixed. The shape of the buckets is of a double hemispherical cup or bowl. Each bucket is divided in to two symmetrical parts by a dividing wall, which is known as splitter.

The jet of water strikes on the splitter. The splitter divides the jet in to two equal parts and the jet comes out at the outer edge of the bucket. The buckets are shaped in such a way that the jet gets deflected through an angle of 160° or 170°. The buckets are made of cast Iron, cast steel, Bronze or stainless steel depending upon the head at the inlet of the turbine.

Casing: The function of casing is to prevent the splashing of the water and to discharge the water to tailrace. It also acts as safeguard against accidents. It is made of Cast Iron or fabricated steel plates. The casing of the Pelton wheel does not perform any hydraulic function.

Breaking jet: When the nozzle is completely closed by moving the spear in the forward direction, the amount of water striking the runner reduces to zero. But the runner due to inertia goes on revolving for a long time. To stop the runner in a short time, a small nozzle is provided, which directs the jet of water on the back of the vanes. This jet of water is called Breaking jet.

Velocity triangles and work done for Pelton wheel:

The jet of water from the nozzle strikes the bucket at the splitter, which splits up the jet into two parts. These parts of the jet, glides over the inner surfaces and comes out at the outer edge. The splitter is the in let tip and outer edge of the bucket is the outlet tip of the bucket. The inlet velocity triangle is drawn at the splitter and outer velocity triangle is drawn at the outer edge of the bucket.

Let

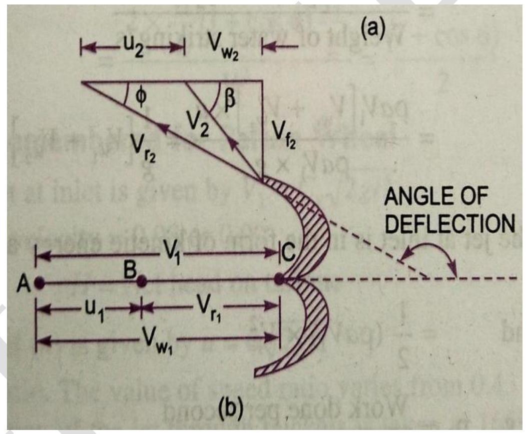
H = Net head acting on the Pelton Wheel

$$= H_g - h_f$$

Where H_g = Gross Head

$$h_f = \frac{4fLV^2}{D^* \times 2g}$$

Where D^* =diameter of penstock,
D = Diameter of wheel,
d = Diameter of Jet,
N = Speed of the wheel in r.p.m



Then V_1 = Velocity of jet at inlet $= \sqrt{2gH}$

$$u = u_1 = u_2 = \frac{\pi DN}{60}$$

The Velocity Triangle at inlet will be a straight line where

$$V_{r_1} = V_1 - u_1 = V_1 - u$$

$$V_{w_1} = V_1 \qquad \alpha = 0^0 \qquad and \;\; \theta = 0^0$$

From the velocity triangle at outlet, we have

$$V_{r_2} = V_{r_1} \; and \; V_{w_2} = V_{r_2} \cos\emptyset - u_2$$

The force exerted by the Jet of water in the direction of motion is

$$F_x = \rho a V_1 \left[V_{w_1} + V_{w_2}\right] \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(1)}$$

As the angle β is an acute angle, +ve sign should be taken. Also this is the case of series of vanes, the mass of water striking is $\rho a V_1$ and not $\rho a V_{r_1}$. In equation (1) „a" is the area of the jet $= \frac{\pi}{4} d^2$

Now work done by the jet on the runner per second

$$= F_x \times u = \rho a V_1 \left[V_{w_1} + V_{w_2}\right] \times u \qquad Nm/s$$

Power given to the runner by the jet $= \dfrac{\rho a V_1 \left[V_{w_1} + V_{w_2}\right] \times u}{1000} \; kW$

Work done/s per unit weight of water striking/s $= \frac{\rho a V_1[V_{w_1}+V_{w_2}]\times u}{Weight\ of\ water \frac{striking}{s}}$

$$= \frac{\rho a V_1[V_{w_1}+V_{w_2}]\times u}{\rho a V_1 \times g} = \frac{1}{g}\left[V_{w_1}+V_{w_2}\right]\times u \quad \text{\_\_\_\_\_\_(3)}$$

The energy supplied to the jet at inlet is in the form of kinetic energy

∴ K.E. of jet per second $= \frac{1}{2}mV^2 = \frac{1}{2}(\rho a V_1)\times {V_1}^2$

∴ **Hydraulic efficiency**, $\eta_h = \frac{Work\ done\ per\ second}{K.E. of\ jet\ per\ second}$

$$= \frac{\rho a V_1[V_{w_1}+V_{w_2}]\times u}{\frac{1}{2}(\rho a V_1)\times {V_1}^2}$$

$$= \frac{2[V_{w_1}+V_{w_2}]\times u}{{V_1}^2} \quad \text{\_\_\_\_\_\_\_\_\_\_\_(4)}$$

Now $V_{w_1} = V_1 \text{ and } V_{r_1} = V_1 - u_1 = (V_1 - u)$

∴ $V_{r_2} = (V_1 - u)$

And $V_{w_2} = V_{r_2}\cos\emptyset - u_2$

$$= V_{r_2}\cos\emptyset - u$$

$$= (V_1 - u)\cos\emptyset - u$$

Substituting the values of V_{w_1} and V_{w_2} in equation (4)

$$\eta_h = \frac{2[V_1+(V_1-u)\cos\emptyset - u]\times u}{{V_1}^2} = \frac{2[V_1-u+(V_1-u)\cos\emptyset]\times u}{{V_1}^2}$$

$$= \frac{2(V_1-u)[1+\cos\emptyset]u}{{V_1}^2} \quad \text{\_\_\_\_\_\_\_\_ (5)}$$

The efficiency will be maximum for a given value of V_1 when

$$\frac{d}{du}(\eta_h) = 0 \ \ or \ \ \frac{d}{du}\left[\frac{2u(V_1-u)[1+\cos\emptyset]}{{V_1}^2}\right] = 0$$

Or $\frac{(1+\cos\emptyset)}{{V_1}^2}\ \frac{d}{du}(2uV_1 - 2u^2) = 0$

Or $\frac{d}{du}[2uV_1 - 2u^2] = 0 \qquad \left(\because \frac{1+\cos\phi}{{V_1}^2} \neq 0\right)$

Or $2V_1 - 4u = 0$ Or $u = \frac{V_1}{2}$ ——(6)————

Equation (6) states that hydraulic efficiency of a Pelton wheel will be maximum when the velocity of the wheel is half the velocity of the jet water at inlet. The expression for maximum efficiency will be obtained by substituting the value of $u = \frac{V_1}{2}$ in equation (5)

Max. $\eta_h = \frac{2\left(V_1 - \frac{V_1}{2}\right)(1+\cos\emptyset)\times\frac{V_1}{2}}{{V_1}^2}$

$$= \frac{2\times\frac{V_1}{2}(1+\cos\emptyset)\frac{V_1}{2}}{{V_1}^2} = \frac{(1+\cos\emptyset)}{2} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_(7)}$$

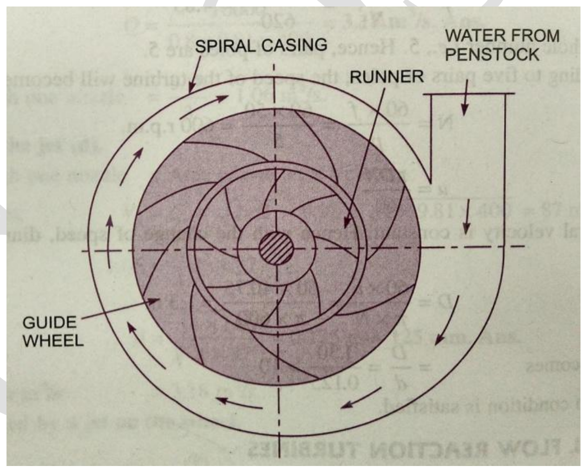
RADIAL FLOW REACTION TURBINE:

In the Radial flow turbines water flows in the radial direction. The water may flow radially from outwards to inwards (i.e. towards the axis of rotation) or from inwards to outwards. If the water flows from outwards to inwards through the runner, the turbine is known as **inwards radial flow turbine**. And if the water flows from inwards to outwards, the turbine is known as **outward radial flow turbine**.

