UNIT -4
HYDRAULIC TURBINE

TURBINES

Turbines are defined as the hydraulic machines which convert **hydraulic energy** into **mechanical energy.**

This mechanical energy is used in running an electric generator which is directly coupled to the shaft of the turbine. Thus the mechanical energy is converted into electrical energy.

The electric power which is obtained from the hydraulic energy (energy of water) is known as **Hydroelectric power.**

At present the generation of hydroelectric power is the cheapest as compared by the power generated by other sources such as oil, coal etc.

GENERAL LAYOUT OF A HYDROELECTRIC POWER PLANT

layout of a hydroelectric power plant which consists of:

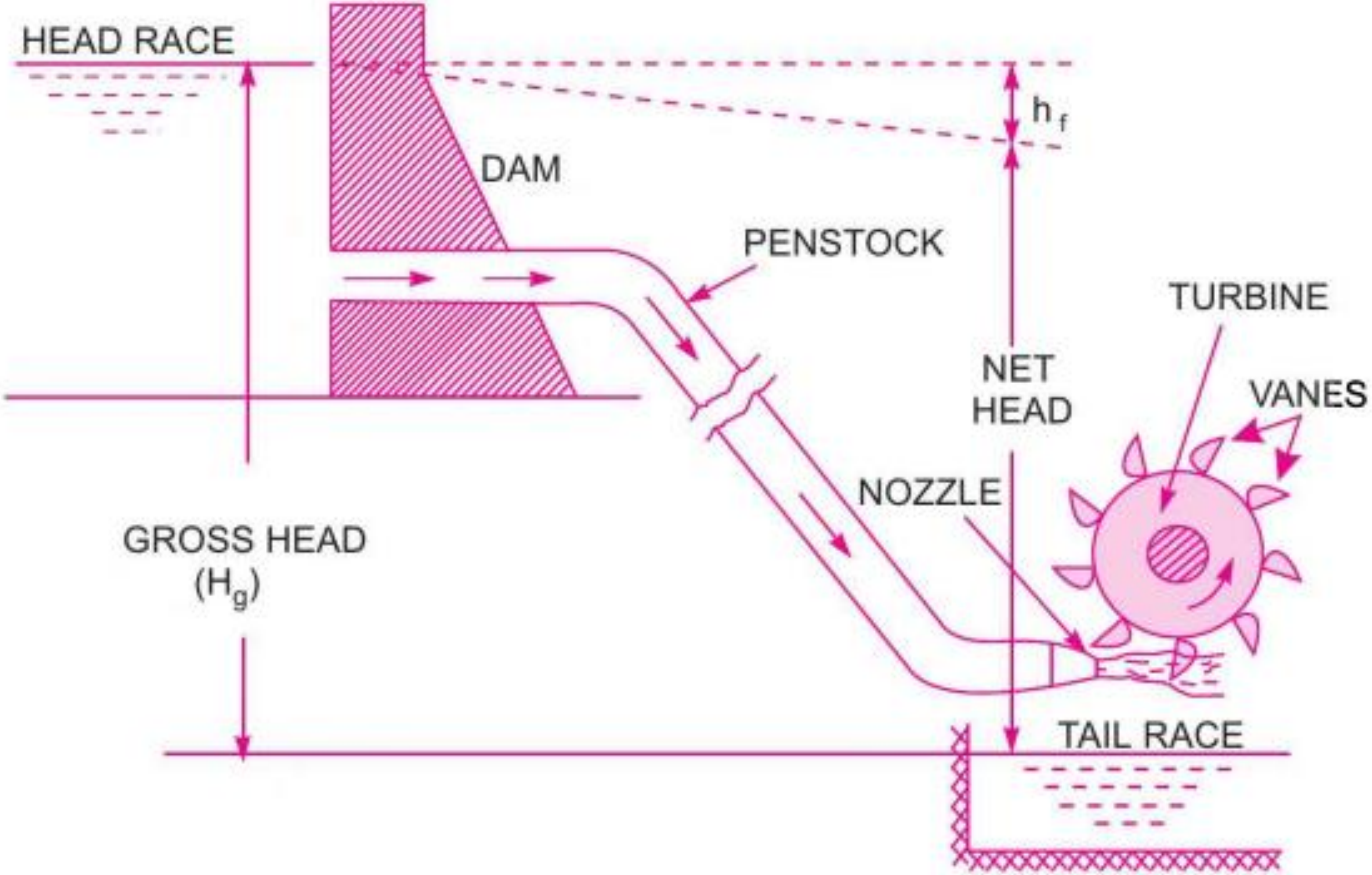
(i) A dam constructed across a river to store water.

(ii) Pipes of large diameters called penstocks, which carry water under pressure from the storage reservoir to the turbines. These pipes are made of steel or reinforced concrete.

(iii) Turbines having different types of vanes fitted to the wheels.

(iv) Tail race, which is a channel which carries water away from the turbines after the water has worked on the turbines.

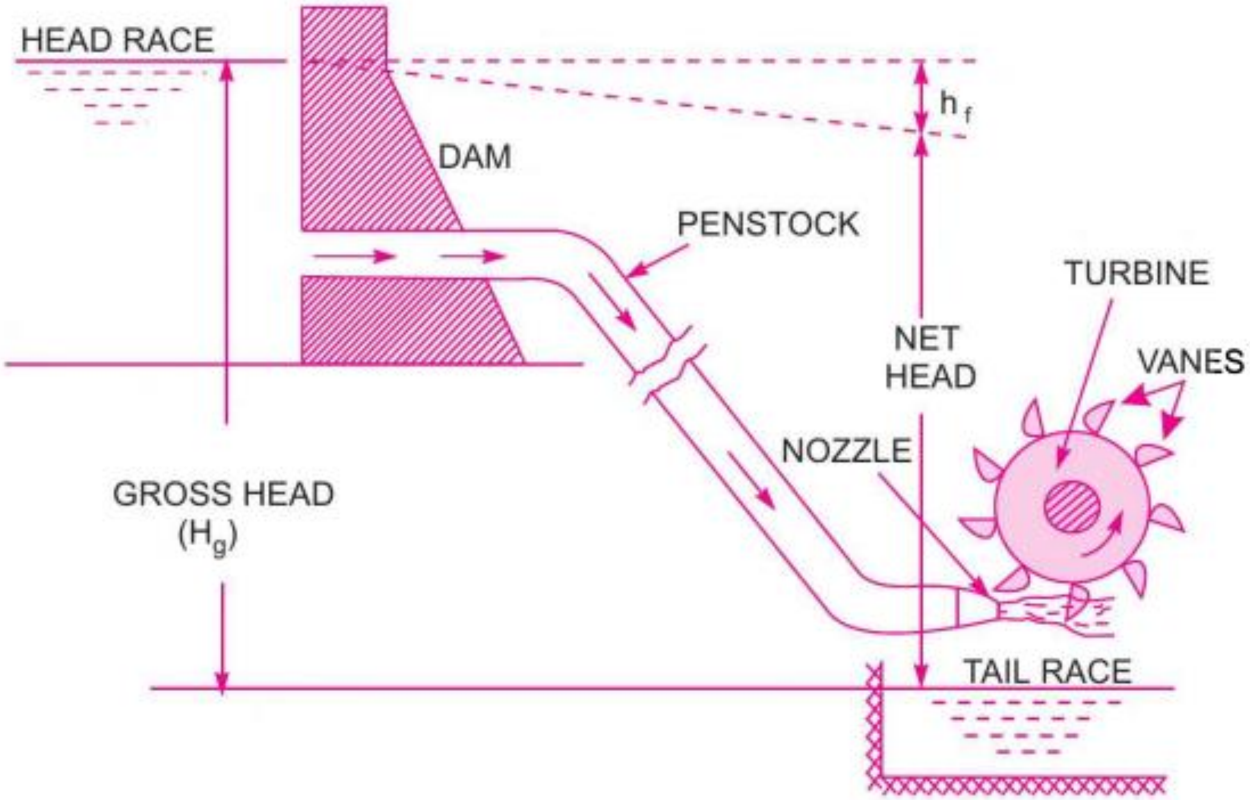
The surface of water in the tail race channel is also known as tail race.



Layout of a hydroelectric power plant.

DEFINITIONS OF HEADS AND EFFICIENCIES OF A TURBINE

1. Gross Head. The difference between the head race level and tail race level when no water is flowing is known as Gross Head. It is denoted by 'H'



Layout of a hydroelectric power plant.

2. Net Head. It is also called effective head and is defined as the head available at the inlet of the turbine. When water is flowing from head race to the turbine, a loss of head due to friction between the water and penstocks occurs.

Though there are other losses also such as loss due to bend, pipe fittings, loss at the entrance of penstock etc., yet they are having small magnitude as compared to head loss due to friction.

If 'h_f' is the head loss due to friction between penstocks and water then net heat on turbine is given by

$$H = H_g - h_f$$

where H_g = Gross head, $h_f = \frac{4 \times f \times L \times V^2}{D \times 2g}$,

V = Velocity of flow in penstock,

L = Length of penstock,

D = Diameter of penstock.

3. Efficiencies of a Turbine.

The following are the important efficiencies of a turbine.

(a) Hydraulic Efficiency,

(b) Mechanical Efficiency,

(c) Volumetric Efficiency,

(d) Overall Efficiency,

(a) Hydraulic Efficiency (η_h).

It is defined as the ratio of power given by 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.**

Thus, mathematically, the hydraulic efficiency of a turbine is written as

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

where R.P. = Power delivered to runner *i.e.*, runner power

$$= \frac{W}{g} \frac{\left[V_{w_1} \pm V_{w_2}\right] \times u}{1000} \text{ kW}$$ ...for Pelton Turbine

$$= \frac{W}{g} \frac{\left[V_{w_1} u_1 \pm V_{w_2} u_2\right]}{1000} \text{ kW}$$ ...for a radial flow turbine

W.P. = Power supplied at inlet of turbine and also called water power

$$= \frac{W \times H}{1000} \text{ kW}$$

W = Weight of water striking the vanes of the turbine per second

$= \rho g \times Q$ in which Q = Volume of water/s,

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 for radial vane,

u_2 = Tangential velocity of vane at outlet for radial vane,

H = Net head on the turbine.

Power supplied at the inlet of turbine in S.I.units is known as water power. It is given by

$$\text{W.P.} = \frac{\rho \times g \times Q \times H}{1000} \text{ kW} \qquad \rho = 1000 \text{ kg/m}^3$$

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

(b) Mechanical Efficiency (η_m).

The power delivered by 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 a turbine.

The ratio of the 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. Hence, mathematically, it is written as

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

(c) Volumetric Efficiency (η_v).

The volume of the water striking the runner of a turbine is slightly less than the volume of the water supplied to the turbine.

Some of the volume of the water is discharged to the tail race without striking the runner of the turbine. Thus the ratio of the volume of the water actually striking the runner to the volume of water supplied to the turbine is defined as **volumetric efficiency.** It is written as

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

(d) 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. It is written as :

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

$$= \frac{\text{S.P.}}{\text{W.P.}}$$

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

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

$$= \eta_m \times \eta_h$$

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

$$\text{Water power in kW} = \frac{\rho \times g \times Q \times H}{1000}, \quad \text{where } \rho = 1000 \text{ kg/m}^3$$

$$\eta_o = \frac{\text{Shaft power in kW}}{\text{Water power in kW}} = \frac{P}{\left(\dfrac{\rho \times g \times Q \times H}{1000}\right)}$$

Topics

1. Classification of Turbines

2. Selection of Turbines

3. Design of Turbines - Pelton, Francis, Kaplan 4. Draft Tube

5. Surge Tanks

6. Governing of Turbines

7. Unit Speed, Unit Discharge, Unit Power

8. Characteristic Curves of Hydraulic Turbines

9. Similitude or Model Analysis

10. Cavitations

Classification of Turbines

1. According to type of energy at Inlet

a) Impulse Turbine

Pelton Wheel : Requires High Head and Low Rate of Flow

b) Reaction Turbine

Francis, Kaplan : Requires Low Head and High Rate of Flow

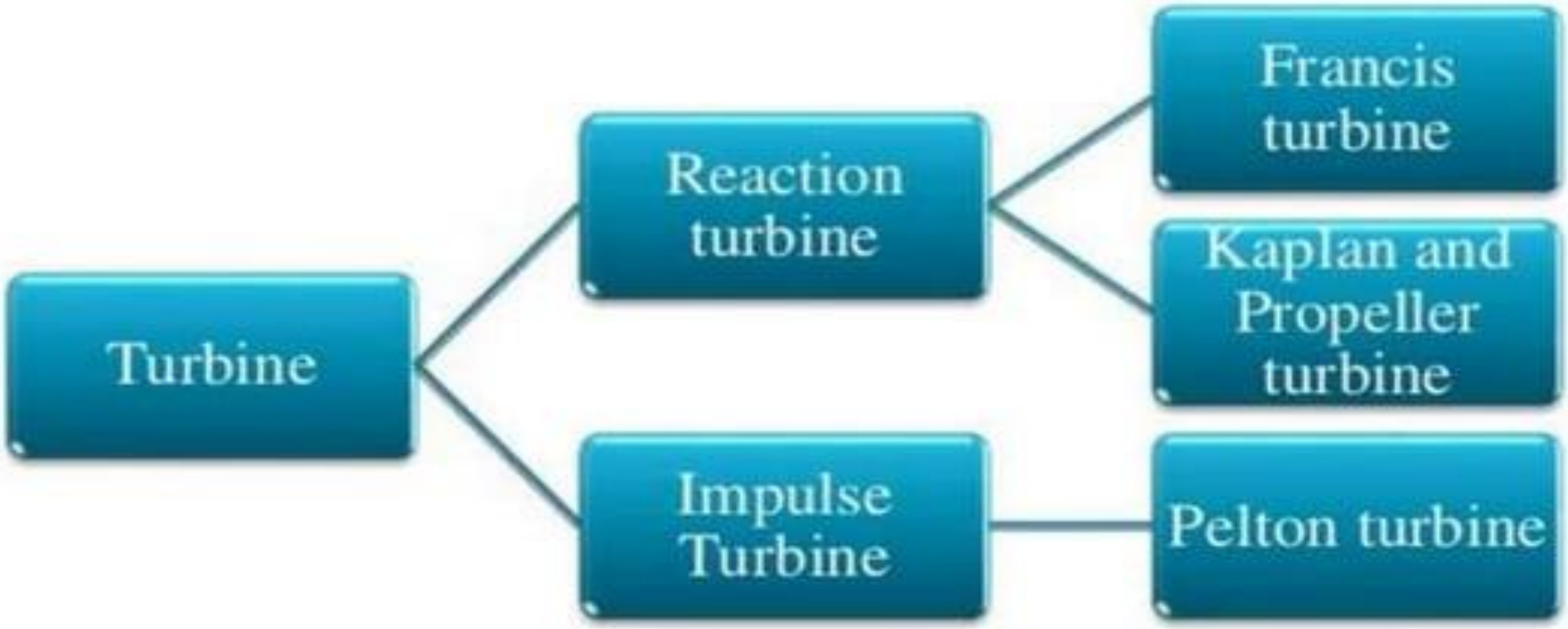
2. According to direction of flow through runner

a) Tangential Flow Turbine **- Pelton Wheel**

b) Radial Flow Turbine - **Francis Turbine**

c) Axial Flow Turbine - **Kaplan Turbine**

d) Mixed Flow Turbine - **Modern Francis Turbine**


Turbine
Reaction turbine
Impulse Turbine
Francis turbine
Kaplan and Propeller turbine
Pelton turbine

Impulse Turbine : If at the inlet of the 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.

Reaction 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 waters flows through the runner, the water is under pressure and the pressure energy goes on changing into 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 the 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 outwards to inwards, radially, the turbine is known as inward radial flow turbine, on the other hand,

If water flows radially from inwards 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 axis of rotation of the runner, the turbine is called mixed flow turbine.

Classification of Turbines

3. According to Head at Inlet of turbine

a) High Head Turbine - Pelton Wheel

b) Medium Head Turbine – Francis Turbine

c) Low Head Turbine - Kaplan Turbine

4. According to Specific Speed of Turbine

a) Low Specific Speed Turbine – Pelton Wheel

b) Medium Specific Speed Turbine -Francis Turbine

c) High Specific Speed Turbine - Kaplan Turbine

Classification according to Specific Speed of Turbines

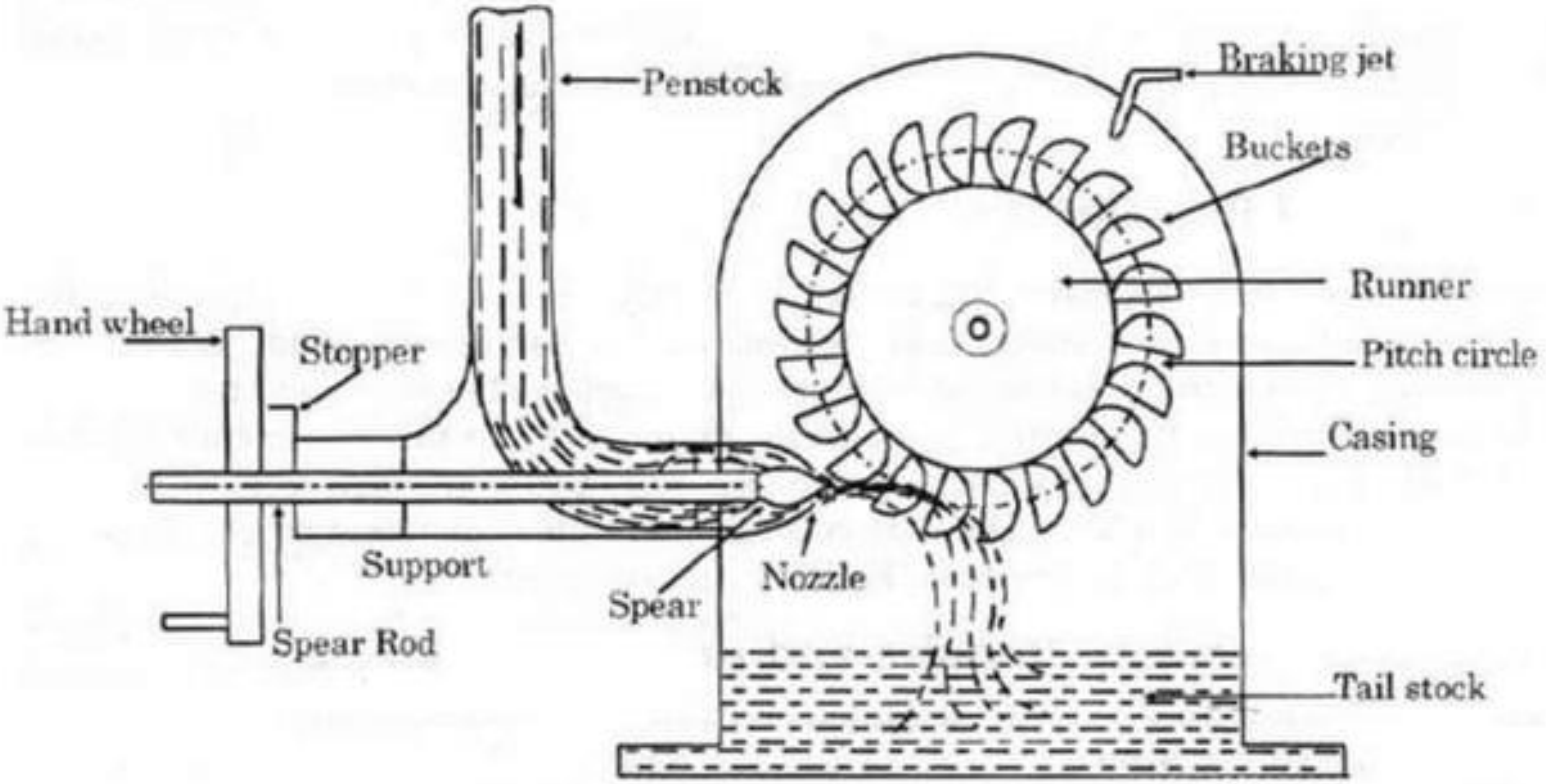
Type of turbine	Type of runner	Specific speed
Pelton	Slow Normal Fast	10 to 20 20 to 28 28 to 35
Francis	Slow Normal Fast	60 to 120 120 to 180 180 to 300
Kaplan	–	300 to 1000