Reaction turbine means that the water at the inlet of the turbine possesses kinetic energy as well as pressure energy. As the water flows through the runner, a part of pressure energy goes on charging into kinetic energy. Thus the water through the runner is under pressure. The runner is completely enclosed in an air-tight casing and the runner is always full of water.

Main parts of a Radial flow Reaction turbine:

Casing
Guide mechanism
Runner and
Draft tube.



Casing: in case of reaction turbine, casing and runner are always full of water. The water from the penstocks enters the casing which is of spiral shape in which area of cross-section one of the casing goes on decreasing gradually. The casing completely surrounds the runner of the turbine. The water enters the runner at constant velocity throughout the circumference of the runner.

Guide Mechanism: It consists of a stationary circular wheel all around the runner of the turbine. The stationary guide vanes are fixed on the guide mechanism. The guide vanes allow the water to strike the vanes fixed on the runner without shock at inlet. Also by suitable arrangement, the width between two adjacent vanes of guide mechanism can be altered so that the amount of water striking the runner can be varied.

Runner: It is a circular wheel on which a series of radial curved vanes are fixed. The surfaces of the vanes are made very smooth. The radial curved vanes are so shaped that the water enters and leaves the runner without shock. The runners are made of cast steel, cast iron or stain less steel. They are keyed to the shaft.

Draft - Tube: The pressure at the exit of the runner of a reaction turbine is generally less than atmospheric pressure. The water at exit can‟t be directly discharged to the tail race. A tube or pipe of gradually increasing area is used for discharging the water from the exit of the turbine to the tail race. This tube of increasing area is called draft-tube.

Inward Radial Flow Turbine: In the inward radial flow turbine, in which case the water from the casing enters the stationary guiding wheel. The guiding wheel consists of guide vanes which direct the water to enter the runner which consists of moving vanes. The water flows over the moving vanes in the inward radial direction and is discharged at the inner diameter of the runner. The outer diameter of the runner is the inlet and the inner diameter is the outlet.

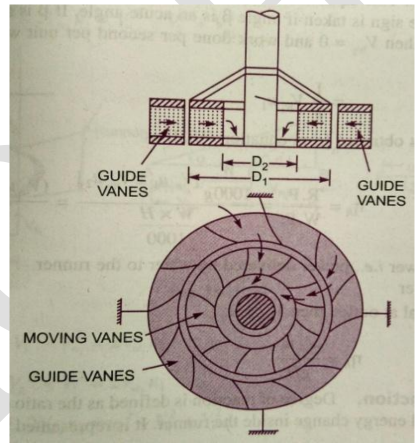
Velocity triangles and work done by water on runner:

Work done per second on the runner by water

$$= \rho a V_1 [V_{w_1} u_1 \pm V_{w_2} u_2]$$

$$= \rho Q [V_{w_1} u_1 \pm V_{w_2} u_2] \quad \_\_\_\_\_\_\_\_\_\_\_\_ (1) \qquad (\because aV_1 = Q)$$

The equation represents the energy transfer per second to the runner.



Where $V_{w_1} =$ Velocity of whirl at inlet

$V_{w_2} =$ Velocity of whirl at outlet

$u_1 =$ Tangential velocity at inlet

$= \frac{\pi D_1 \times N}{60}$, Where $D_1 =$ Outer dia. Of runner,

$u_2 =$ Tangential velocity at outlet

$= \frac{\pi D_2 \times N}{60}$

Where $D_1 =$ Inner dia. Of runner,

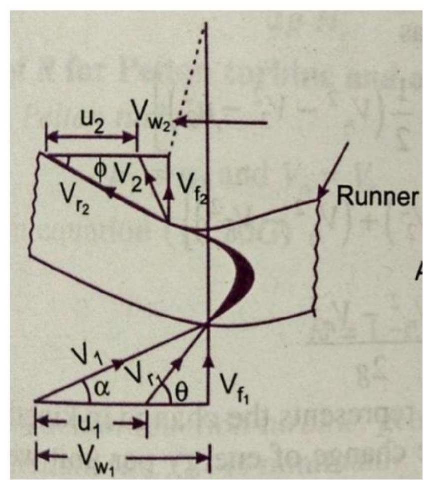
N = Speed of the turbine in r.p.m.

The work done per second per unit weight of water per second

$$= \frac{\text{work done per second}}{\text{weight of water striking per second.}}$$

$$= \frac{\rho Q [V_{w_1} u_1 \pm V_{w_2} u_2]}{\rho Q \times g}$$

$$= \frac{1}{g} [V_{w_1} u_1 \pm V_{w_2} u_2] \quad \_\_\_\_\_\_\_\_\_\_ (2)$$



Equation (2) represents the energy transfer per unit weight/s to the runner. This equation is known by **Euler's equation.**

In equation +ve sign is taken if β is an acute angle,

-ve sign is taken if β is an obtuse angle.

If $\beta = 90^0$ then $V_{w_2} = 0$ and work done per second per unit weight of water striking/s

$$\text{Work done} = \frac{1}{g} V_{w_1} u_1$$

Hydraulic efficiency $\eta_h = \frac{R.P.}{W.P.} = \frac{\text{Power delivered to runner}}{\text{Power supplied at inlet}}$

$$= \frac{\frac{W}{1000 \times g} [V_{w_1} u_1 \pm V_{w_2} u_2]}{\frac{W \times H}{1000}} = \frac{(V_{w_1} u_1 \pm V_{w_2} u_2)}{gH} \quad \_\_\_\_\_\_\_\_\_\_ (3)$$

Where R.P. = Runner Power i.e. power delivered by water to the runner

W.P. = Water Power

If the discharge is radial at outlet, then $V_{w_2} = 0$

$$\eta_h = \frac{V_{w_1} u_1}{gH}$$

Definitions:

The following terms are generally used in case of reaction radial flow turbines which are defined as:

Speed Ratio: The speed ratio is defined as $= \frac{u_1}{\sqrt{2gH}}$

Where $u_1 =$ tangential velocity of wheel at inlet

Flow Ratio: The ratio of velocity of flow at inlet (V_{f_1}) to the velocity given $\sqrt{2gH}$ is known as the flow ratio.

$$= \frac{V_{f_1}}{\sqrt{2gH}}$$

Where H = Head on turbine

Discharge of the turbine: The discharge through a reaction radial flow turbine is

$$Q = \pi D_1 B_1 \times V_{f_1} = \pi D_2 B_2 \times V_{f_2}$$

Where $D_1 =$ Dia of runner at inlet

$D_2 =$ Dia of runner at outlet

$B_1 =$ Width of the runner at inlet

$B_2 =$ Width of runner at outlet

$V_{f_1} =$ Velocity of flow at inlet

$V_{f_2} =$ Velocity of flow at outlet

If the thickness of the vanes are taken into consideration then the area through which flow takes place is given by

$$= \pi D_1 - n \times t$$

Where $n =$ Number of vanes and

Thickness of each vane

Head: The (H) on the turbine is given by

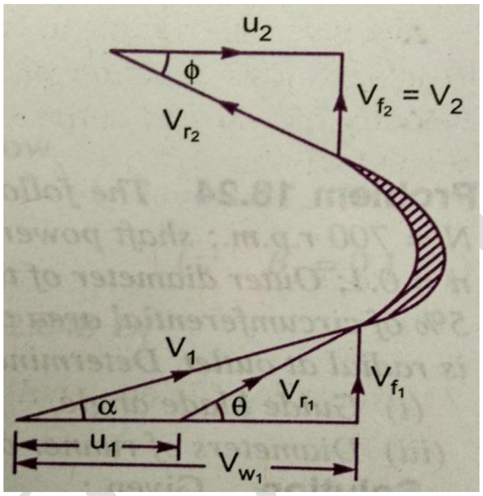
$$H = \frac{P_1}{\rho g} + \frac{V_1^{\,2}}{2g}$$

Where $P_1 =$ Pressure at inlet

Radial Discharge: This means the angle made by absolute velocity with the tangent on the wheel is 90^0 and the component of whirl velocity is zero. The radial discharge at outlet means $\beta = 90^0$ and $V_{w_2} = 0$ while radial discharge at inlet means $\alpha = 90^0$ and $V_{w_1} = 0$

If there is no loss of energy when the water flows through the vanes then we have

$$H - \frac{V_2^{\ 2}}{2g} = \frac{1}{g}\left[V_{w_1}u_1 \pm V_{w_2}u_2\right]$$



FRANCIS TURBINE:

The inward flow reaction turbine having radial discharge at outlet is known as Francis Turbine. The water enters the runner of the turbine in the radial direction at outlet and leaves in the axial direction at the inlet of the runner. Thus the Francis turbine is a mixed flow type turbine.