Classification of Turbines

5. According to Disposition of Turbine Shaft

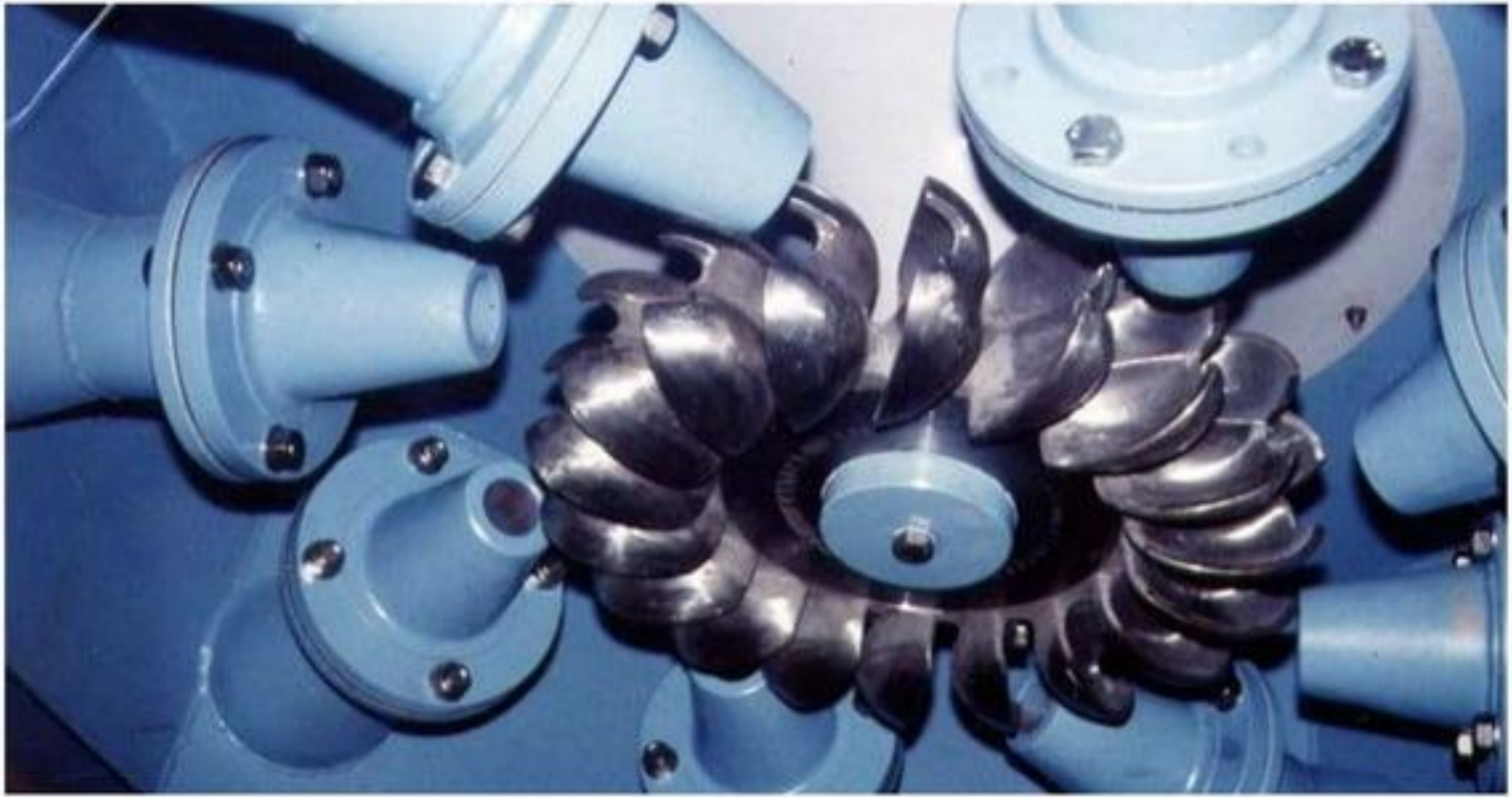
a) Horizontal Shaft - Pelton Wheel

b) Vertical Shaft - Francis & Kaplan Turbines



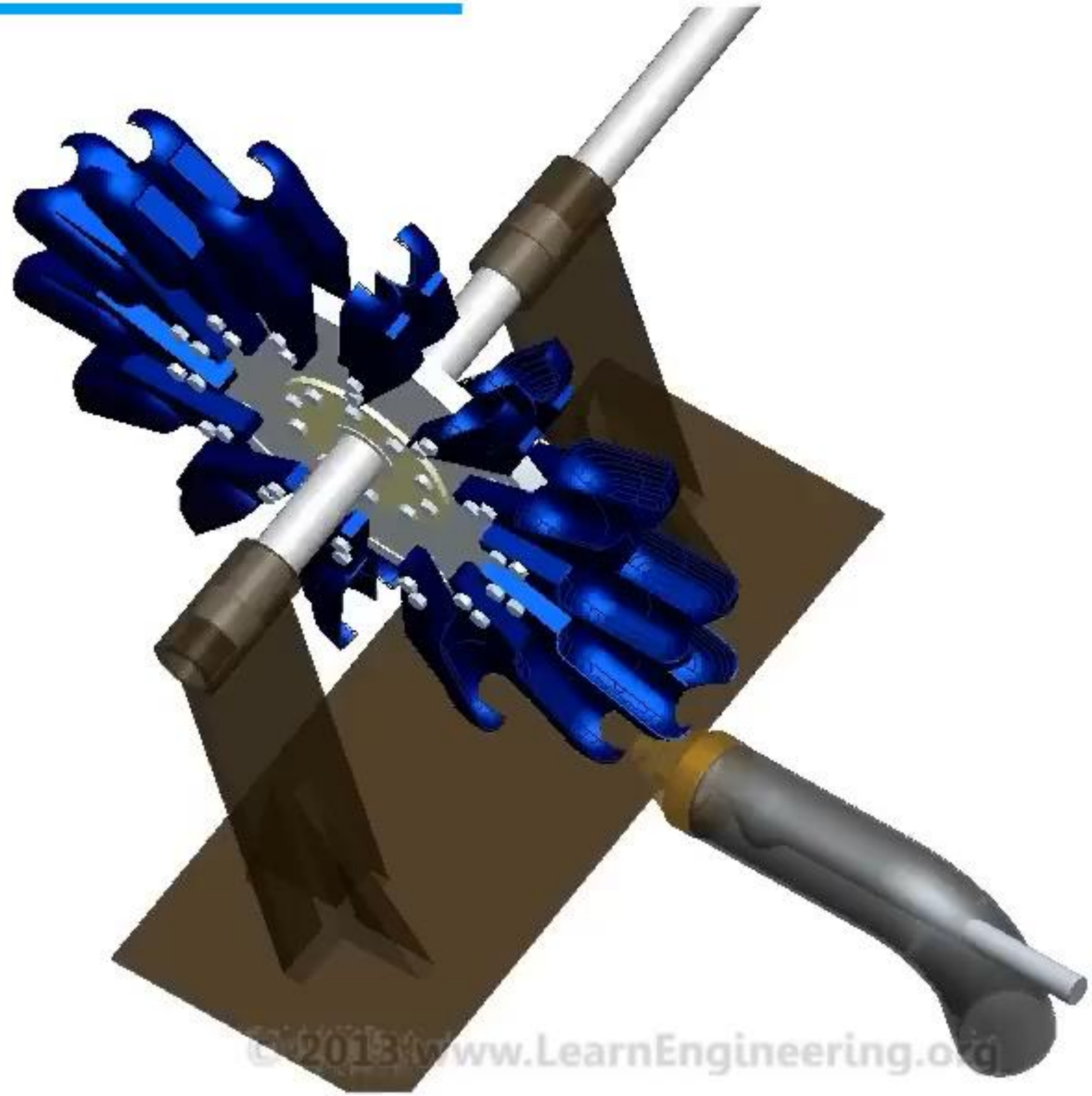
PELTON WHEEL

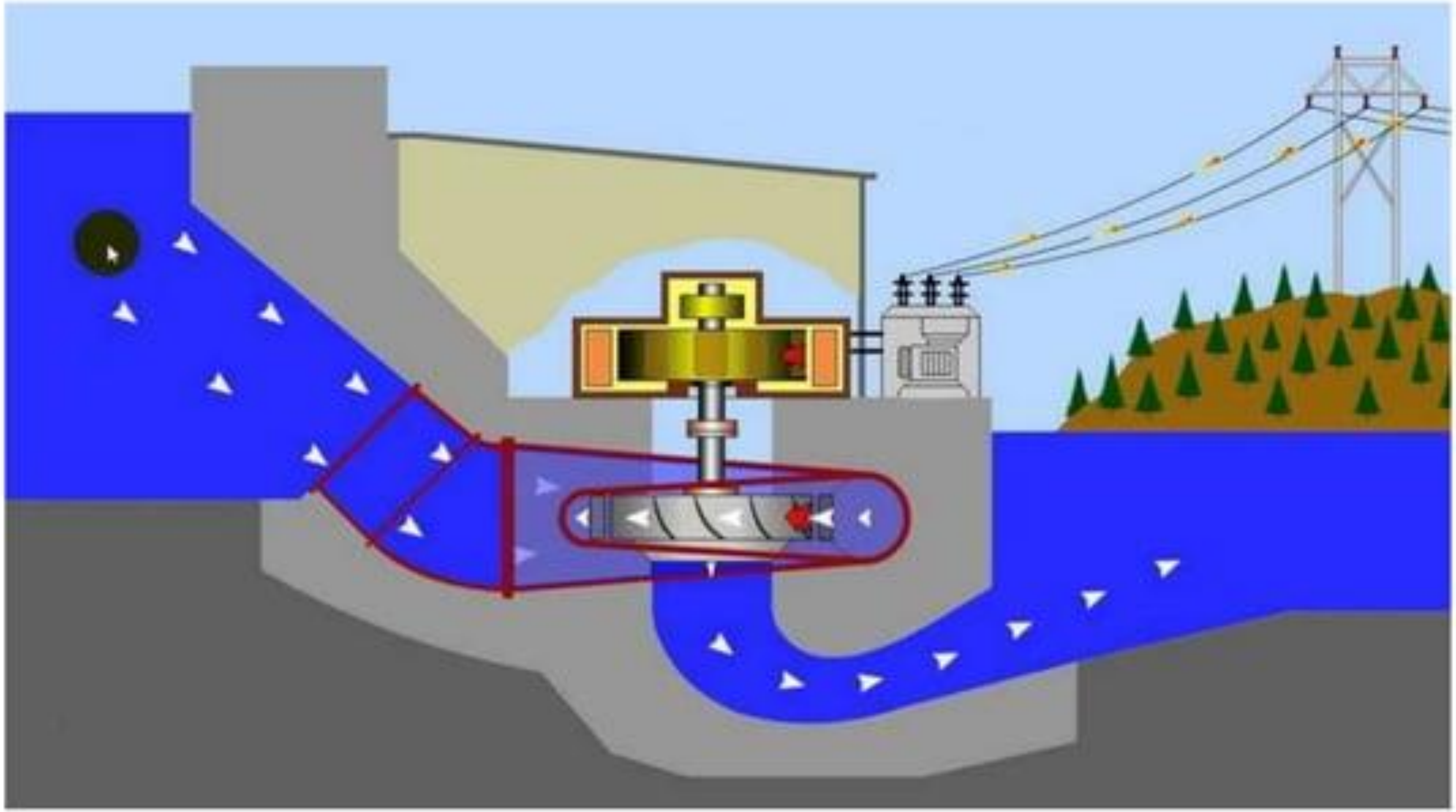
PELTON



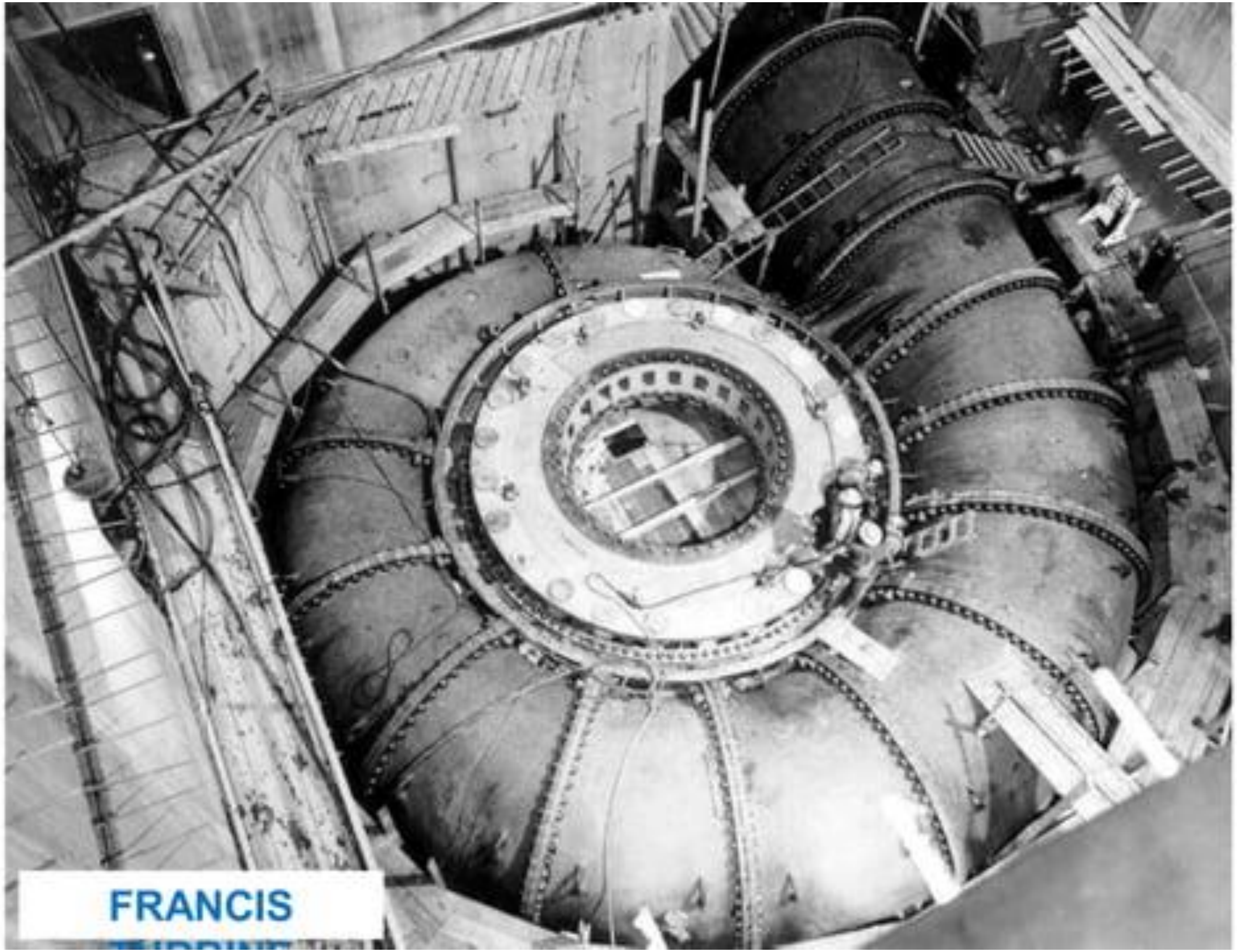
PELTON WHEEL WITH MULTILE JETS

PELTON TURBINE

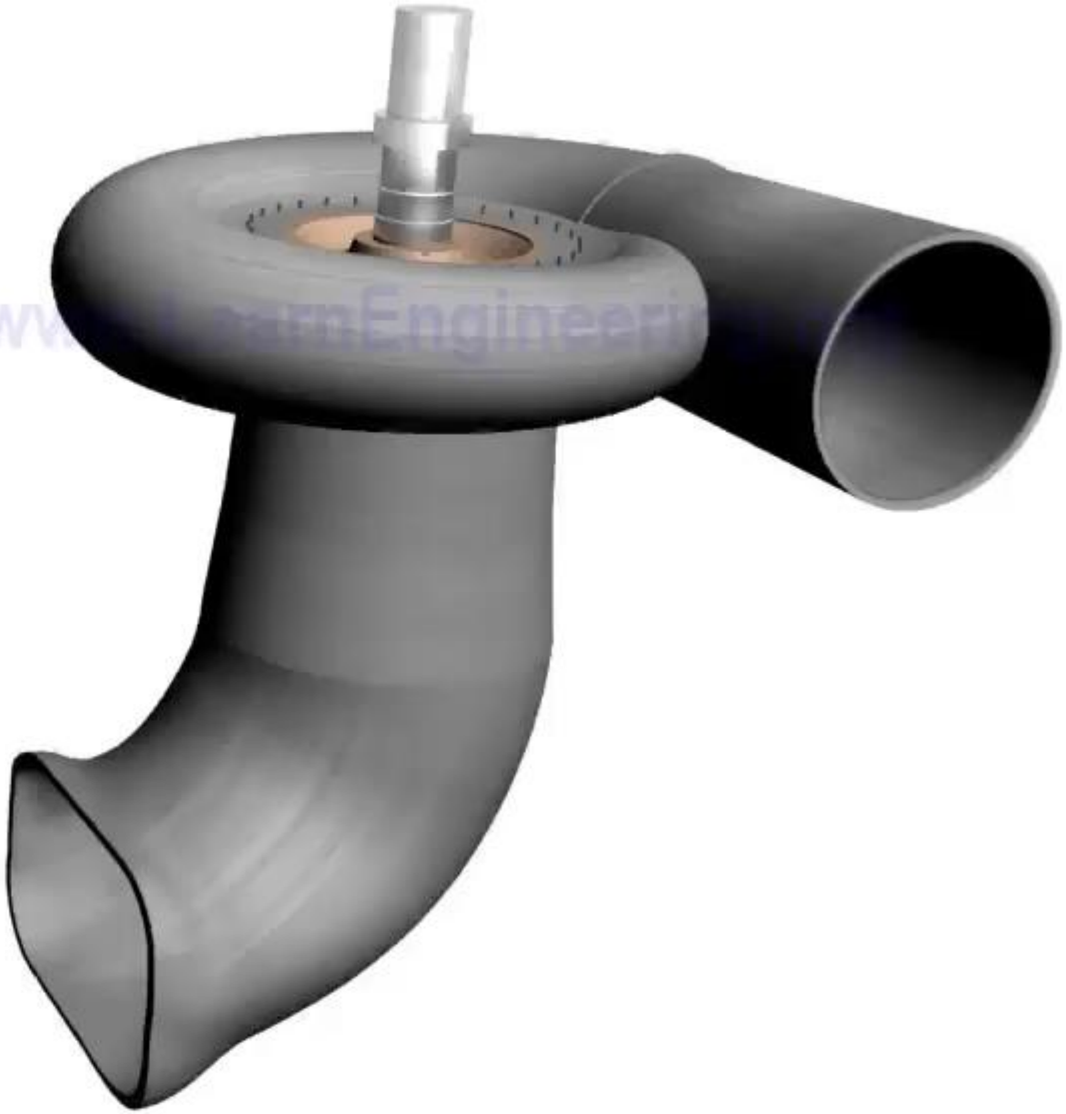




FRANCIS TURBINE


FRANCIS

FRANCIS TURBINE



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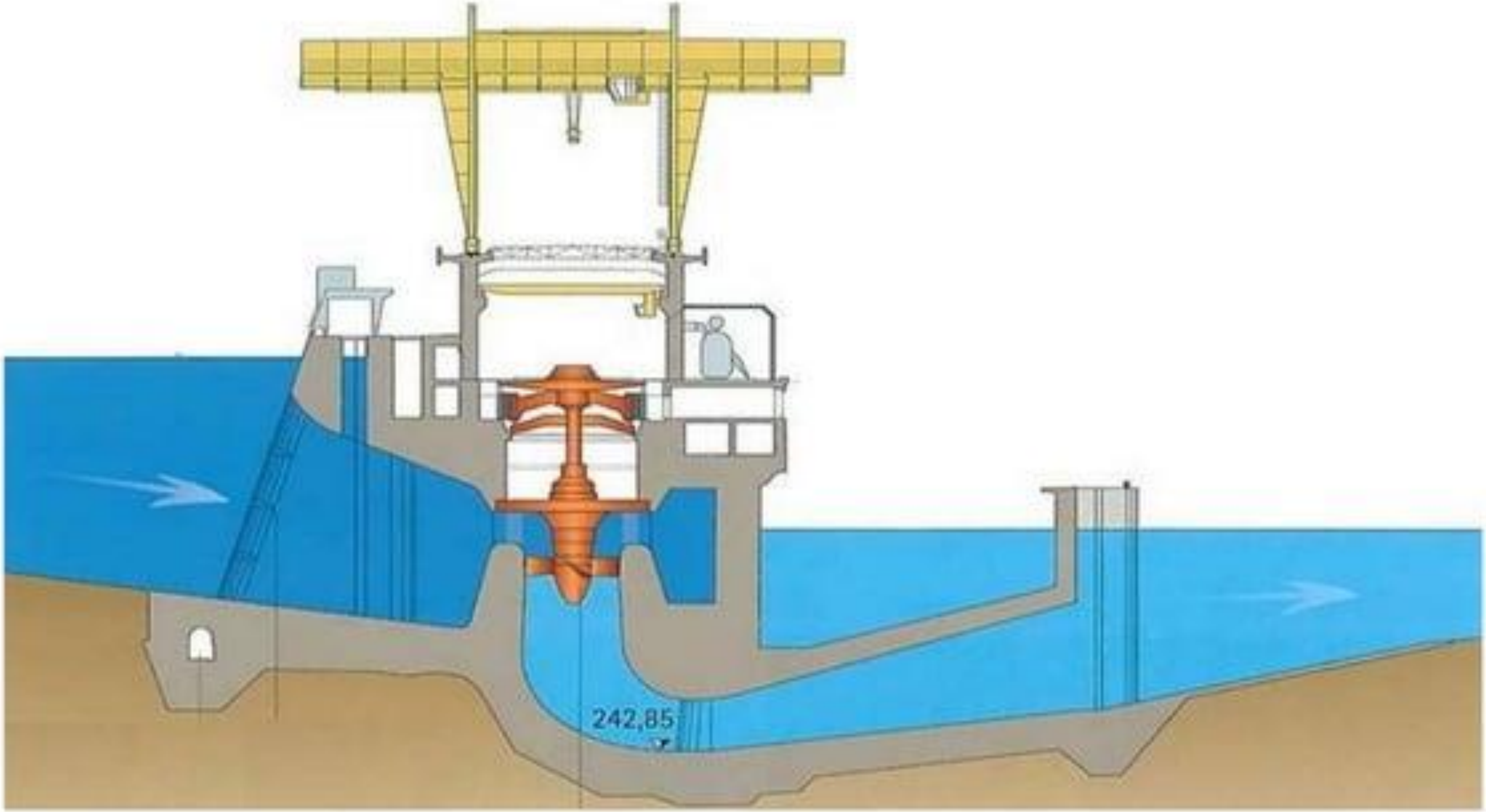
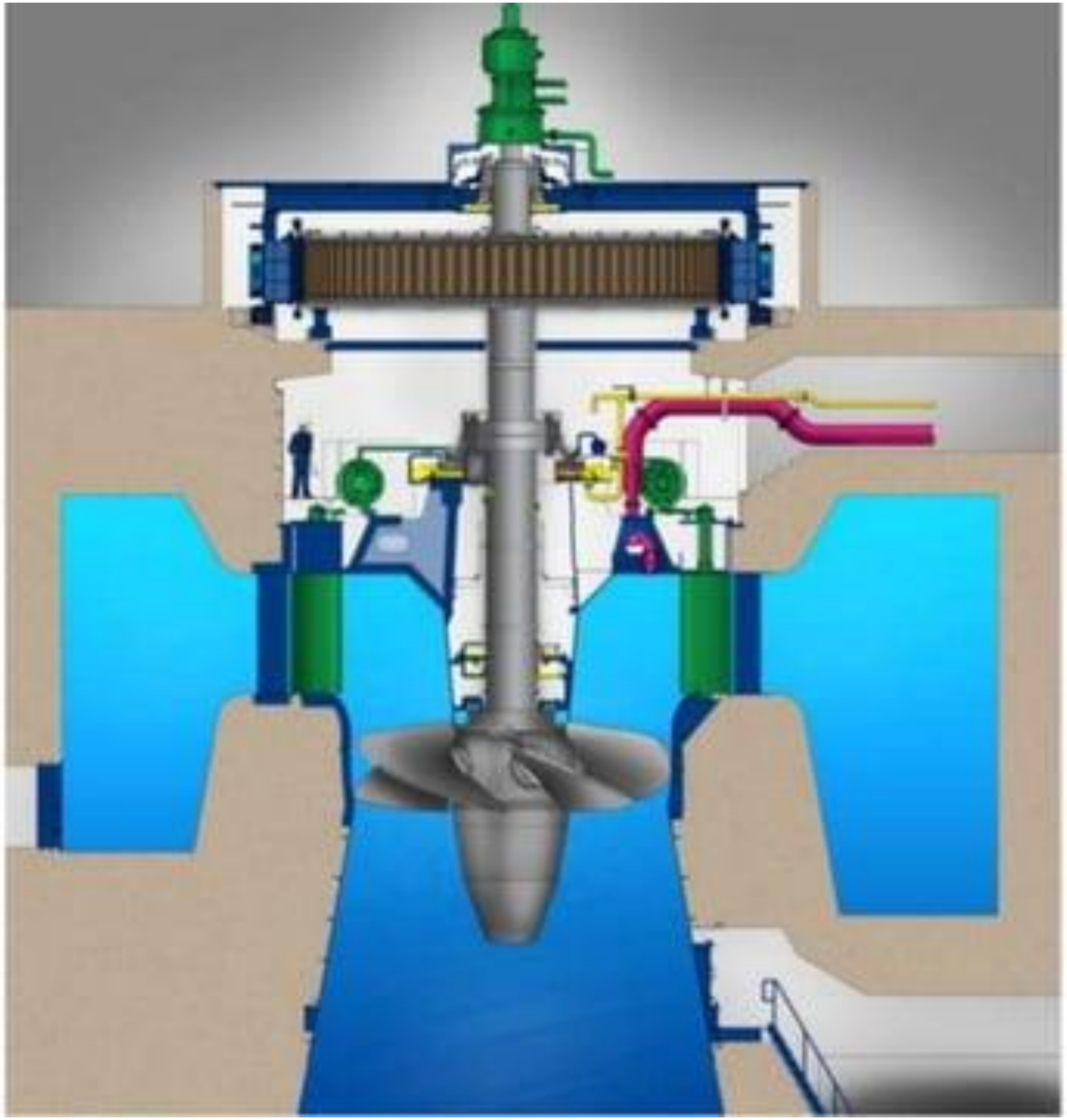


KAPLAN TURBINE



KAPLAN
TURBINE

FRANCIS
TURBINE

KAPLAN TURBINE

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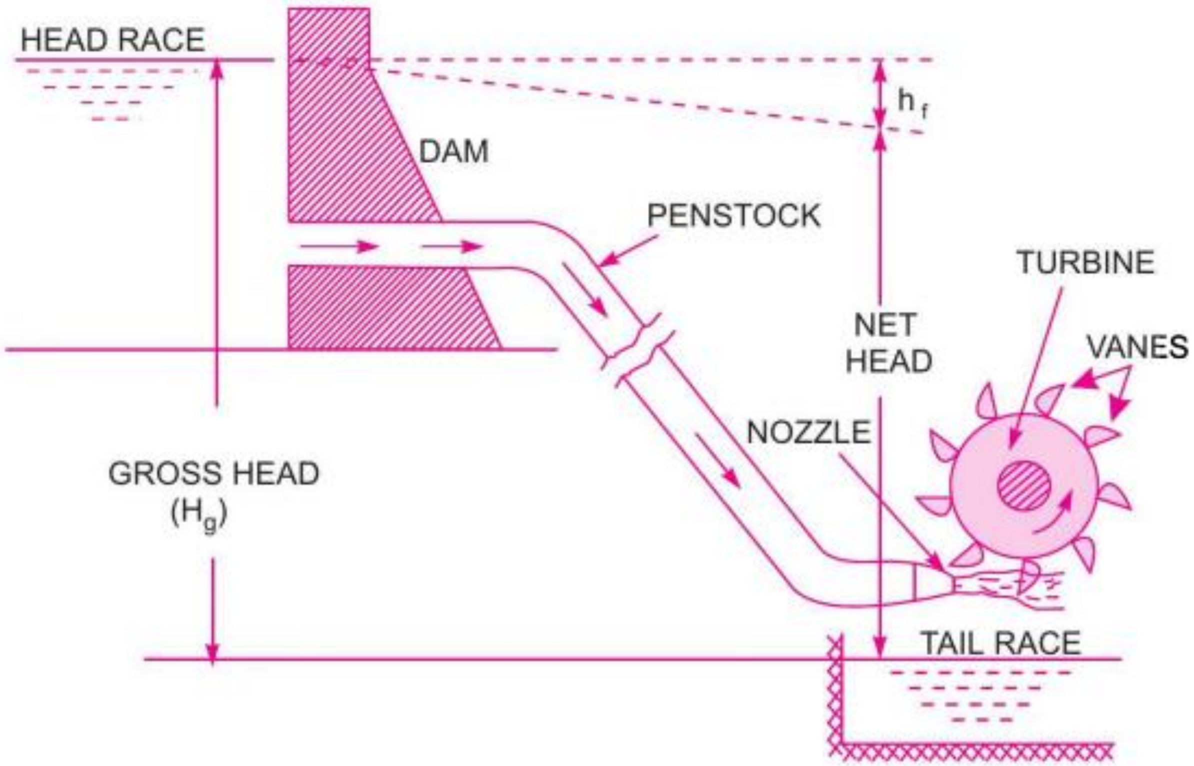
PART –II

PELTON WHEEL (OR TURBINE)

- The Pelton wheel or Pelton turbine 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 outlet of the turbine is atmospheric.
- This turbine is used for high heads and is named after L.A. Pelton, an American Engineer.

Figure shows the layout of a hydroelectric power plant in which the turbine is Pelton wheel. The water from the reservoir flows through the penstocks at the outlet 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.