The velocity triangle at inlet and outlet of the Francis turbine are drawn in the same way as in case of inward flow reaction turbine. As in case of inward radial flow turbine. The discharge of Francis turbine is radial at outlet; the velocity of whirl at outlet (V_{w_2}) will be zero. Hence the work done by water on the runner per second will be

$$= \rho Q\left[V_{w_1}u_1\right]$$

The work done per second per unit weight of water striking/sec = $\frac{1}{g}\left[V_{w_1}u_1\right]$

Hydraulic efficiency $\eta_h = \frac{V_{w_1}u_1}{gH}$

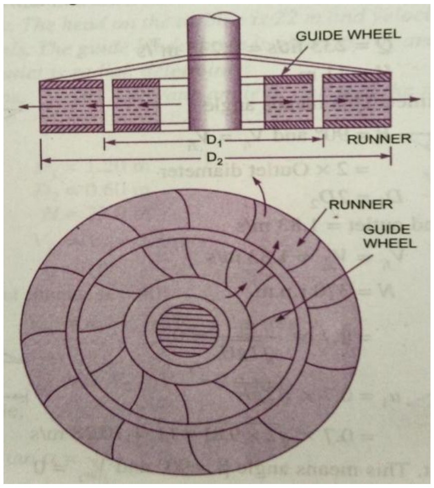
Important relations for Francis turbines:

The ratio of width of the wheel to its diameter is given as $n = \frac{B_1}{D_1}$. The value of n varies from 0.10 to 0.40

The flow ratio is given as

Flow ratio $= \frac{V_{f_1}}{\sqrt{2gH}}$ and varies from 0.15 to 0.30

3. The speed ratio $= \frac{u_1}{\sqrt{2gH}}$ varies from 0.6 to 0.9

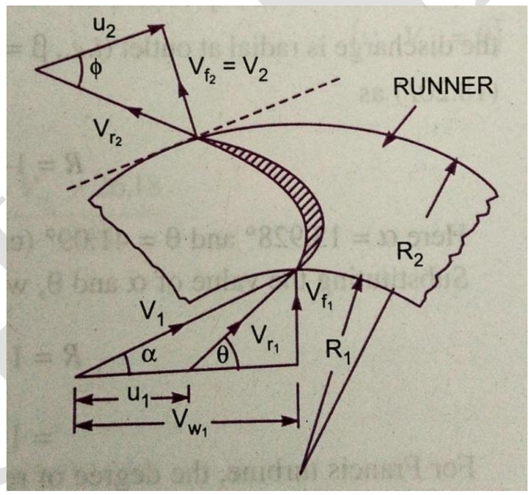


Outward radial Flow Reaction Turbine:

In the outward radial flow reaction turbine water from the casing enters the stationary guide wheel. The guide wheel consists of guide vanes which direct the water to enter the runner which is around the stationary guide wheel. The water flows through the vanes of the runner in the outward radial direction and is discharges at the outer diameter of the runner. The inner diameter of the runner is inlet and outer diameter is the outlet.

The velocity triangles a inlet and outlet will be drawn by the same procedure as adopted for inward flow turbine. The work done by the water on the runner per second, the horse power developed and hydraulic efficiency will be obtained from the velocity triangles. In this case as the inlet of the runner is at the inner diameter of the runner, the tangential velocity at inlet will be less than that of an outlet. i.e.

$u_1 < u_2$ As $D_1 < D_2$ All the working conditions flow through the runner blades without shock. As such eddy losses which are inevitable in Francis and propeller turbines are almost completely eliminated in a Kaplan turbine.



The discharge through the runner is obtained as

$$Q = \frac{\pi}{4}\left(D_0^{\,2} - D_b^{\,2}\right) \times V_{f_1}$$

Where $D_0 =$ outer diameter of the runner

$D_b =$ Diameter of the hub

$V_{f_1} =$ Velocity of flow at inlet

Important points for Kaplan turbine:

1. The peripheral velocity at inlet and outlet are equal.

$$u_1 = u_2 = \frac{\pi D_0 N}{60}$$

Where $D_0 =$ Outer diameter of runner.

Velocity of flow at inlet and outlet are equal.

$$V_{f_1} = V_{f_2}$$

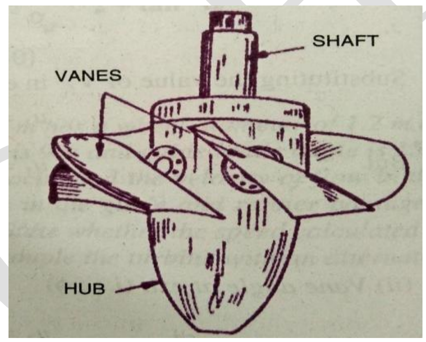
Area of flow at inlet = Area of flow at outlet

$$= \frac{\pi}{4}\left(D_0^{\,2} - D_b^{\,2}\right)$$

AXIAL FLOW REACTION TURBINE:

If the water flows parallel to the axis of the rotation shaft the turbine is known as axial flow turbine. If the head at inlet of the turbine is the sum of pressure energy and kinetic energy and during the flow of the water through the runner a part of pressure energy in converted in to kinetic energy, the turbine is known as reaction turbine.

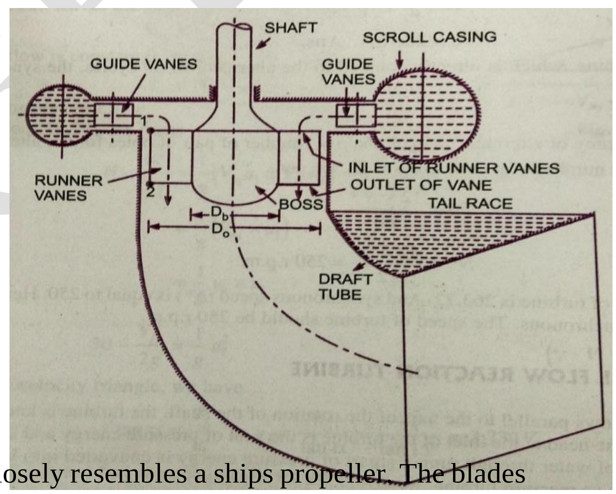
For axial flow reaction turbine, the shaft of the turbine is vertical. The lower end of the shaft is made longer known as "hub" or "boss". The vanes are fixed on the hub and acts as a runner for the axial flow reaction turbine. The important types of axial flow reaction turbines are:



Propeller Turbine
Kaplan Turbine

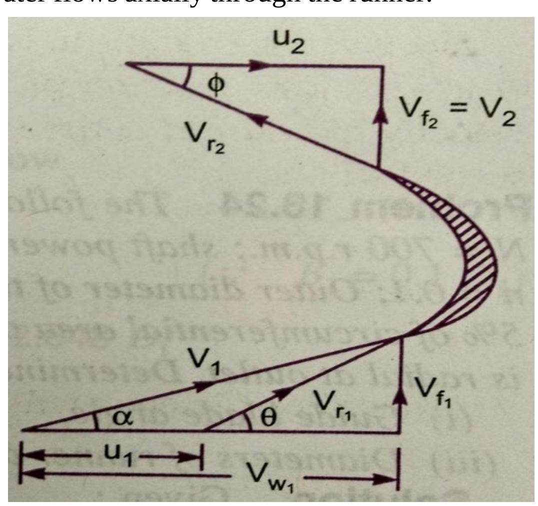
When the vanes are fixed to the hub and they are not adjustable the turbine is known as propeller turbine. But if the vanes on the hub are adjustable, the turbine is known as Kaplan turbine. This turbine is suitable, where large quantity of water at low heads is available.

The main parts of the Kaplan turbine are:



Scroll casing
Guide vanes mechanism
Hub with vanes or runner of the turbine
Draft tube

Between the guide vanes and the runner the water in the Kaplan turbine turns through a right angle in to the axial angle direction and then posses through the runner. The runner of the Kaplan turbine has four or six or eight in some cases blades and it closely resembles a ships propeller. The blades (vanes) attached to a hub or bosses are so shaped that water flows axially through the runner.



The runner blades of a propeller turbine are fixed but the Kaplan turbine runner heads can be turned about their own axis, so that their angle of inclination may be adjusted while the turbine is in motion. The adjustment of the runner blades in usually carried out automatically by means of a servomotor operating inside the hollow coupling of turbine and generator shaft. When both guide vane angle and runner blade angle may thus be varied a high efficiency can be maintained over a wide range of operating conditions. i.e. even at part load, when a lower discharge is following through the runner a high efficiency can be attained in case of Kaplan turbine. The flow through turbine runner does not affect the shape of velocity triangles as blade angles are simultaneously adjusted, the water under all the working conditions flows through the runner blades without shock. The eddy losses which are inevitable in Francis and propeller turbines are completely eliminated in a Kaplan Turbine.

Working Proportions of Kaplan Turbine:

The main dimensions of Kaplan Turbine runners are similar to Francis turbine runner. However the following are main deviations,

Choose an appropriate value of the ratio $n = \frac{d}{D}$, where d in hub or boss diameter and D is runner outside diameter. The value of n varies from 0.35 to 0.6

The discharge Q flowing through the runner is given by

$$Q = \frac{\pi}{4}(D^2 - d^2)V_f = \frac{\pi}{4}(D^2 - d^2)\psi\sqrt{2gH}$$

The value of flow ratio ψ for a Kaplan turbine is 0.7

The runner blades of the Kaplan turbine are twisted, the blade angle being greater at the outer tip than at the hub. This is because the peripheral velocity of the blades being directly proportional to radius. It will valy from section to section along the blade, and hence in order to have shock free entry and exit of water over the blades with angles varying from section to section will have to be designed.

DRAFT TUBE:

The draft tube is a pipe of gradually increasing area, which connects the outlet of the runner to the tail race. It is used for discharging water from the exit of the turbine to the tail race. This pipe of gradually increasing area is called a draft tube. One end of the draft tube is connected to the outlet of the runner and the other end is submerged below the level of water in the tail race. The draft tube in addition to save a passage for water discharge has the following two purposes also:

It permits a negative head to be established at the outlet of the runner and their by increase the net head on the turbine. The turbine may be placed above the tail race without any loss of net head and hence turbine may be inspected properly.

It converts a large portion of the kinetic energy $\left(\frac{V_2{}^2}{2g}\right)$ rejected at the outlet of the turbine into useful energy. Without the draft tube the kinetic energy rejected at the turbine will go waste to the tail race.

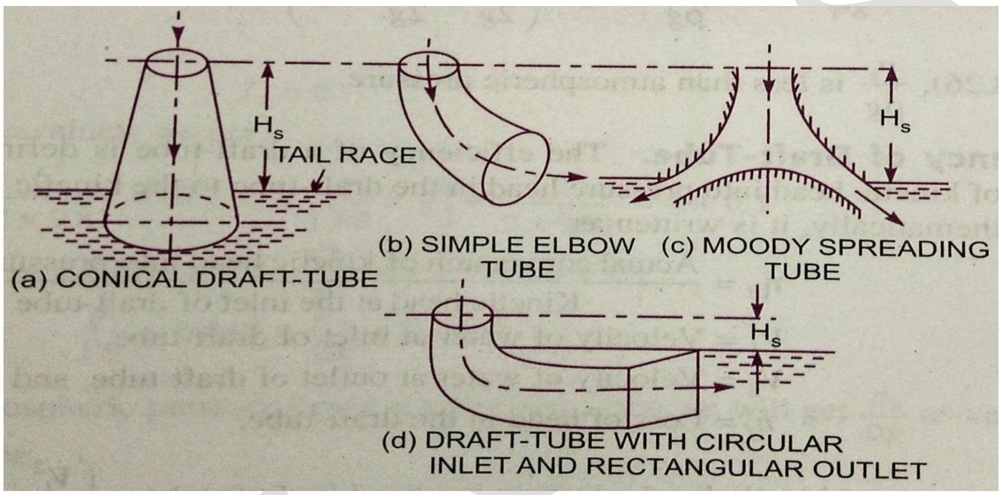
Hence by using the draft tube, the net head on turbine increases. The turbine develops more power and also the efficiency of the turbine increase.

If a reaction turbine is not fitted with a draft tube, the pressure at the outlet of the runner will be equal to atmospheric pressure. The water from the outlet of the runner will discharge freely into the tail race. The net head on the turbine will be less than that of a reaction turbine fitted with a draft tube. Also without draft tube the kinetic energy $\left(\frac{V_2^2}{2g}\right)$ rejected at the outlet of the will go water to the tail race.

Types of Draft Tube:

Conical Draft Tube
Simple Elbow Tubes
Moody Spreading tubes
Elbow Draft Tubes with Circular inlet and rectangular outlet

The conical draft tubes and moody spreading draft tubes are most efficient while simple elbow draft tube and elbow draft tubes with circular inlet and rectangular outlet require less space as compared to other draft tubes.



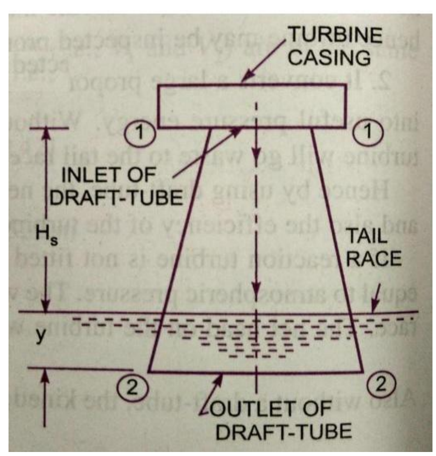
Draft tube theory: Consider a conical draft tube

Vertical height of draft tube above tail race

Y= Distance of bottom of draft tube from tail race.

Applying Bernoulli‟s equation to inlet section 1-1 and outlet section 2-2of the draft tube and taking section 2-2 a datum, we get

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + (H_s + y) = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + 0 + h_f \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_ (1)}$$



Where $h_f =$ loss of energy between section 1-1 and 2-2.

But $\frac{p_2}{\rho g} =$ Atmospheric Pressure + y = $\frac{p_a}{\rho g} + y$

Substituting this value of $\frac{p_2}{\rho g}$ in equation (1) we get

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + (H_s + y) = \frac{p_a}{\rho g} + y + \frac{V_2^2}{2g} + h_f$$

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + H_s = \frac{p_a}{\rho g} + \frac{V_2^2}{2g} + h_f$$

$$\frac{p_1}{\rho g} = \frac{p_a}{\rho g} + \frac{V_2^2}{2g} + h_f - \frac{V_1^2}{2g} - H_s$$

$$\frac{p_1}{\rho g} = \frac{p_a}{\rho g} - H_s - \left[\frac{V_1^2}{2g} - \frac{V_2^2}{2g} - h_f\right] \quad \_\_\_\_\_\_\_\_(2)$$

In equation (2) is less than atmospheric pressure.

Efficiency of Draft Tube: the efficiency of a draft tube is defined as the ratio of actual conversion of kinetic head in to pressure in the draft tube to the kinetic head at the inlet of the draft tube.

$$\eta_d = \frac{Actual\ conversion\ of\ Kinetic\ head\ in\ to\ Pressure\ head}{Kintic\ head\ at\ the\ inlet\ of\ draft\ tube}$$

Let $V_1 =$ Velocity of water at inlet of draft tube

$V_2 =$ Velocity of water at outlet of draft tube

$h_f =$ Loss of head in the draft tube

Theoretical conversion of Kinetic head into Pressure head in

Draft tube $= \left[\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right]$

Actual conversion of Kinetic head into pressure head $= \left[\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right] - h_f$

Now Efficiency of draft tube

$$\eta_d = \frac{\left[\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right] - h_f}{\frac{V_1^2}{2g}}$$

Performance of Hydraulic Turbines

In order to predict the behavior of a turbine working under varying conditions of head, speed, output and gate opening , the results are expressed in terms of quantities which may be obtained when the head on the turbine is reduced to unity. The conditions of the turbine under unit head are such that the efficiency of the turbine remains unaffected. The three important unit quantities are:

Unit speed,
Unit discharge, and
Unit power

Unit Speed: it is defined as the speed of a turbine working under a unit head. It is denoted by $'N_u'$. The expression of unit speed (N_u) is obtained as:

Let N = Speed of the turbine under a head H

H = Head under which a turbine is working

u = Tangential velocity.