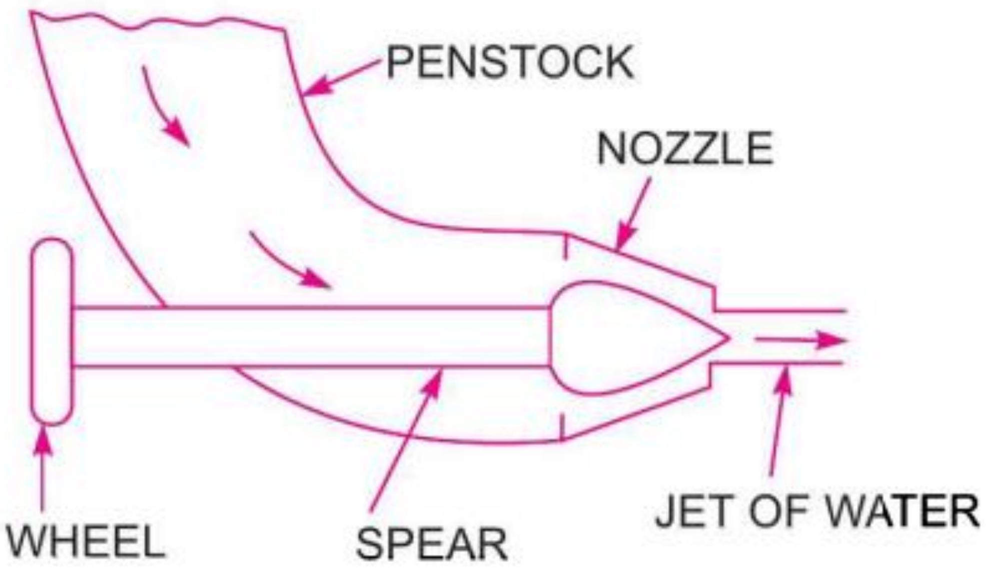
Layout of a hydroelectric power plant.

The main parts of the Pelton turbine are:

1. Nozzle and flow regulating arrangement (spear),
2. Casing, and
3. Runner and buckets,
4. Breaking jet.

1. 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 as shown in Figure.
- The spear is a conical needle which is operated either by a hand wheel or automatically in an axial direction depending upon the size of the unit.
- When the spear is pushed forward into 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.



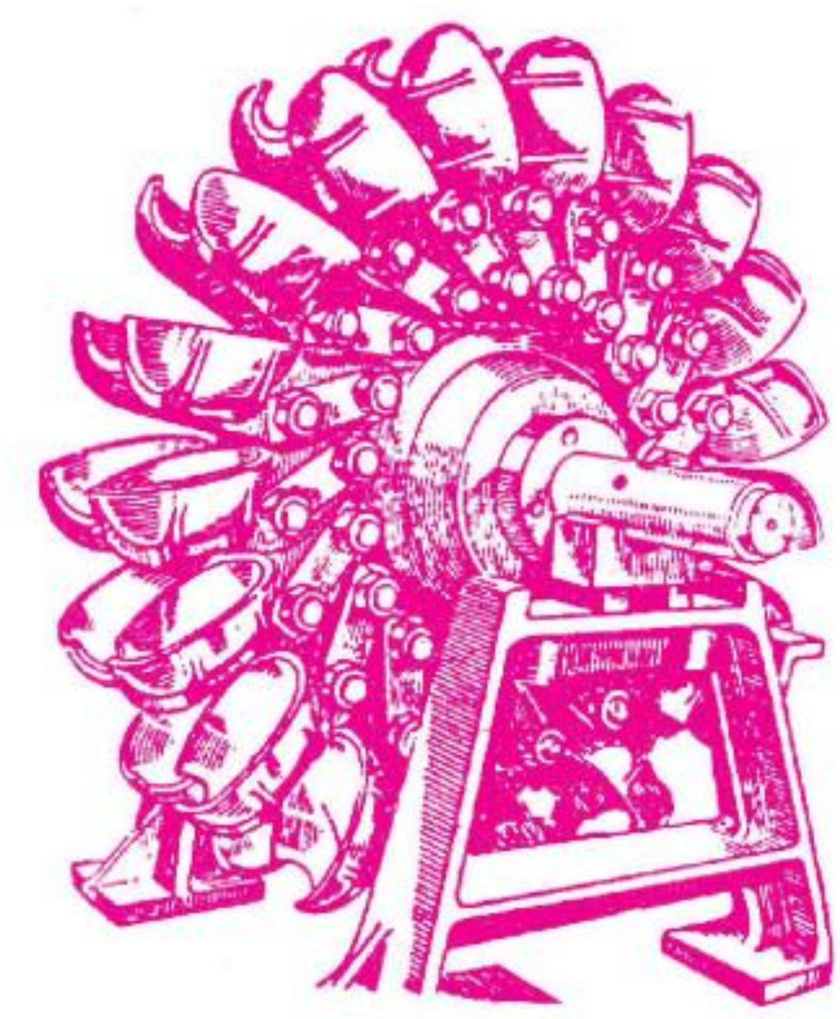
Nozzle with a spear to regulate flow.

2. Runner with Buckets :

Figure shows the runner of a Pelton wheel. 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 into two symmetrical parts by a dividing wall which is known as **splitter.**



Runner of a pelton wheel.

2. Runner with Buckets :

The jet of water strikes on the **splitter.**

The splitter divides the jet into 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 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.

Runner of a pelton wheel.

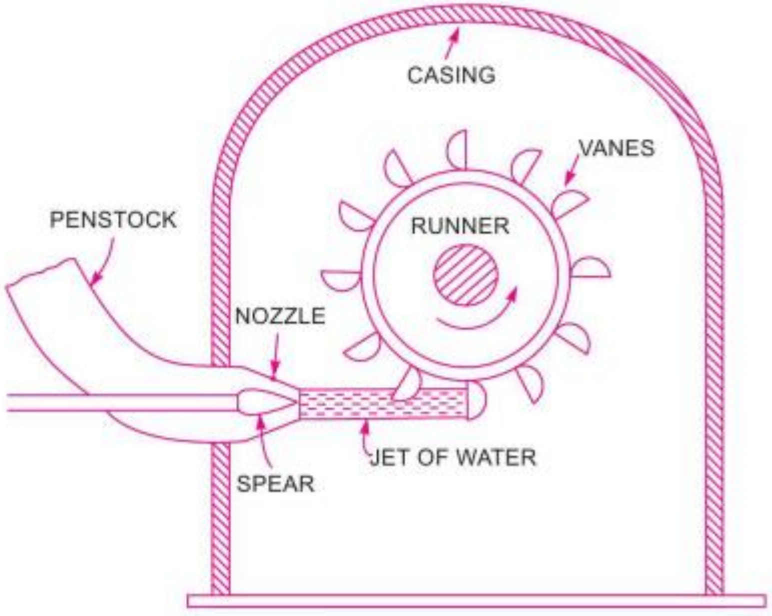
3. Casing. Figure shows a Pelton turbine with a casing.

The function of the casing is to prevent the splashing of the water and to discharge water to tail race.

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.



Pelton turbine.

4. 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. Figure shows the shape of the vanes or buckets of the 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. Fig. 18.5 (b) shows the section of the bucket at Z-Z.

The splitter is the inlet tip and outer edge of the bucket is the outlet tip of the bucket. The inlet velocity triangle is drawn at the splitter and outlet velocity triangle is drawn at the outer edge of the bucket.

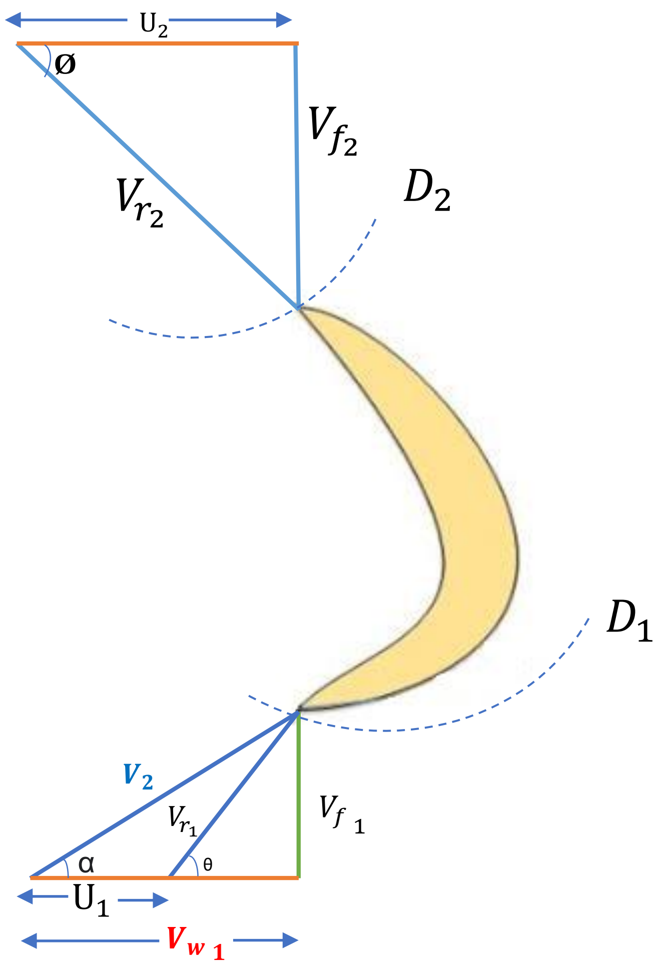
Francis turbine (Maximum Efficiency)

Condition for Francis turbine

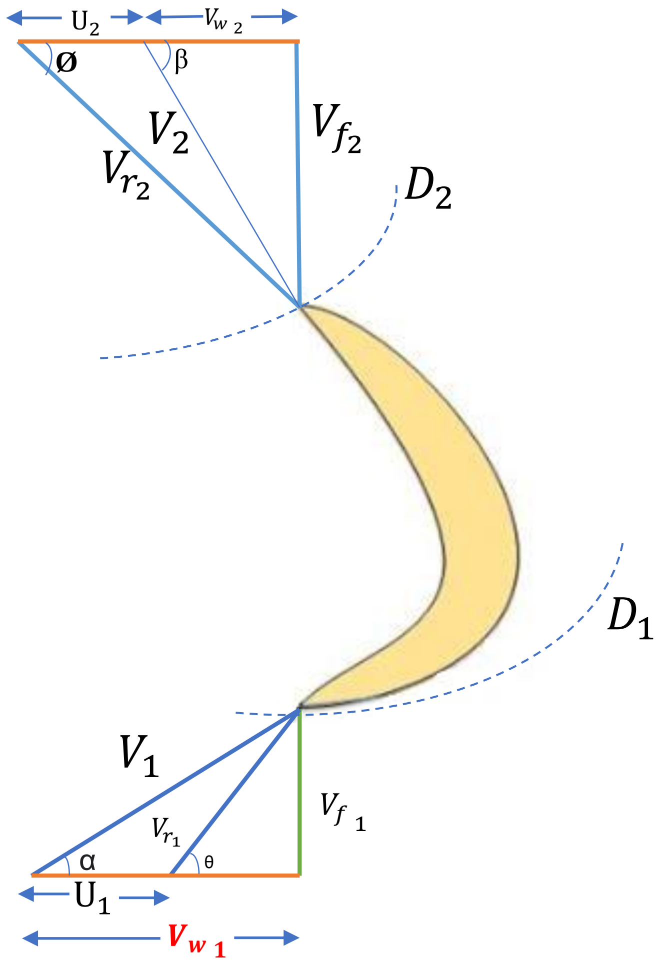
$V_{w\,2} = 0$

$V_2 = V_{f_2}$

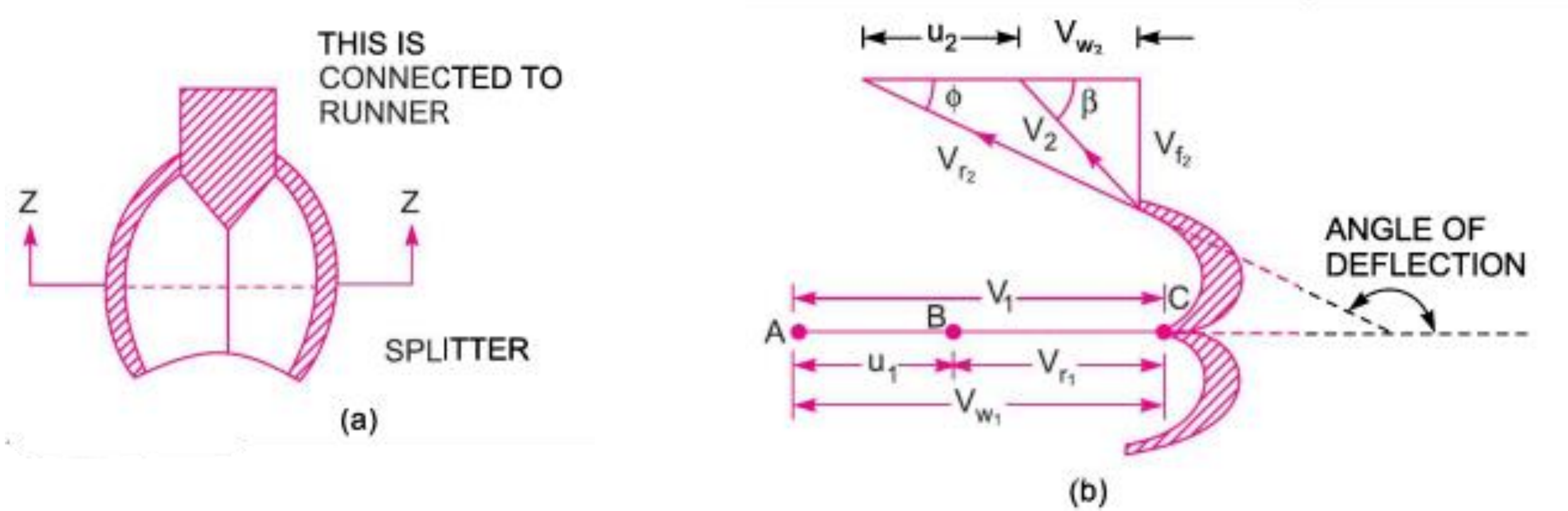
$\beta = 90^0$



Velocity diagram for Francis turbine



Velocity diagram for Inward radial flow turbine



Shape of bucket.

H = Net head acting on the Pelton wheel

$= H_g - h_f$

H_g = Gross head $\quad h_f = \dfrac{4fLV^2}{D^* \times 2g}$

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

D^* = Dia. of Penstock,

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

D = Diameter of the wheel,

N = Speed of the wheel in r.p.m.,

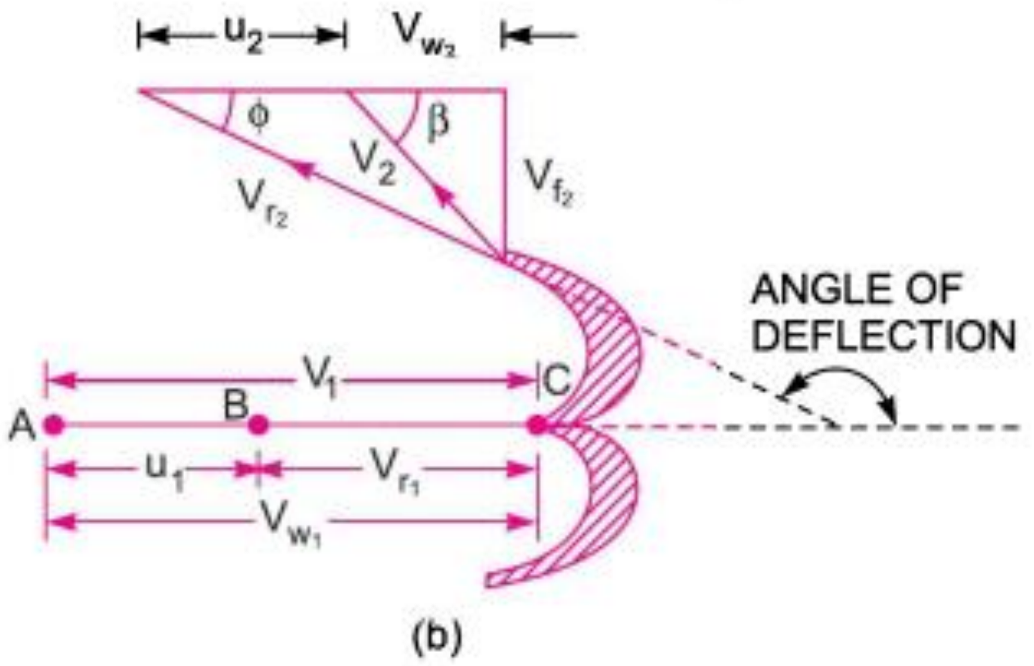
d = Diameter of the jet.

The velocity triangle at inlet will be a straight line where

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

$$V_{w_1} = V_1$$

$$\alpha = 0^\circ \text{ and } \theta = 0^\circ$$



Shape of bucket.