The tangential velocity, absolute velocity of water and head on turbine are related as:

$u \propto V$ Where $V \propto \sqrt{H}$

$$\propto \sqrt{H} \quad \_\_\_\_\_\_\_\_\_\_\_\_(1)$$

Also tangential velocity (*u*) is given by

$$u = \frac{\pi D N}{60}$$ Where D = Diameter of turbine.

For a given turbine, the diameter (D) is constant

$$u \propto N \quad \text{Or} \quad N \propto u \quad \text{Or} \quad N \propto \sqrt{H} \quad (\because From\,(1),\, u \propto \sqrt{H})$$

$\therefore$ $N = K_1\sqrt{H}$ __________(2) Where K_1 is constant of proportionality.

If head on the turbine becomes unity, the speed becomes unit speed or

When $H = 1, N = N_u$

Substituting these values in equation (2), we get

$$N_u = K_1\sqrt{1.0} = K_1$$

Substituting the value of K_1 in equation (2)

$$N = N_u\sqrt{H} \quad or \quad N_u = \frac{N}{\sqrt{H}} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_(I)}$$

Unit Discharge: It is defined as the discharge passing through a turbine, which is working under a unit head (i.e. 1 m). It is denoted by $'Q_u'$ the expression for unit discharge is given as:

Let H = head of water on the turbine
Q = Discharge passing through turbine when head is H on the turbine.
a = Area of flow of water

The discharge passing through a given turbine under a head *'H'* is given by,

Q=Area of flow $\times$ Velocity

But for a turbine, area of flow is constant and velocity is proportional to $\sqrt{H}$

$$Q \propto velocity \propto \sqrt{H}$$

Or $Q = K_2\sqrt{H}$ ___________(3)

Where K_2 is constant of proportionality

If H = 1, $Q = Q_u$ (By definition)

Substituting these values in equation (3) we get

$$Q_u = K_2\sqrt{1.0} = K_2$$

Substituting the value of K_2 in equation (3) we get

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

$$Q_u = \frac{Q}{\sqrt{H}} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_(II)}$$

Unit Power: It is defined as the power developed by a turbine working under a unit head (i.e. under a head of 1m). It is denoted by $'P_u'$. The expression for unit power is obtained as:

Let H= Head of water on the turbine
P= Power developed by the turbine under a head of H
Q= Discharge through turbine under a head H

The overall efficiency (η_0) is given as

$$\eta_0 = \frac{Power\ developed}{Water\ power} = \frac{P}{\frac{pgQH}{1000}}$$

$$P = \eta_0 \times \frac{pgQh}{1000}$$

$$\propto Q \times H \quad \propto \sqrt{H} \times H \qquad (\because Q \propto \sqrt{H})$$

$$\propto H^{\frac{3}{2}}$$

$$P = K_3 H^{3/2}$$ ________ (4) Where K_3 is a constant of proportionality

When H=1 m, $P = P_u$

$$\therefore \quad P_u = K_3(1)^{3/2} \quad = K_3$$

Substituting the value of K_3 in equation (4) we get

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

$$P_u = \frac{P}{H^{3/2}}$$ ____________ **(III)**

Use of Unit Quantities $(N_u\ ,\ Q_u\ ,\ P_u)$:

If a turbine is working under different heads, the behaviour of the turbine can be easily known from the values of the unit quantities i.e. from the value of unit speed, unit discharge and unit power.

Let H_1, H_2, H_3,----------are the heads under which a turbine works,
N_1, N_2, N_3,-----------are the corresponding speeds,
Q_1, Q_2, Q_3,----------are the discharge and
P_1, P_2, P_3,---------- are the power developed by the turbine.

Using equation I, II, III respectively,

$$\left.\begin{aligned} N_u &= \frac{N_1}{\sqrt{H_1}} = \frac{N_2}{\sqrt{H_2}} = \frac{N_3}{\sqrt{H_3}} \\ Q_u &= \frac{Q_1}{\sqrt{H_1}} = \frac{Q_2}{\sqrt{H_2}} = \frac{Q_3}{\sqrt{H_3}} \\ P_u &= \frac{P_1}{{H_1}^{3/2}} = \frac{P_2}{{H_2}^{3/2}} = \frac{P_3}{{H_3}^{3/2}} \end{aligned}\right\}$$ ____________(IV)

Hence, if the speed, discharge and power developed by a turbine under a head are known, then by using equation (IV) the speed, discharge, power developed by the same turbine a different head can be obtained easily.

CHARACTERISTIC CURVES OF HYDRAULIC TURBINES:

Characteristic curves of a hydraulic turbine are the curves, with the help of which the exact behaviour and performance of the turbine under different working conditions can be known. These curves are plotted from the results of the tests performed on the turbine under different working conditions.

The important parameters which are varied during a test on turbine are:

1) Speed (N)	2)Head (H)	3)Discharge (Q)
4) Power (P)	5)Overall Efficiency (η_0) and	6)Gate opening.

Out of the above six parameters, three parameters namely speed (N), Head (H) and discharge (Q) are independent parameters.

Out of the three independent parameters, (N, H, Q) one of the parameter is kept constant (say H) and the variation of other two parameters with respect to any one of the remaining two independent variables (say N and Q) are plotted and various curves are obtained. These curves are called characteristic curves. The following are the important characteristic curves of a turbine.

Main Characteristic Curves or Constant Head Curves.
Operating Characteristic Curves or Constant Speed Curves.
Muschel Curves or Constant Efficiency Curves.

GOVERNING OF TURBINES

The governing of a turbine is defined as the operation by which the speed of the turbine is kept constant under all conditions of working. It is done automatically by means of a governor which regulates the rate of flow through turbines according to the changing load conditions on the turbine.

Governing of a turbine is necessary as a turbine is directly coupled to an electric generator, which is required to run at constant speed under all fluctuating load conditions. The frequency of power generation by a generator of constant number of pairs of poles under all varying conditions should be constant. This is only possible when the speed of the generator, under all changing load condition, is constant. The speed of the generator will be constant, when the speed of the turbine (which is coupled to the generator) is constant.

When the load on the generator decreases, the speed of the generator increases beyond the normal speed (constant speed). Then the speed of the turbine also increases beyond the normal speed. If the turbine or the generator is to run at constant (normal) speed, the rate of flow of water to the turbine should be decreased it-till the speed becomes normal. This process by which the speed of the turbine (and hence generator) is kept constant under varying conditions of load is called governing.

Governing of Pelton Turbine (Impulse Turbine):

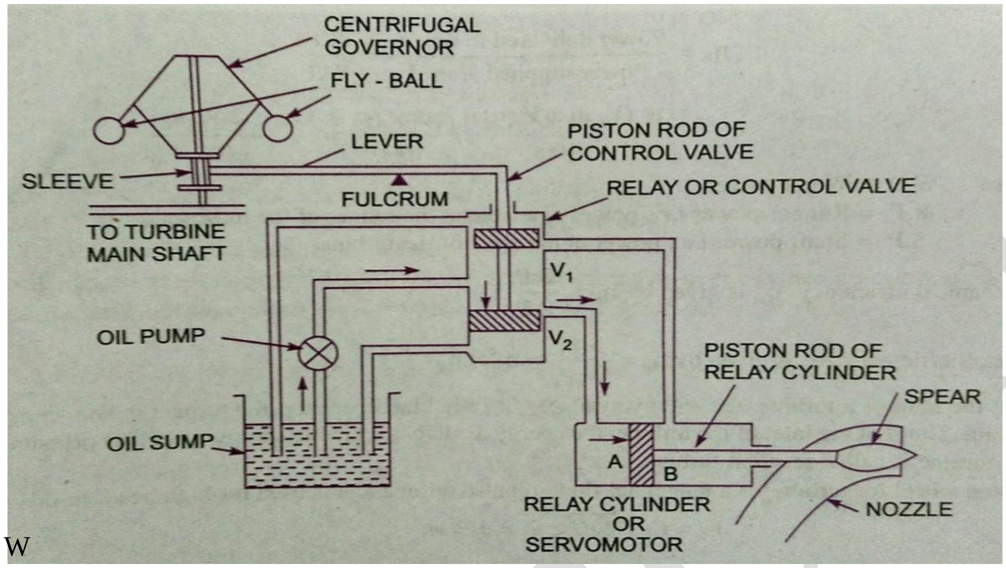
Governing of Pelton turbine is done by means of oil pressure governor, which consists of the following parts.