From the velocity triangle at outlet, we have

$$V_{r_2} = V_{r_1} \qquad V_{w_2} = V_{r_2} \cos\phi - u_2.$$

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

$$F_x = \rho a V_1 \, [V_{w_1} + V_{w_2}]$$

$$a = \text{Area of jet} = \frac{\pi}{4} d^2.$$

Now work done by the jet on the runner per second $= F_x \times u = \rho a V_1 \, [V_{w_1} + V_{w_2}] \times u$ Nm/s

Power given to the runner by the jet

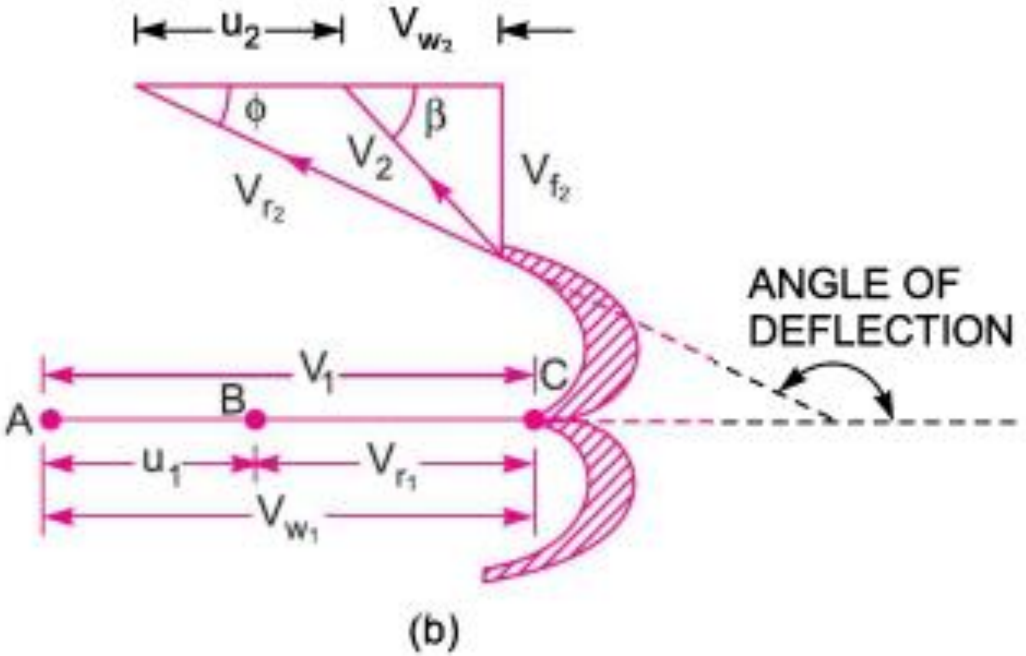
$$= \frac{\rho a V_1 \left[V_{w_1} + V_{w_2}\right] \times u}{1000} \text{ kW}$$

Work done/s per unit weight of water striking/s

$$= \frac{\rho a V_1 \left[V_{w_1} + V_{w_2}\right] \times u}{\text{Weight of water striking/s}}$$

$$= \frac{\rho a V_1 \left[V_{w_1} + V_{w_2}\right] \times u}{\rho a V_1 \times g}$$

$$= \frac{1}{g}\left[V_{w_1} + V_{w_2}\right] \times u$$



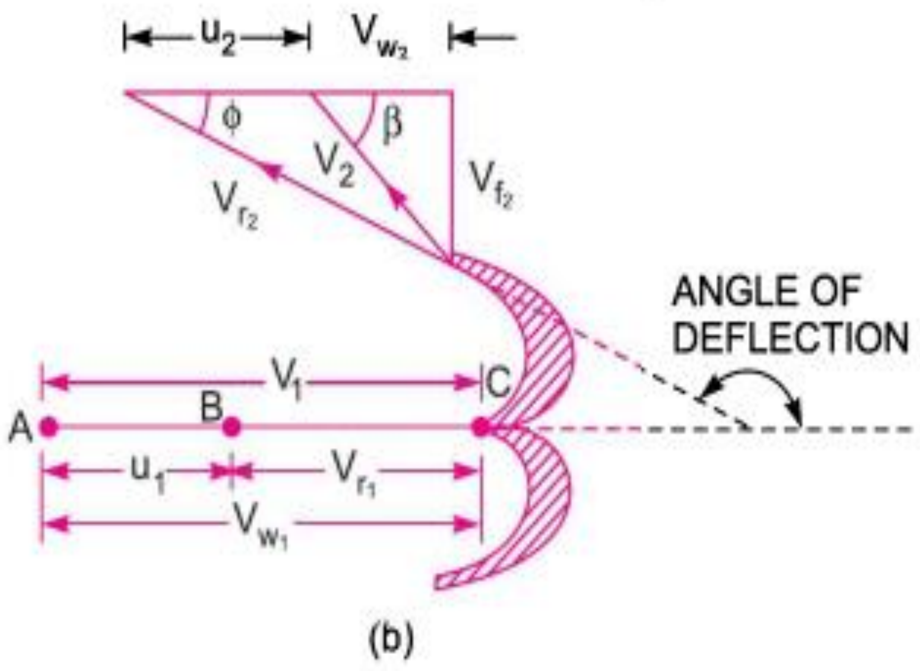
Shape of bucket.

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

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

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

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



Shape of bucket.

$V_{w_1} = V_1$ $\quad V_{r_1} = V_1 - u_1 = (V_1 - u)$

$V_{r_2} = (V_1 - u)$

$$V_{w_2} = V_{r_2}\cos\phi - u_2 = V_{r_2}\cos\phi - u = (V_1 - u)\cos\phi - u$$

Hydraulic efficiency, $\eta_h = \dfrac{\text{Work done per second}}{\text{K.E. of jet per second}} = \dfrac{2\left[V_{w_1} + V_{w_2}\right] \times u}{V_1^2}$

$$V_{w_1} = V_1 \qquad V_{r_2} = (V_1 - u)$$

$$V_{w_2} = V_{r_2} \cos\phi - u_2 = V_{r_2} \cos\phi - u = (V_1 - u)\cos\phi - u$$

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

$$= \frac{2\left[V_1 - u + (V_1 - u)\cos\phi\right] \times u}{V_1^2}$$

$$= \frac{2(V_1 - u)\,[1 + \cos\phi]\,u}{V_1^2}$$

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

$$\frac{d}{du}(\eta_h) = 0$$

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

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

$$\frac{d}{du}\ [2uV_1 - 2u^2] = 0$$

$$2V_1 - 4u = 0$$

$$u = \frac{V_1}{2}$$

Hydraulic efficiency, $\eta_h = \dfrac{\text{Work done per second}}{\text{K.E. of jet per second}} = \dfrac{2\left[V_{w_1} + V_{w_2}\right] \times u}{V_1^2}$

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

$$= \frac{2 \times \dfrac{V_1}{2}\left(1 + \cos\phi\right)\dfrac{V_1}{2}}{V_1^2}$$

$$= \frac{\left(1 + \cos\phi\right)}{2}$$

Points to be Remembered for Pelton Wheel

(*i*) The velocity of the jet at inlet is given by $V_1 = C_v\sqrt{2gH}$

where C_v = Co-efficient of velocity = 0.98 or 0.99

H = Net head on turbine

(*ii*) The velocity of wheel (u) is given by $u = \phi\sqrt{2gH}$

where ϕ = Speed ratio. The value of speed ratio varies from 0.43 to 0.48.

(*iii*) The angle of deflection of the jet through buckets is taken at 165° if no angle of deflection is given.

(*iv*) The mean diameter or the pitch diameter D of the Pelton wheel is given by

$$u = \frac{\pi DN}{60} \text{ or } D = \frac{60u}{\pi N}.$$

(*v*) **Jet Ratio.** It is defined as the ratio of the pitch diameter (D) of the Pelton wheel to the diameter of the jet (d). It is denoted by 'm' and is given as

$$m = \frac{D}{d} \ (= 12 \text{ for most cases})$$

(*vi*) Number of buckets on a runner is given by

$$Z = 15 + \frac{D}{2d} = 15 + 0.5 \text{ m}$$

Problem 18.1 *A Pelton wheel has a mean bucket speed of 10 metres per second with a jet of water flowing at the rate of 700 litres/s under a head of 30 metres. The buckets deflect the jet through an angle of 160°. Calculate the power given by water to the runner and the hydraulic efficiency of the turbine. Assume co-efficient of velocity as 0.98.*

Solution. Given :

Speed of bucket, $u = u_1 = u_2 = 10$ m/s

Discharge, $Q = 700$ litres/s $= 0.7\ m^3/s$,

Head of water, $H = 30$ m

Angle of deflection $= 160°$

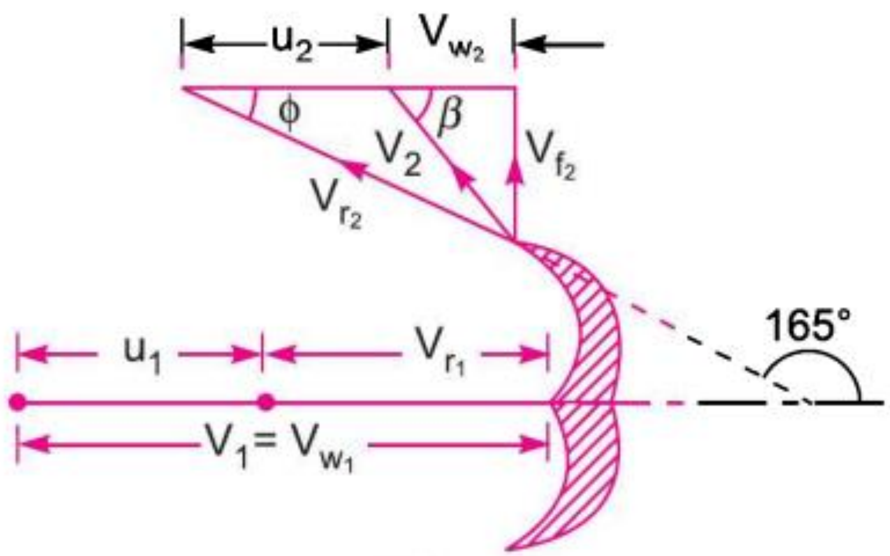
Co-efficient of velocity, $C_v = 0.98$.

The velocity of jet, $V_1 = C_v\sqrt{2gH}$

$$= 0.98\sqrt{2 \times 9.81 \times 30} = 23.77 \text{ m/s}$$

$$V_{r_1} = V_1 - u_1 = 23.77 - 10 = 13.77 \text{ m/s}$$

$$V_{w_1} = V_1 = 23.77 \text{ m/s}$$

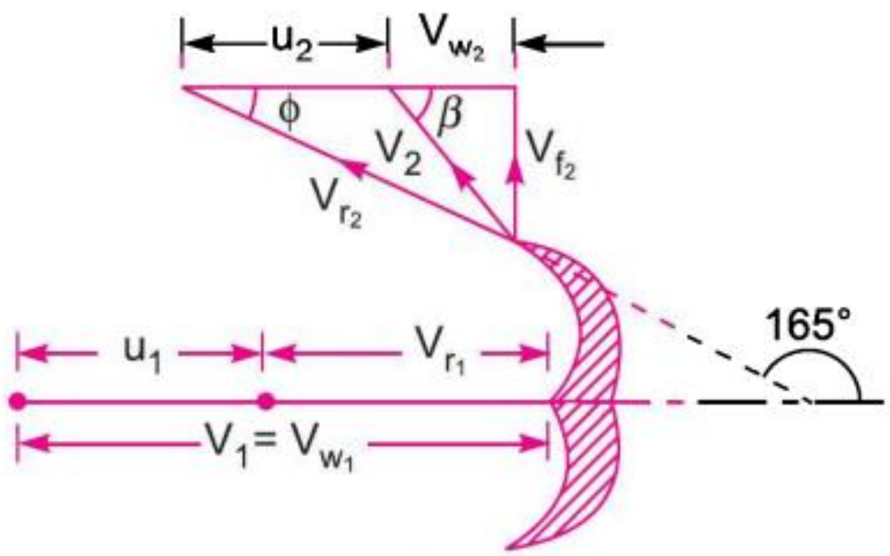


From outlet velocity triangle,

$$V_{r_2} = V_{r_1} = 13.77 \text{ m/s}$$

$$V_{w_2} = V_{r_2} \cos\phi - u_2$$

$$= 13.77 \cos 20° - 10.0 = 2.94 \text{ m/s}$$



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

$$= \rho a V_1 \left[V_{w_1} + V_{w_2}\right] \times u$$

$$= 1000 \times 0.7 \times [23.77 + 2.94] \times 10 \qquad (\because \quad aV_1 = Q = 0.7 \text{ m}^3\text{/s})$$

$$= 186970 \text{ Nm/s}$$

Power given to turbine $= \dfrac{186970}{1000} =$ **186.97 kW. Ans.**

The hydraulic efficiency of the turbine is given by equation

$$\eta_h = \frac{2\left[V_{w_1} + V_{w_2}\right] \times u}{V_1^2}$$

$$= \mathbf{0.9454} \quad \text{or} \quad \mathbf{94.54\%}. \ \textbf{Ans.}$$

PART –II

18.6.3 Design of Pelton Wheel. Design of Pelton wheel means the following data is to be determined :

1. Diameter of the jet (d),
2. Diameter of wheel (D),
3. Width of the buckets which is $= 5 \times d$,
4. Depth of the buckets which is $= 1.2 \times d$, and
5. Number of buckets on the wheel.

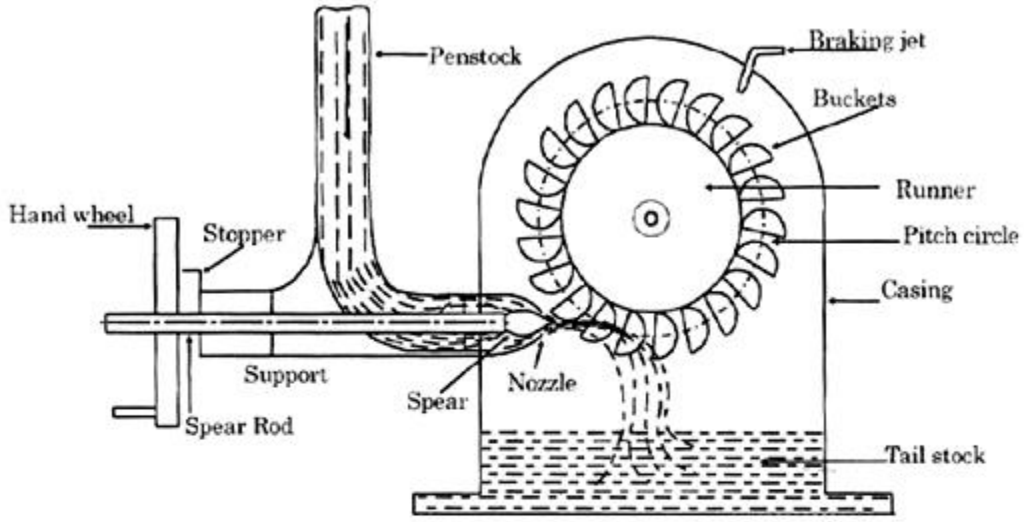


Fig. : Pelton Turbine

Size of buckets means the width and depth of the buckets.

Problem 18.11 *A Pelton wheel is to be designed for a head of 60 m when running at 200 r.p.m. The Pelton wheel develops 95.6475 kW shaft power. The velocity of the buckets = 0.45 times the velocity of the jet, overall efficiency = 0.85 and co-efficient of the velocity is equal to 0.98.*

Solution. Given :

Head, $H = 60$ m

Speed $N = 200$ r.p.m

Shaft power, S.P. = 95.6475 kW

Velocity of bucket, $u = 0.45 \times$ Velocity of jet

Overall efficiency, $\eta_o = 0.85$

Co-efficient of velocity, $C_v = 0.98$

Design of Pelton wheel means to find diameter of jet (d), diameter of wheel (D), Width and depth of buckets and number of buckets on the wheel.

(*i*) *Velocity of jet*, $V_1 = C_v \times \sqrt{2gH} = 0.98 \times \sqrt{2 \times 9.81 \times 60} = 33.62$ m/s

$\therefore$ Bucket velocity, $u = u_1 = u_2 = 0.45 \times V_1 = 0.45 \times 33.62 = 15.13$ m/s

But $u = \frac{\pi DN}{60}$, where D = Diameter of wheel

$$15.13 = \frac{\pi \times D \times 200}{60} \quad \text{or} \quad D = \frac{60 \times 15.13}{\pi \times 200} = \textbf{1.44 m. Ans.}$$

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

Overall efficiency $\eta_o = 0.85$

$$\eta_o = \frac{\text{S.P.}}{\text{W.P.}} = \frac{95.6475}{\left(\frac{\text{W.P.}}{1000}\right)} = \frac{95.6475 \times 1000}{\rho \times g \times Q \times H} \qquad (\because \quad \text{W.P.} = \rho g Q H)$$

$$= \frac{95.6475 \times 1000}{1000 \times 9.81 \times Q \times 60} = \frac{95.6475 \times 1000}{0.85 \times 1000 \times 9.81 \times 60} = 0.1912 \text{ m}^3/\text{s}.$$

But the discharge, Q = Area of jet × Velocity of jet

$$0.1912 = \frac{\pi}{4} d^2 \times V_1 = \frac{\pi}{4} d^2 \times 33.62 \qquad d = \sqrt{\frac{4 \times 0.1912}{\pi \times 33.62}} = 0.085 \text{ m} = \textbf{85 mm. Ans.}$$

(iii) Size of buckets

Width of buckets $= 5 \times d = 5 \times 85 = 425$ mm

Depth of buckets $= 1.2 \times d = 1.2 \times 85 =$ **102 mm. Ans.**

(*iv*) *Number of buckets on the wheel* is given by equation (18.17) as

$$Z = 15 + \frac{D}{2d} = 15 + \frac{1.44}{2 \times .085} = 15 + 8.5 = \mathbf{23.5\ say\ 24.\ Ans.}$$

RADIAL FLOW REACTION TURBINES

Radial flow turbines are those turbines in which the 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 inward radial flow turbine.
- 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 changing into **kinetic energy**.

Thus the water through the runner is under pressure. The **runner** is completely enclosed in an **air-tight casing** and casing and the runner is always full of water.

Main Parts of a Radial Flow Reaction Turbine.

The main parts of a radial flow reaction turbine are :

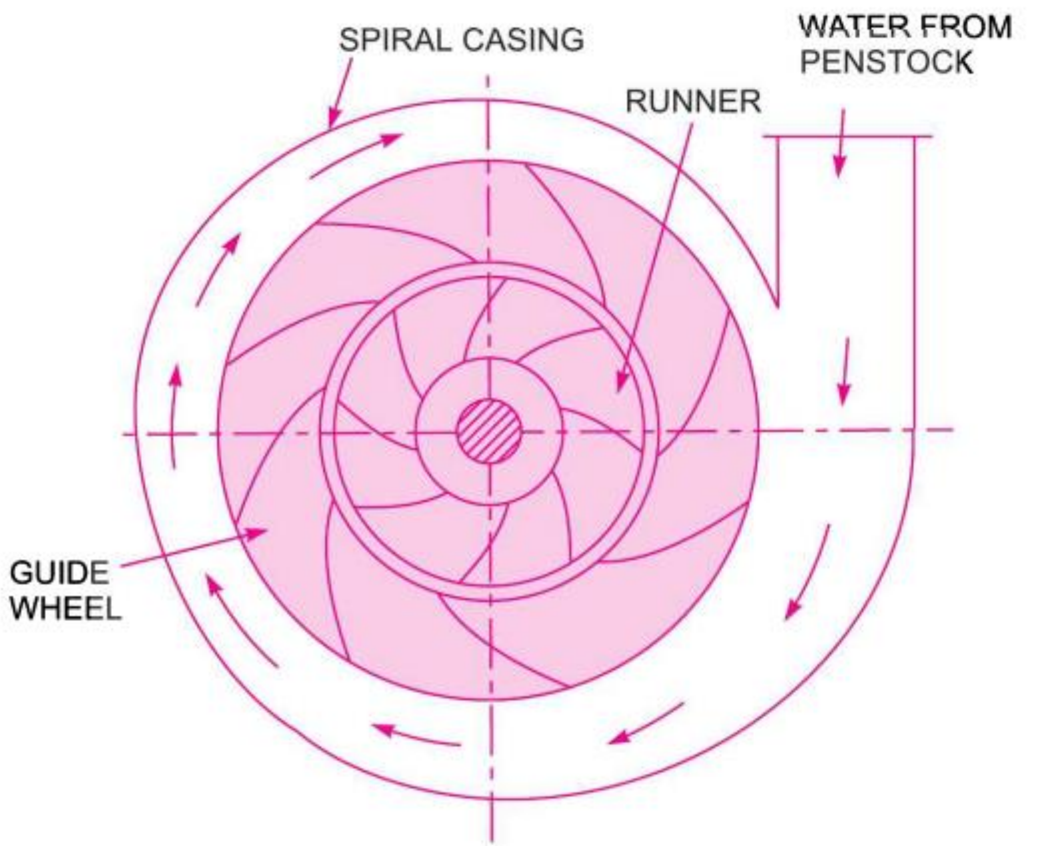
1. Casing,
2. Guide mechanism
3. Runner, and
4. Draft-tube.

1. Casing:

- As mentioned above that 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 of the casing goes on decreasing gradually. The casing completely surrounds the runner of the turbine.
- The casing is made of spiral shape, so that the water may enter the runner at constant velocity throughout the circumference of the runner.
- The casing is made of concrete, cast steel or plate steel.

2. Guide Mechanism

- It consists of a stationary circular wheel all round 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 a 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.



Main parts of a radial reaction turhines.

3. Runner :

- It is a circular wheel on which a series of radial curved vanes are fixed.
- The surface 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 stainless steel. They are keyed to the shaft.

4. Draft-tube:

- The pressure at the exit of the runner of a reaction turbine is generally less than atmospheric pressure.
- The water at exit cannot be directly discharged to the tail race. A tube or pipe of gradually increasing area is used for discharging water from the exit of the turbine to the tail race.
- This tube of increasing area is called draft tube.

Inward Radial Flow Turbine: Figure shows 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.**

The work done per second on the runner by water is given by equation

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

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

V_{w_1} = Velocity of whirl at inlet,

V_{w_2} = Velocity of whirl at outlet,

u_1 = Tangential velocity of wheel at inlet

$= \dfrac{\pi D_1 \times N}{60}$, where D_1 = Outer dia. of runner,

u_2 = Tangential velocity of wheel at outlet

$= \dfrac{\pi D_2 \times N}{60}$, where D_2 = Inner dia. of runner,

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

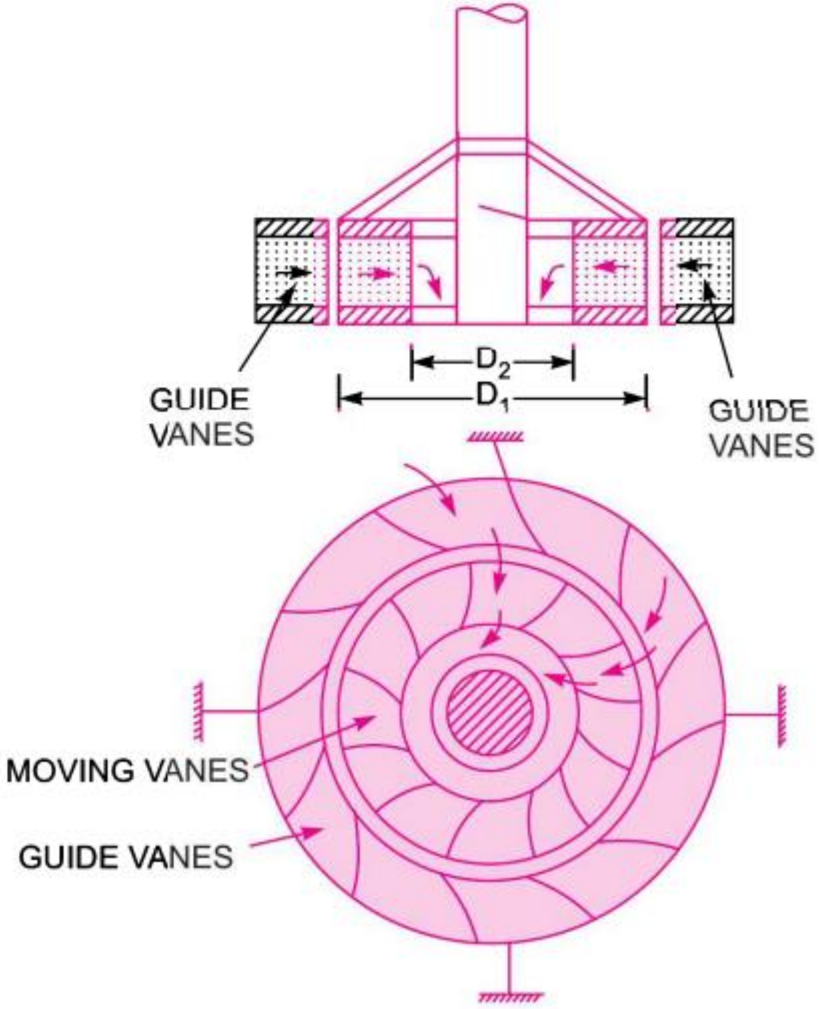


Fig. 18.11 *Inward radial flow turbine.*

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

$$= \frac{\text{Work done per second}}{\text{Weight of water striking per second}}$$

$$= \frac{\rho Q\left[V_{w_1}u_1 \pm V_{w_2}u_2\right]}{\rho Q \times g} \qquad = \frac{1}{g}\left[V_{w_1}u_1 \pm V_{w_2}u_2\right]$$

The equation represents the energy transfer per unit weight/s to the runner.

This equation is known by **Euler's equation** of hydrodynamics machines.

This is also known as fundamental equation of hydrodynamic machines.

This equation was given by Swiss scientist *L.* Euler.

In equation (18.19), +ve sign is taken if angle β is an acute angle. If β is an obtuse angle then –ve sign is taken. If β = 90°, then $V_{w_2} = 0$ and work done per second per unit weight of water striking/s become as

$$= \frac{1}{g} V_{w_1} u_1$$

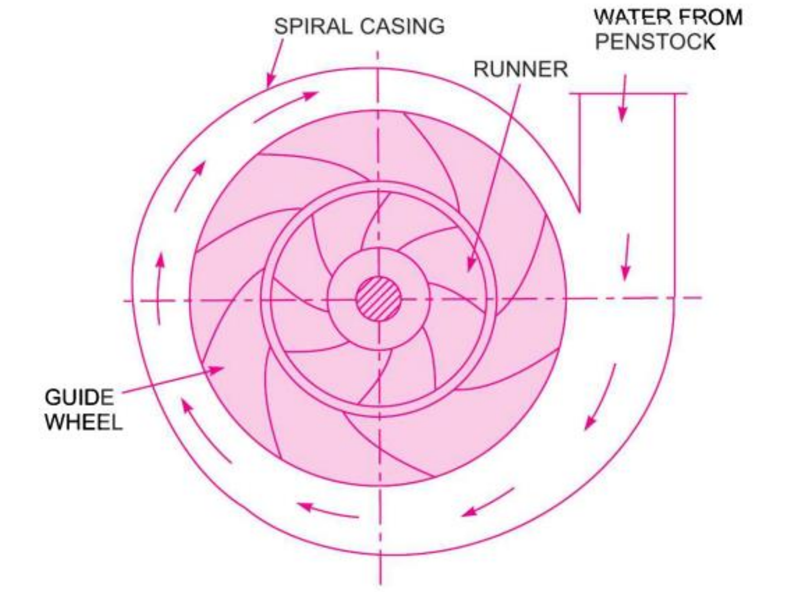
Hydraulic efficiency $\eta_h = \dfrac{\text{R.P.}}{\text{W.P.}}$

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

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 $V_{w_2} = 0$

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



Main parts of a radial reaction turbines.

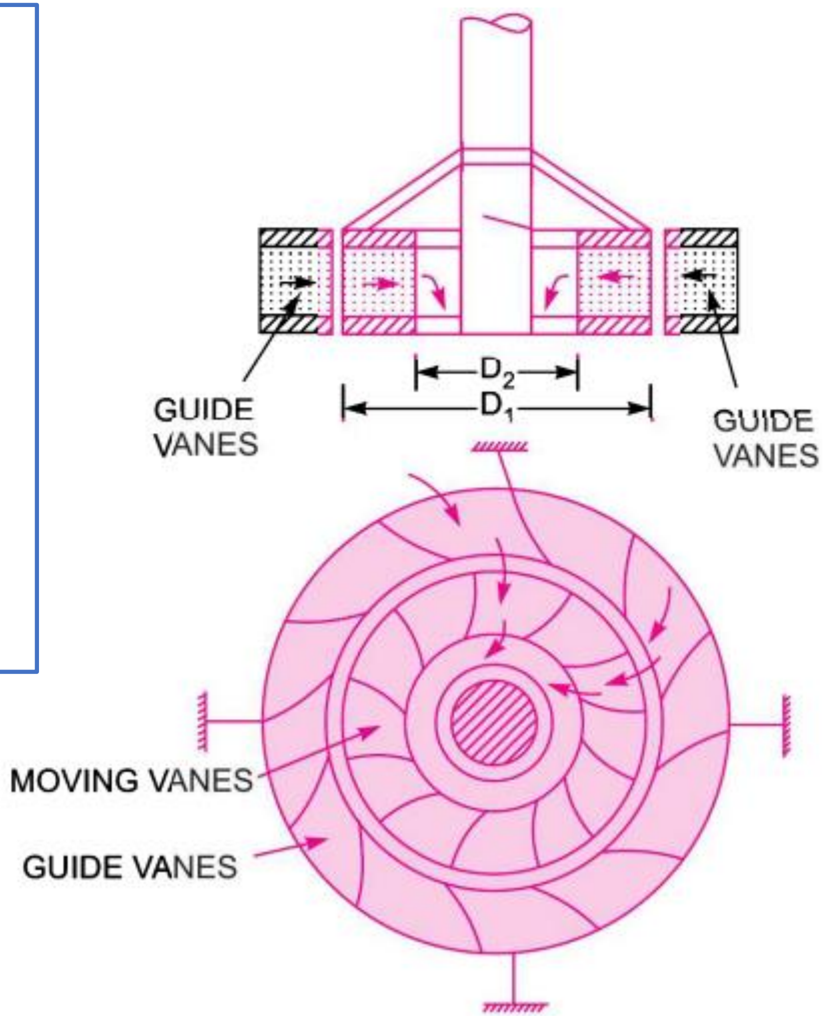
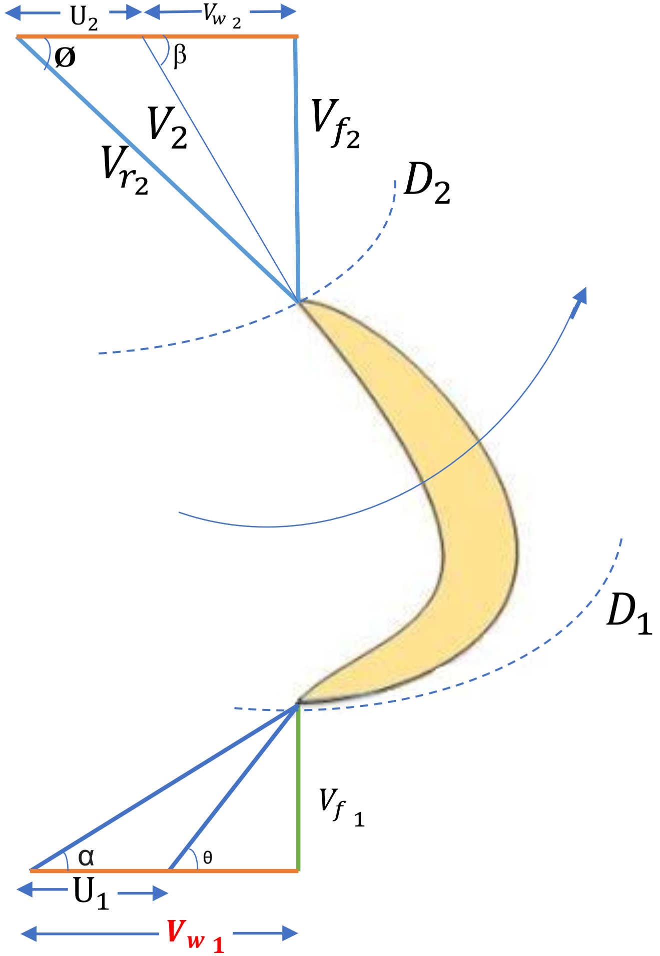


Fig. 18.11 *Inward radial flow turbine.*



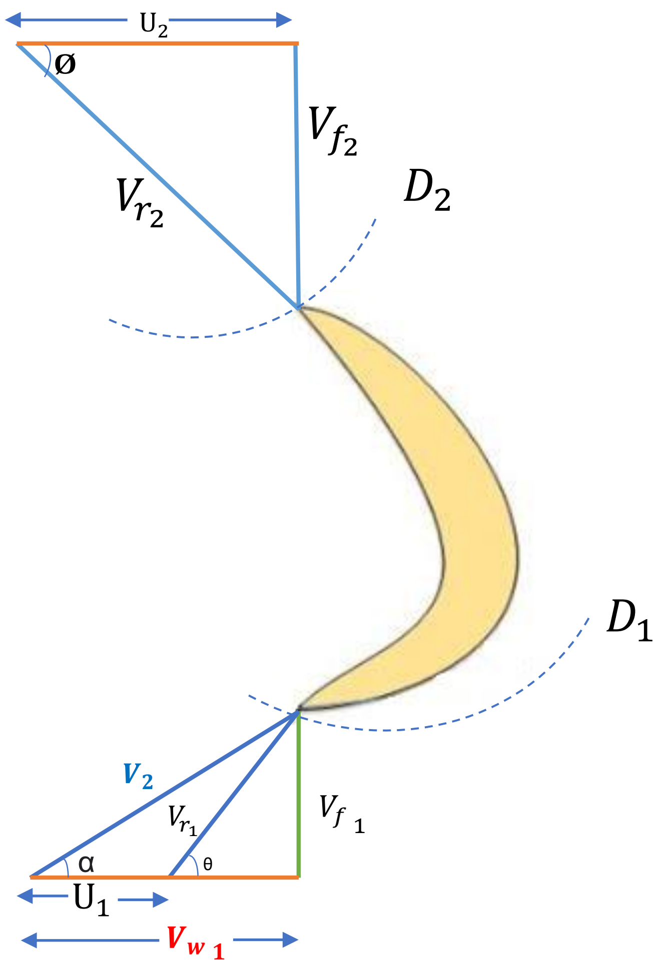
Francis turbine (Maximum Efficiency)