Oil sump.
Gear pump is also called Oil pump, which is driven by the power obtained from turbine shaft.
The Servomotor or relay cylinder.
The control valve.

The centrifugal valve.

Pipes connecting oil sump and control valve

The spear rod.



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Then the load on the generator decreases, the speed of the generator increases. This increases the speed of the turbine beyond normal speed. The centrifugal governor, which is connected to the turbine main shaft, will be rotating at an increased speed. Due to increase in the speed of the centrifugal governor, the fly balls move upwards due to increased centrifugal force on them. Due to the upward movement of the fly balls, the sleeve will also move upward. A horizontal lever, supported over a fulcrum, connect the sleeve and the piston rod of the control valve moves downward. This closes the valve V_1 and opens the valve V_2.

The oil pumped from the oil sump to the control valve, under pressure will flow through valve V_2 to the servomotor or relay cylinder and will exert force on the face A of the piston of the relay cylinder. The piston along the piston rod and spear will move towards right. This will decrease the area of flow of water to the turbine which consequently reduces the speed of the turbine. When the speed of the turbine becomes normal, the fly balls, sleeve, lever and piston rod of control valve comes to its normal piston.

When the load on the generator increases, the speed of the generator and hence the turbine decreases. The speed of the centrifugal governor also decreases and hence the centrifugal force acting on the fly-balls also reduces. This brings the fly-balls in the down ward direction. Due to this, the sleeve moves downward and the lever turns about the fulcrum, moving the piston rod of the control valve in the upward direction. This closes the valve V_2 and opens valve V_1. The oil under pressure from the control valve will move through the valve V_1 to the servomotor and will exert force on the face B of the piston. This will move the piston along with piston rod and spear towards left, increasing the area of flow of water at the outlet of the nozzle. This will increase the rate of flow of water to the turbine and consequently, the speed of the turbine will also increase, till the speed of the turbine becomes normal.

Selection of Types of Turbine:

Selection of a suitable type of turbine is usually governed by

i) Head and Specific Speed. ii) Part load Operation.

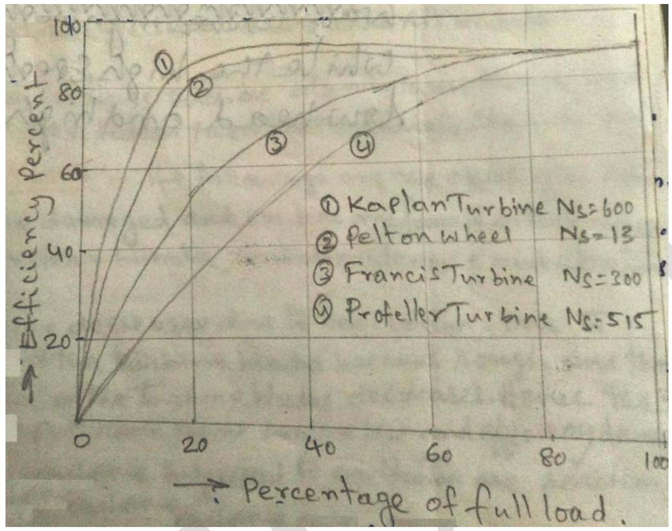
Head and Specific Speed: It has been found that there is a range of head and specific speed for which each type of a turbine is most suitable.

S. No	Head in meters	Types of Turbine	Specific Speed
1	300 or more	Pelton wheel single or multiple Jet	8.5 to 47
2	150-300	Pelton or Francis	30 to 85
3	60-150	Francis	85 to 188
4	Less than 60	Kaplan or Propeller	188 to 860

A turbine with highest permissible specific speed should be chosen which will be cheapest and relatively small in size and high rotational speed will reduce the size of the generator as well as the power house. But the specific speed cannot be increased indefinitely because it results is cavitations. The cavitations may be avoided by installing the turbine at a lower level with respect to the tail race.

Part load Operation: The turbines may be required to work with considerable load variations. As the load derivates from the normal working load, the efficiency would also vary.

At part load the performance of Kaplan and pelton turbines is better in comparison to that of Francis and Propeller turbines. The variability of load will influence the choice of type of turbine, if the head lies between 150m to 300m or lies below 30m. For higher range of heads pelton wheel is preferable for part load operation in comparison to Francis turbine, through the former involves higher initial cost. For heads below 30m Kaplan turbine is preferable for part load operation in comparison to propeller turbine.



In addition to the above factors the overall cost, which includes the initial cost and running cost should be considered. The cavitations characteristics of the turbine should be considered.

Specific Speed (N_s):

The specific speed of a turbine is defined as the speed of a geometrically similar turbine that would develop 1kW under 1 m head. All geometrically similar turbines (Irrespective of sizes) will have the same specific speeds when operating under the same speed.

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

Where N=Normal working speed

P = Power output of the turbine

H = The net or effective head in meters.

The turbine with low specific speeds work under high and low discharge conditions, while the high specific speed turbines work under low head and high discharge conditions.

Cavitation : Cavitation is defined as the phenomenon of formation of vapour bubbles of a flowing liquid in a region, where the pressure of the liquid falls below its vapour pressure and the sudden collapsing of these vapour bubbles in a region of higher pressure. When the vapour bubbles collapse, a very high pressure is created. The metallic surfaces, above which these vapour bubbles collapse, is subjected to these high pressures, which cause pitting action on the surface. Thus cavities are formed on the metallic surface and also considerable noise and vibrations are produced.

Cavitation includes formation of vapour bubbles of the flowing liquid and collapsing of the vapour bubbles. Formation of vapour bubbles of the flowing liquid take place only whenever the pressure in any region falls below vapour pressure. When the pressure of the flowing liquid is less than its vapour pressure, the liquid starts boiling and the vapour bubbles are formed. These vapour bubbles are carried along with the flowing liquid to higher pressure zones, where these vapour condense and the bubbles collapse. Due to sudden collapsing of the bubbles on the metallic surface, high pressure is produced and metallic surfaces are subjected to high local stress. Thus the surfaces are damaged.

Precaution against Cavitation: The following are the Precaution against cavitation

The pressure of the flowing liquid in any part of the hydraulic system should not be allowed to fall below its vapour pressure. If the flowing liquid is water, then the absolute pressure head should not be below 2.5m of water.

The special materials or coatings such as Aluminum-bronze and stainless steel, which are cavitation resistant materials, should be used.

Effects of Cavitation: the following are the effects of cavitation.

The metallic surfaces are damaged and cavities are formed on the surfaces.

Due to sudden collapse of vapour bubbles, considerable noise and vibrations are produced.

The efficiency of a turbine decreases due to cavitation. Due to pitting action, the surface of the turbine blades becomes rough and the force exerted by the water on the turbine blades decreases. Hence, the work done by water or output horse power becomes less and efficiency decreases.

Hydraulic Machines Subjected to Cavitation: The hydraulic machines subjected to Cavitation are reaction turbine and centrifugal pumps.

Cavitation in Turbines: in turbines, only reaction turbines are subjected to cavitation. In reaction turbines the cavitation may occur at the outlet of the runner or at the inlet of the draft tube where the pressure is considerably reduced. (i.e. which may be below vapour pressure of the liquid flowing through the turbine) Due to cavitation, the metal of the runner vanes and draft tube is gradually eaten away, which results in lowering the efficiency of the turbine. Hence the cavitation in a reaction turbine can be noted by a sudden drop in efficiency. In order to determine whether cavitation will occur in any portion of a reaction turbine, the critical value of Thoma"s cavitation factors σ sigma is calculated.

$$\sigma = \frac{H_b - H_s}{H} = \frac{(H_{atm} - H_v) - H_s}{H} ,$$

Where $H_b =$ Barometric pressure head in m of water,

$H_{atm} =$ Atmospheric pressure head in m of water,

$H_v =$ Vapour pressure head in m of water,

$H_s =$ Suction pressure at the outlet of reaction turbine in m of water or height of turbine runner above the tail water surface,

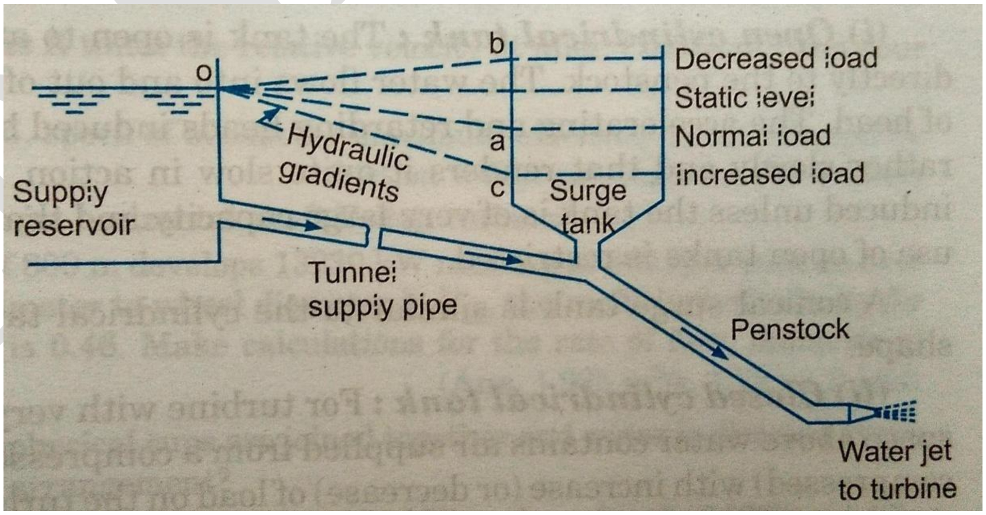
H = Net head on the turbine in m.

Surge Tank:

When the load on the generator decreases, the governor reduces the rate of flow of water striking the runner to main constant speed for the runner. The sudden reaction of rate of flow in the penstock may lead to water hammer in pipe due to which the pipe may burst. When the load on the generator increases the turbine requires more water. Sugar tank and fore bays are usually employed to meet the above requirements. Surge tanks are employed in case of high head and medium head hydro power plants where the penstock is very long and fore bays are suitable for medium and low head hydro power plants where the length of penstock is short.

An ordinary sugar tank is a cylindrical open toped storage reservoir, which is connected to the penstock at a point as close as possible to the turbine. The upper lip of the tank is kept well above the maximum water level in the supply reservoir. When the load on the turbine is steady and normal and there are no velocities variations in the pipe line there will be normal pressure gradient oaa_1. The water surface in the surge tank will be lower than the reservoir surface by an amount equal to friction head loss in the pipe connecting reservoir and sugar tank. When the load on the generator is reduced, the turbine gates are closed and the water moving towards the turbine has to move back ward. The rejected water is then stored in the surge tank, raising the pressure gradient. The retarding head so built up in the surge tank reduces the velocity of flow in the pipe line corresponding to the reduced discharge required by the turbine.

When the load on the generator increases the governor opens the turbine gates to increase the rate of flow entering the runner. The increased demand of water by the turbine is partly met by the water stored in the surge tank. As such the water level in the surge tank falls and falling pressure gradient is developed. In other words, the surge tank develops an accelerating head which increases the velocity of flow in the pipe line to a valve corresponding to the increased discharge required by the turbine.



CENTRIFUGAL PUMPS

The hydraulic machines which convert the mechanical energy in to hydraulic energy are called pumps. The hydraulic energy is in the form of pressure energy. If the mechanical energy is converted in to pressure energy by means of centrifugal force acting on the fluid, the hydraulic machine is called centrifugal pump.

The centrifugal pump acts as a reversed of an inward radial flow reaction turbine. This means that the flow in centrifugal pumps is in the radial outward directions. The centrifugal pump works on the principle of forced vertex flow which means that when a certain mass of liquid is rotated by an external torque, the rise in pressure head of the rotating liquid takes place. The rise in pressure head at any point of the rotating liquid is proportional to the square of tangential velocity of the liquid at that point. (i.e. rise in pressure head = 2 2
or 2 2 2). Thus the outlet of the impeller, where radius is more, the rise in pressure head will be more and the liquid will be discharged at the outlet with a high pressure head. Due to this high pressure head, the liquid can be lifted to a high level.

The following are the main parts of a centrifugal pump.

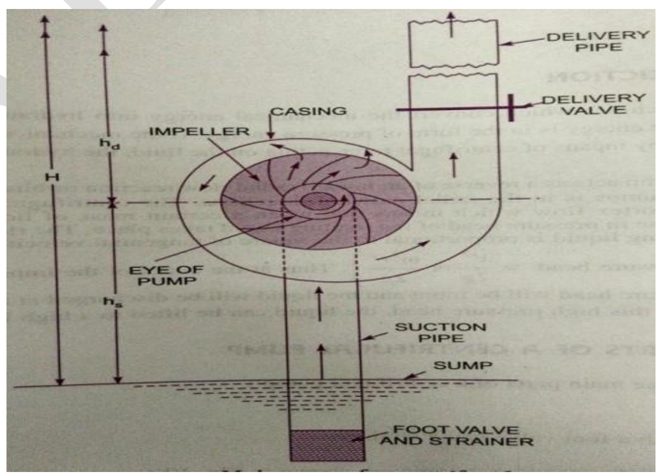
1) Impeller. 2) Casing. 3) Suction pipe with foot valve and a strainer 4) Delivery pipe.

Impeller: The rotating part of a centrifugal pump is called impeller. It consists of a series of backward curved vanes. The impeller is mounted on a shaft which is connected to the shaft of an electric motor.

Casing: the casing of a centrifugal pump is similar to the casing of a reaction turbine. It is an air tight passage surrounding the impeller and is designed in such a way that the kinetic energy of the water discharged at the outlet of the impeller is converted in to pressure energy before the water leaves the casing and enters the delivery pipe. The following three types of the casing are commonly adopted.

a) Volute b) Vortex

c) Casing with guide blades



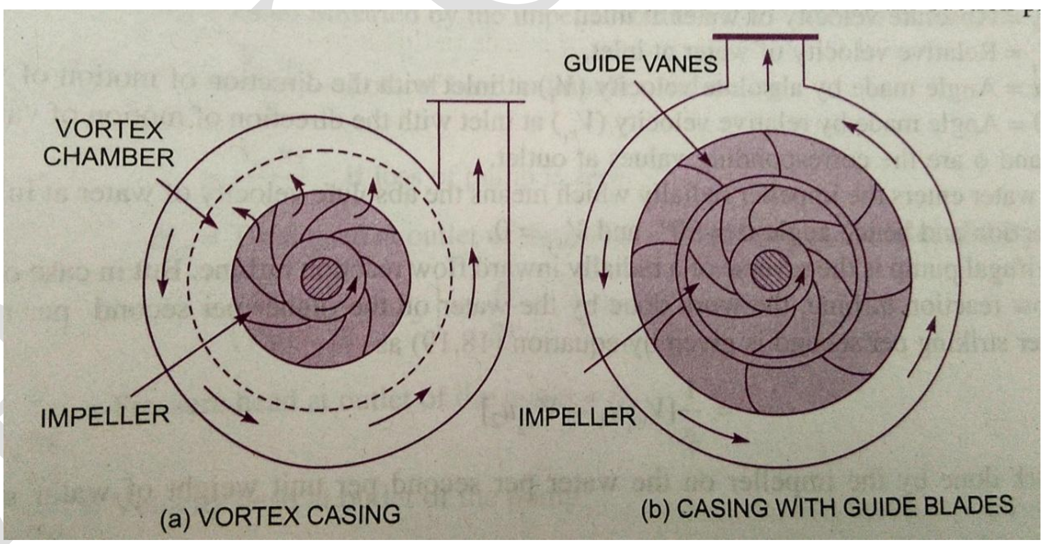
Volute Casing: It is the casing surrounding the impeller. It is of a spiral type, in which area of flow increases gradually. The increase in area of flow decreases the velocity of flow. The decrease in velocity increases the pressure of the water flowing through the casing. It has been observed that in case of volute casing, the efficiency of the pump increase slightly as a large amount of energy in lost due to the formation of eddies in this type of casing.