Condition for Francis turbine

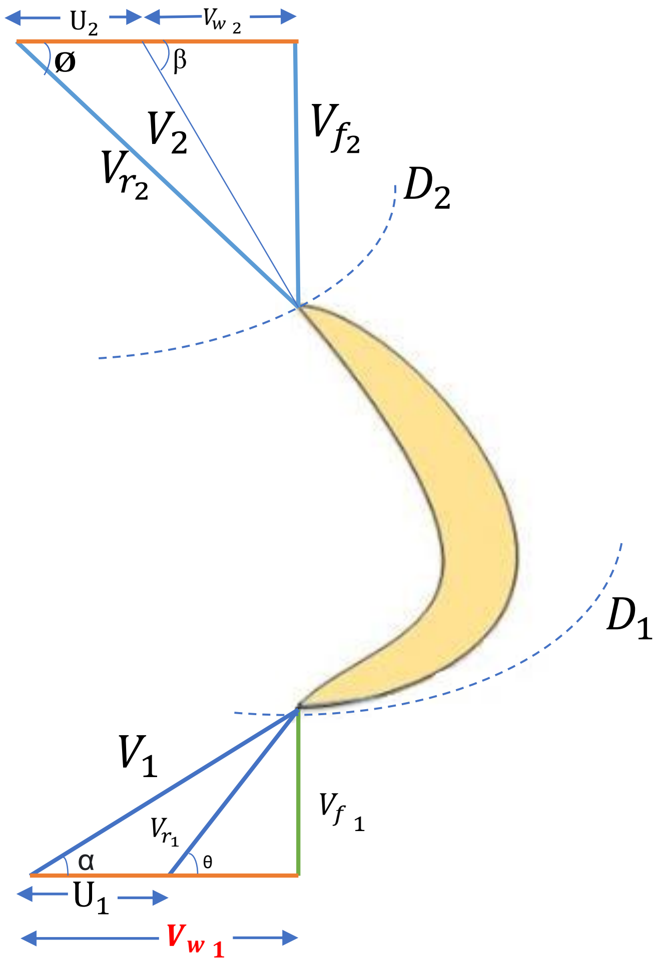
$V_{w\,2} = 0$

$V_2 = V_{f_2}$

$\beta = 90^0$



Velocity diagram for Francis turbine



Velocity diagram for Inward radial flow turbine

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

(*i*) **Speed Ratio.** The speed ratio is defind as $= \dfrac{u_1}{\sqrt{2gH}}$

where u_1 = Tangential velocity of wheel at inlet.

(*ii*) **Flow Ratio.** $\dfrac{\text{The ratio of the velocity of flow at inlet } (V_{f_1})}{\text{the velocity given } \sqrt{2gH}}$

$$= \frac{V_{f_1}}{\sqrt{2gH}}, \text{ where } H = \text{Head on turbine}$$

(*iii*) **Discharge of the Turbine.**

The discharge through a reaction radial flow turbine

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

D_1 = Diameter of runner at inlet,
B_1 = Width of runner at inlet,
V_{f_1} = Velocity of flow at inlet, and
D_2, B_2, V_{f_2} = Corresponding values at outlet.

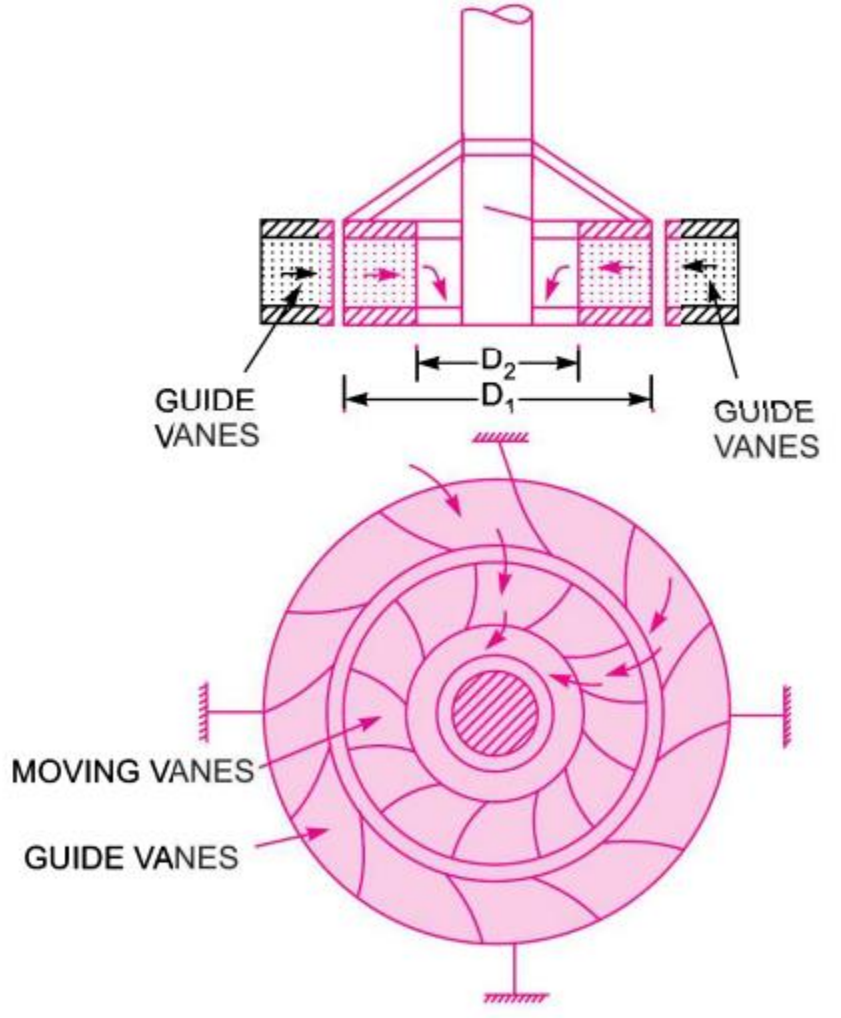
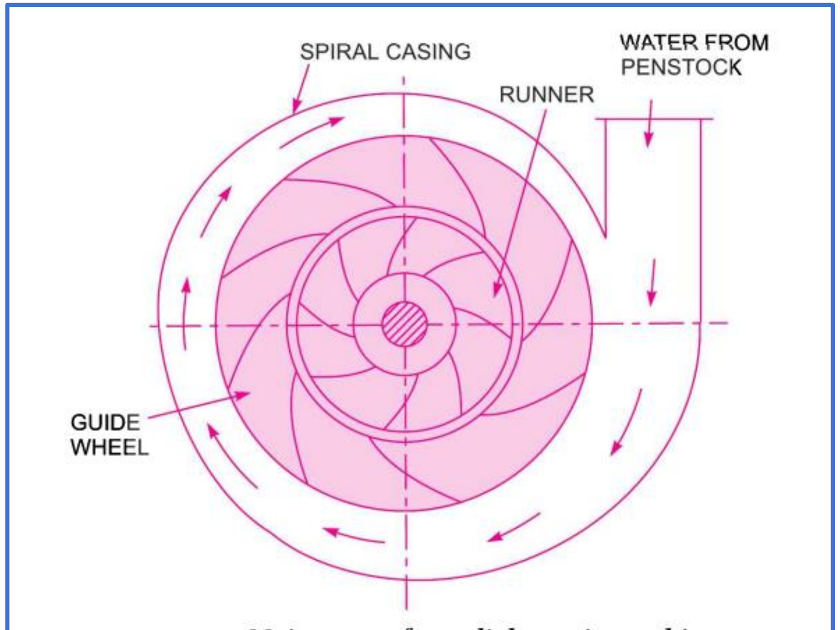


Fig. 18.11 *Inward radial flow turbine.*



Main parts of a radial reaction turbines.

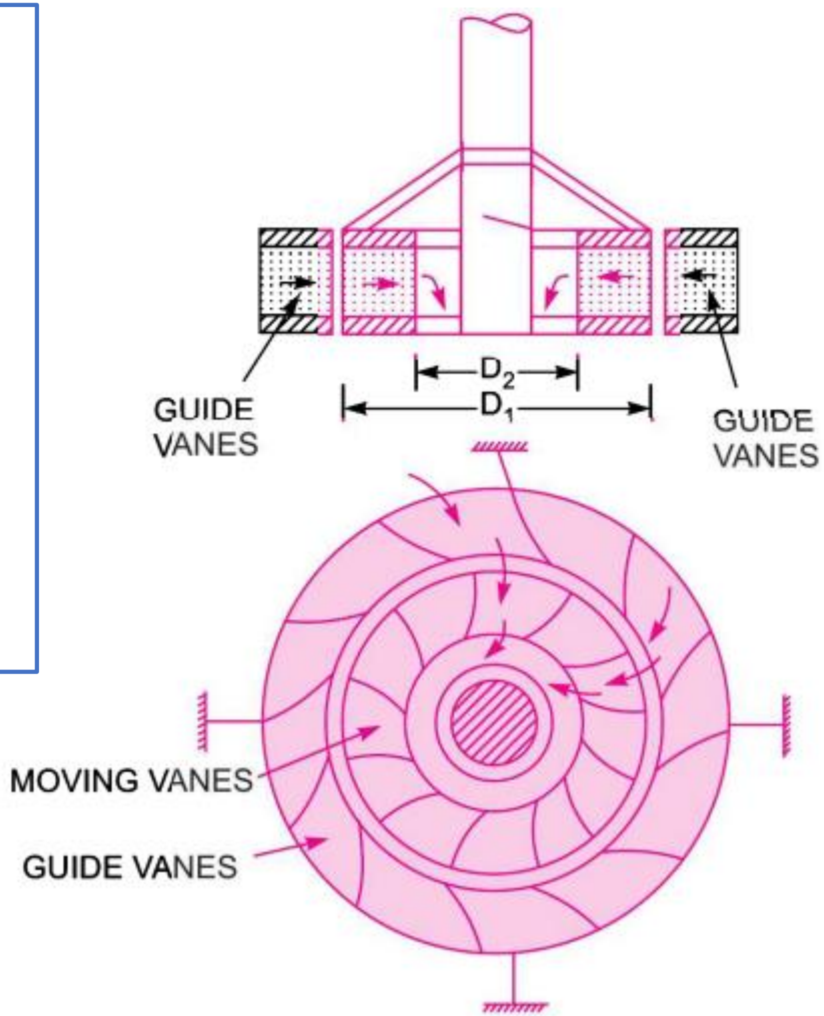
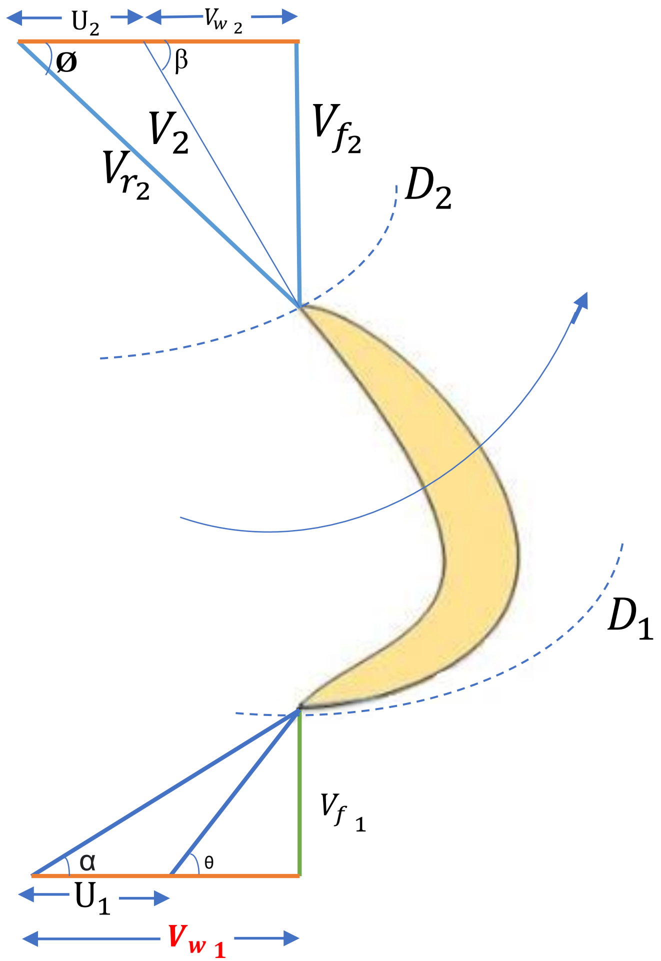
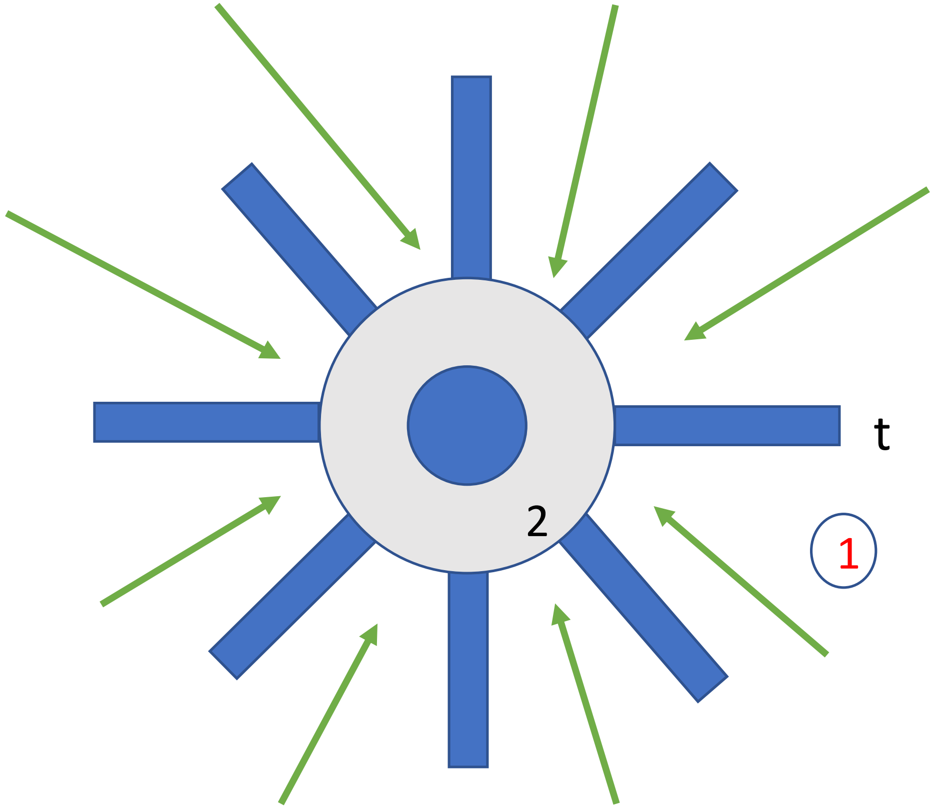