Vortex Casing: If a circular chamber is introduced between the casing and the impeller, the casing is known as vortex casing. By introducing the circular chamber, the loss of energy due to the formation of eddies is reduced to a considerable extent. Thus the efficiency of the pump is more than the efficiency when only volute casing is provided.

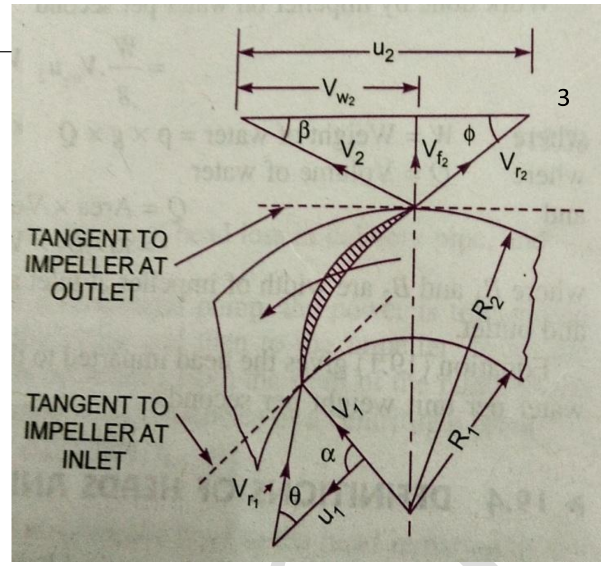
Casing with guide blades: in this type of casing the impeller is surrounded by a series of guide blades mounted on a ring known as diffuser. The guide vanes are designed in which away that the water from the impeller enters the guide vanes without shock.

Also the area of guide vanes increases thus reducing the velocity of flow through guide vanes and consequently increasing the pressure of the water. The water from the guide vanes then pass through the surrounding casing, which is in most of the cases concentric with the impeller.

Suction pipe with a foot valve and a strainer: A pipe whose one end is connected to the inlet of the pump and other end dips in to water in a sump is known as suction pipe. A foot valve which is a non-return valve or one-way type of valve is fitted at the lower end of the suction pipe. The foot valve opens only in the upward direction. A strainer is also fitted at the lower end of the suction pipe.



Delivery pipe: A pipe whose one end is connected to the outlet of the pump and the other end delivers the water at the required height is known as delivery pipe.



Work done by the centrifugal pump on water:

In the centrifugal pump, work is done by the impeller on the water. The expression for the work done by the impeller on the water is obtained by drawing velocity triangles at inlet and outlet of the impeller in the same way as for a turbine. The water enters the impeller radially at inlet for best efficiency of the pump, which means the absolute velocity of water at inlet makes an angle of 90^0 with the direction of motion of the impeller at inlet. Hence angle = 90^0 and $_1$ = 0 for drawing the velocity triangles the same notations are used as that for turbines.

Let N = Speed of the impeller in r.p.m.

$_1$ = Diameter of impeller at inlet

A centrifugal pump is the reverse of a radially inward flow reaction turbine. But in case of a radially inward flow reaction turbine, the work done by the water on the runner per second per unit weight of the water striking per second is given by equation.

= 1 1 1 − 2 2

Head imparted to the water by the impeller or energy given by impeller to water per unit weight per second

HEADS OF A CENTRIFUGAL PUMP:

Suction Head: It is the vertical height of the centre line of centrifugal pump, above the water surface in the tank or sump from which water is to be lifted. This height is also called suction lift ′ ′.

Delivery Head: The vertical distance between the centre line of the pump and the water surface in the tank to which water is delivered is known as delivery head. This is denoted by ′ ′.

Static Head: The sum of suction head and delivery head is known as statics head′ ′.

= +

Manometric Head : Manometric head is defined as the head against which a centrifugal pump has to work. It is denoted by .

Efficiencies of a Centrifugal Pump: In a centrifugal pump, the power is transmitted from electric motor shaft to pump shaft and then to the impeller. From the impeller, the power is given to the water. Thus the power is decreasing from the shaft of the pump to the impeller and then to the water. The following are the important efficiencies of a centrifugal pump:

a) Manometric efficiency, b) Mechanical efficiency, and

Overall efficiency, 0.

Manometric Efficiency : The ratio of the Manometric head to the head imparted by the impeller to the water is known as

=

= =

The ratio of power given to the water at outlet of the pump to the power available at the impeller is known as Manometric efficiency.

The power given to the water at outlet of the pump = 1000

The power at the impeller of the pump is more than the power given to the water at outlet of the pump.

1000

b) **Mechanical Efficiency :** The power at the shaft of the centrifugal pump is more the power available at the impeller of the pump. The ratio of the power available at the impeller to the power at the shaft of the centrifugal pump is known as mechanical efficiency.

Overall Efficiency : It is defined as the ratio of power output of the pump to the power input to the pump.

The power output of the pump in kW = 1000 1000

The power input to the pump = Power supplied by the electric motor = S.P. Of the pump

∴ =

= ×

SPECIFIC SPEED OF A CENTRIFUGAL PUMP :

The specific speed of a centrifugal pump is defined as the speed of a geometrically similar pump, which would deliver one cubic meter of liquid per second against a head of one meter. It is denoted by ′ ′.

The discharge Q for a centrifugal pump is given by the relation

=×

= × × Or ∝ × × (1)

Where D = Diameter of the impeller of the pump and

B = Width of the impeller

We know that ∝

From equation (1) we have ∝ 2 × (2)

We also know that the tangential velocity is given by

= ____∝ ____________(3)

60

Now the tangential velocity (u) and velocity of floware related to Manometric headas

∝ ∝ __________ (4)

Substituting the value of (u) in equation (3), we get

∝ Or ∝

Substituting the values of D in equation (2)

∝ 2 ×

∝ ∝

2

2 3/2

Where K is a constant of proportionality (5)

If = 1 and = 1 3/ N becomes Substituting these values in equation (5), we get

1 = 1 3/2 = 2 = 2

3/2

= 2

Substituting the value of K in equation (5), we get (6)

3/2

= 2

2

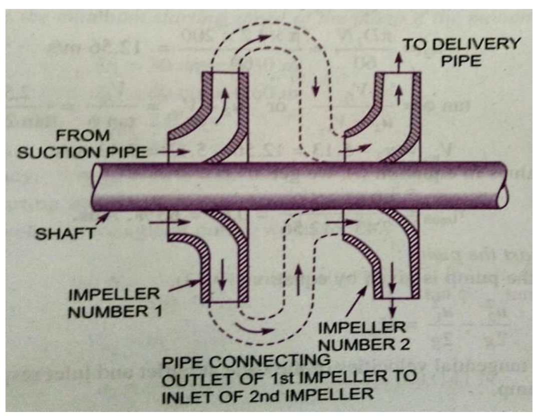
=

MULTI- STAGE CENTRIFUGAL PUMPS:

If centrifugal pump consists of two or more impellers, the pump is called a multi-stage centrifugal pump. The impeller may be mounted on the same shaft or on different shafts. A multi- stage pump is having the following two important functions:

1) To produce a high head and 2) To discharge a large quantity of liquid.

If a high head is to be developed, the impellers are connected in series (or on the same shaft) while for discharging large quantity of liquid, the impellers (or pumps) are connected in parallel.



Multi-Stage Centrifugal Pumps for High Heads: For developing a high head, a number of impellers are mounted in series on the same shaft.

The water from suction pipe enters the 1st impeller at inlet and is discharged at outlet with increased pressure. The water with increased pressure from the outlet of the 1st impeller is taken to the inlet of the 2nd impeller with the help of a connecting pipe. At the outlet of the 2nd impeller the pressure of the water will be more than the water at the outlet of the 1st impeller. Thus if more impellers are mounted on the same shaft, the pressure at the outlet will be increased further.

Let n= Number of identical impellers mounted on the same shaft,

= Head developed by each impeller.

Then total Head developed = ×

The discharge passing through each impeller is same.

Multi-Stage Centrifugal Pumps for High Discharge:

For obtaining high discharge, the pumps should be connected in parallel. Each of the pumps lifts the water from a common sump and discharges water to a common pipe to which the delivery pipes of each pump is connected. Each of the pumps is working against the same head.

Let n = Number of identical pumps arranged in parallel.

Q = Discharge from one pump.

∴ Total Discharge = ×