Fig. 18.11 *Inward radial flow turbine.*





Water flows in in circumference in area

$$A_F = \pi.D.B$$

$$A_F = \pi.D_1.B_1$$

$$A_F = \pi.D_2.B_2$$

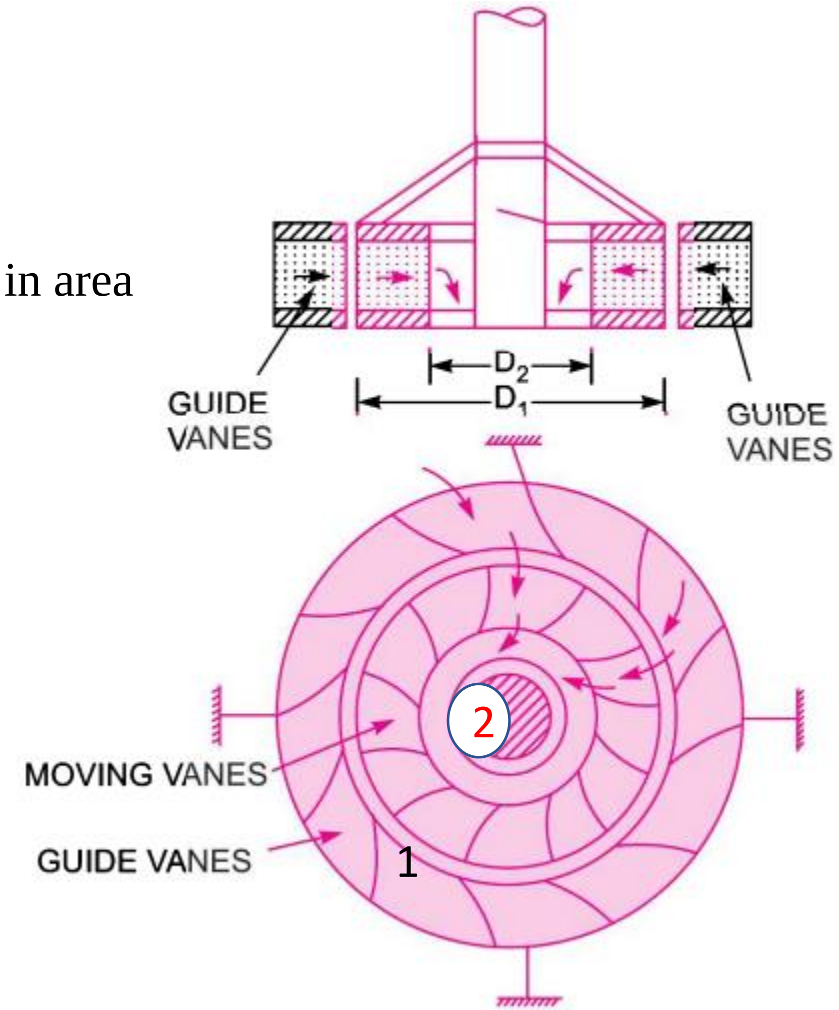
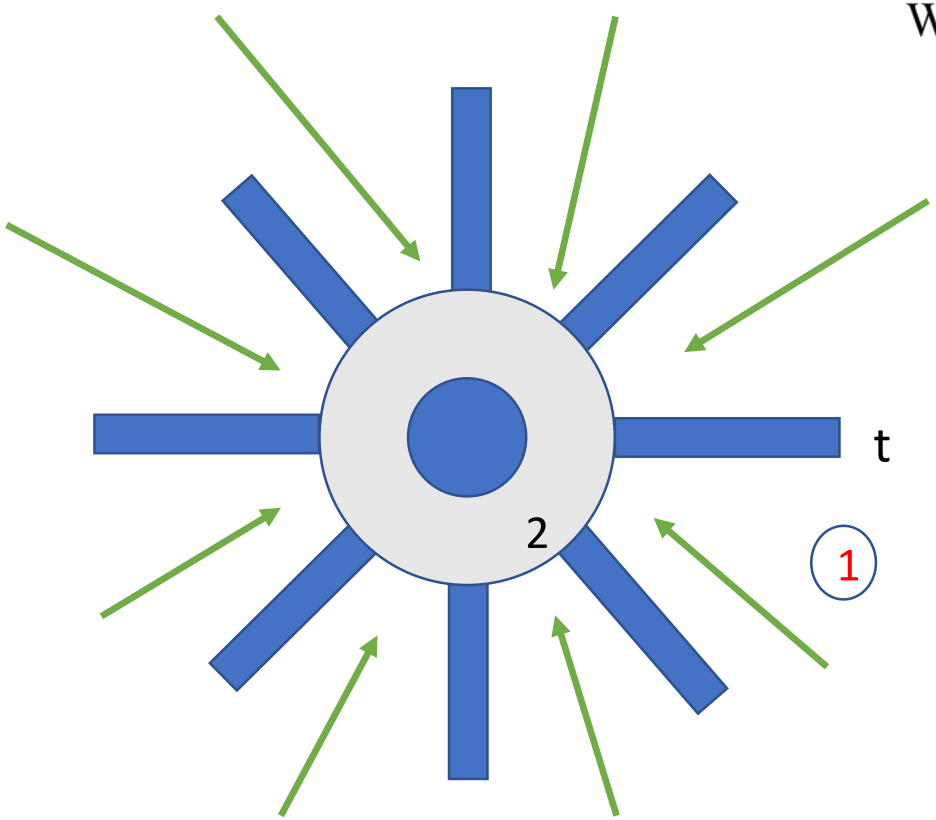


Fig. 18.11 *Inward radial flow turbine.*

Actual water flow in circumference area

$$A_F = (\pi.D\text{-}nt)B$$

$$A_F = K.\ \pi.D.B$$



D_1 = Diameter of runner at inlet,
B_1 = Width of runner at inlet,
V_{f_1} = Velocity of flow at inlet, and

Water flows in in circumference in area

A_F = π.D.B

$A_F = π.D_1.B_1$

$A_F = π.D_2.B_2$

to get F_y = 0 (No radial force on the runner)

$V_{F1} = V_{F2}$

$A_F.V_{F1} = A_F.V_{F2}$

$π.D_1.B_1 = π.D_2.B_2$

$D_1 > D_2$

$B_2 > B_1$

Discharge Q = $A_F.V_F.$

Discharge Q = $A_{F1}.V_{F1} = A_{F2}.V_{F2}$

Discharge Q = $π.D_1.B_1V_F = π.D_2.B_2V_F.$

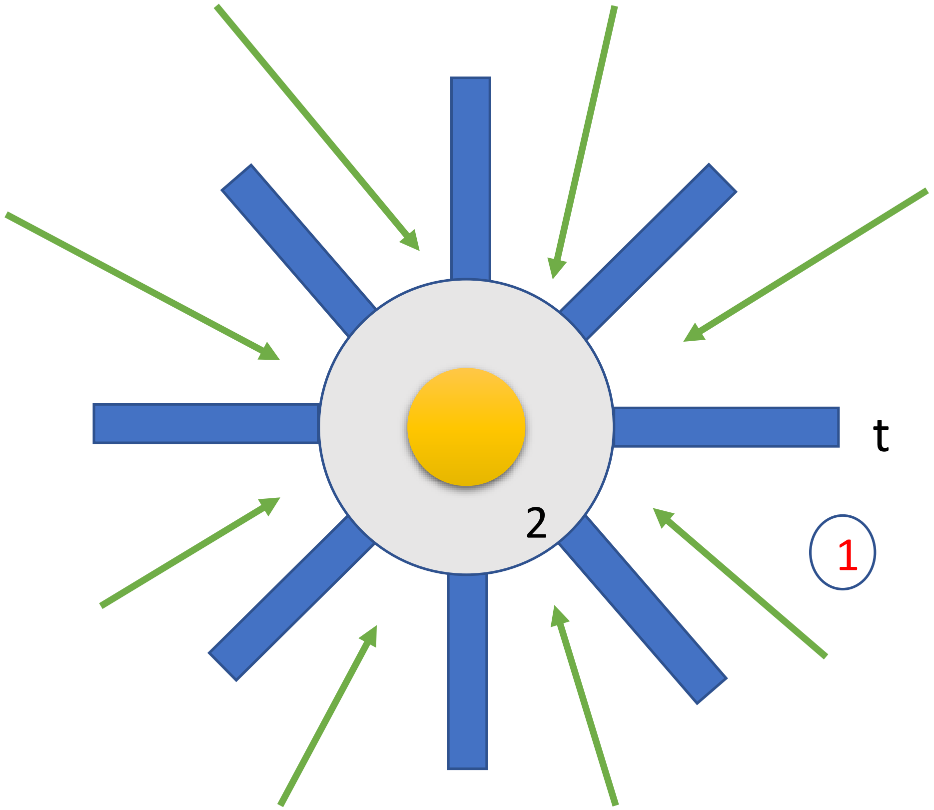
If given

$B_1 = B_2$

$V_{F1} \neq V_{F2}$

$F_y \neq 0$

D_1 = Diameter of runner at inlet,
B_1 = Width of runner at inlet,
V_{f_1} = Velocity of flow at inlet, and



to get $F_y = 0$ (No radial force on the runner)

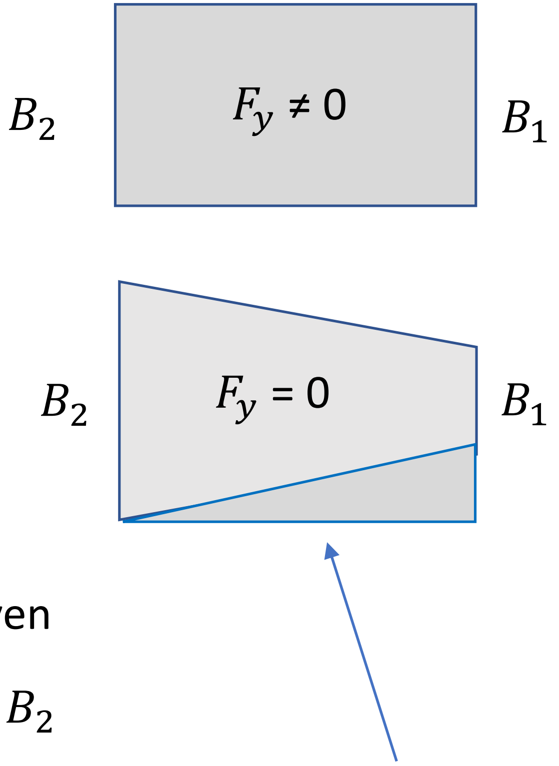
$$\boxed{V_{F1} = V_{F2}}$$

$$A_F . V_{F1} = A_F . V_{F2}$$

$$\pi . D_1 . B_1 = \pi . D_2 . B_2$$

$$D_1 > D_2$$

$$B_2 > B_1$$



If given

$$B_1 = B_2$$

$$V_{F1} \neq V_{F2}$$

$$F_y \neq 0$$

TO Avoid radial force acts on the runner
$B_1 > B_2$ is maintained in design

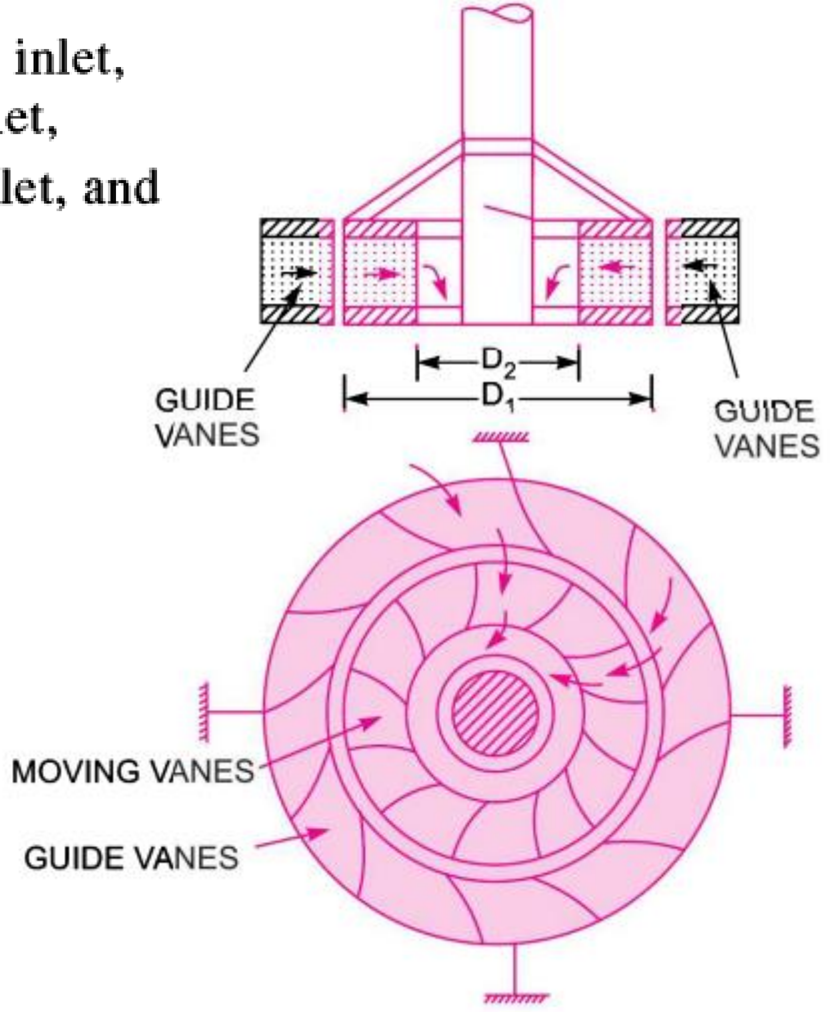
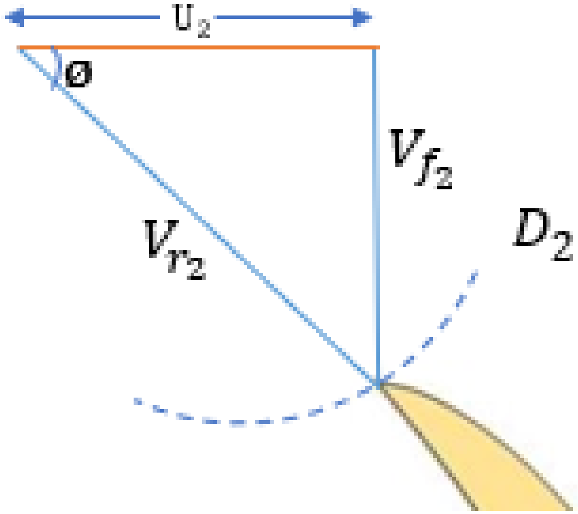


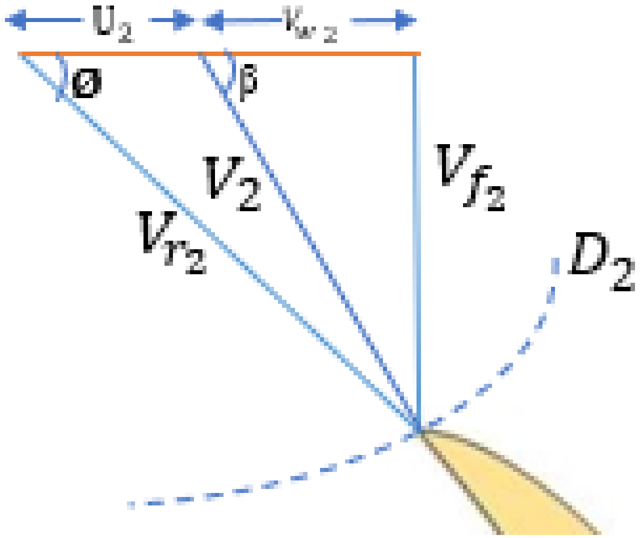
Fig. 18.11 *Inward radial flow turbine.*

(*iv*) The head (H) on the turbine is given by $H = \frac{p_1}{\rho \times g} + \frac{V_1^2}{2g}$

where p_1 = Pressure at inlet.

(*v*) **Radial Discharge.** This means the angle made by absolute velocity with the tangent on the wheel is 90° and the component of the whirl velocity is zero. Radial discharge at outlet means $\beta = 90°$ and $V_{w_2} = 0$, while radial discharge at outlet means $\alpha = 90°$ and $V_{w_1} = 0$.





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

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

Problem 18.14 *An inward flow reaction turbine has external and internal diameters as 1 m and 0.5 m respectively. The velocity of flow through the runner is constant and is equal to 1.5 m/s. Determine :*

(i) Discharge through the runner, and

(ii) Width of the turbine at outlet if the width of the turbine at inlet = 200 mm.

Solution. Given :

External diameter of turbine, $D_1 = 1$ m

Internal diameter of turbine, $D_2 = 0.5$ m

Velocity of flow at inlet and outlet, $V_{f_1} = V_{f_2} = 1.5$ m/s

Width of turbine at inlet, $B_1 = 200$ mm $= 0.20$ m

Let the width at outlet $= B_2$

$$Q = \pi D_1 B_1 \times V_{f_1} = \pi \times 1 \times 0.20 \times 1.5 = \mathbf{0.9425\ m^3/s.\ Ans.}$$

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

$$B_2 = \frac{D_1 \times B_1}{D_2} = \frac{1 \times 0.20}{0.5} = 0.40 \text{ m} = \mathbf{400\ mm.\ Ans.}$$

Problem 18.15 *An inward flow reaction turbine has external and internal diameters as 0.9 m and 0.45 m respectively. The turbine is running at 200 r.p.m. and width of turbine at inlet is 200 mm. The velocity of flow through the runner is constant and is equal to 1.8 m/s. The guide blades make an angle of 10° to the tangent of the wheel and the discharge at the outlet of the turbine is radial. Draw the inlet and outlet velocity triangles and determine:*

(i) The absolute velocity of water at inlet of runner,
(ii) The velocity of whirl at inlet, *(iii) The relative velocity at inlet,*
(iv) The runner blade angles, *(v) Width of the runner at outlet,*
(vi) Mass of water flowing through the runner per second,
(vii) Head at the inlet of the turbine,
(viii) Power developed and hydraulic efficiency of the turbine.

External Dia., $D_1 = 0.9$ m

Internal Dia., $D_2 = 0.45$ m

Speed, $N = 200$ r.p.m.

Width at inlet, $B_1 = 200$ mm $= 0.2$ m

Velocity of flow, $V_{f_1} = V_{f_2} = 1.8$ m/s

Guide blade angle, $\alpha = 10°$

Discharge at outlet = Radial

$\therefore$ $\beta = 90°$ and $V_{w_2} = 0$

External Dia., $D_1 = 0.9$ m

Internal Dia., $D_2 = 0.45$ m

Speed, $N = 200$ r.p.m.

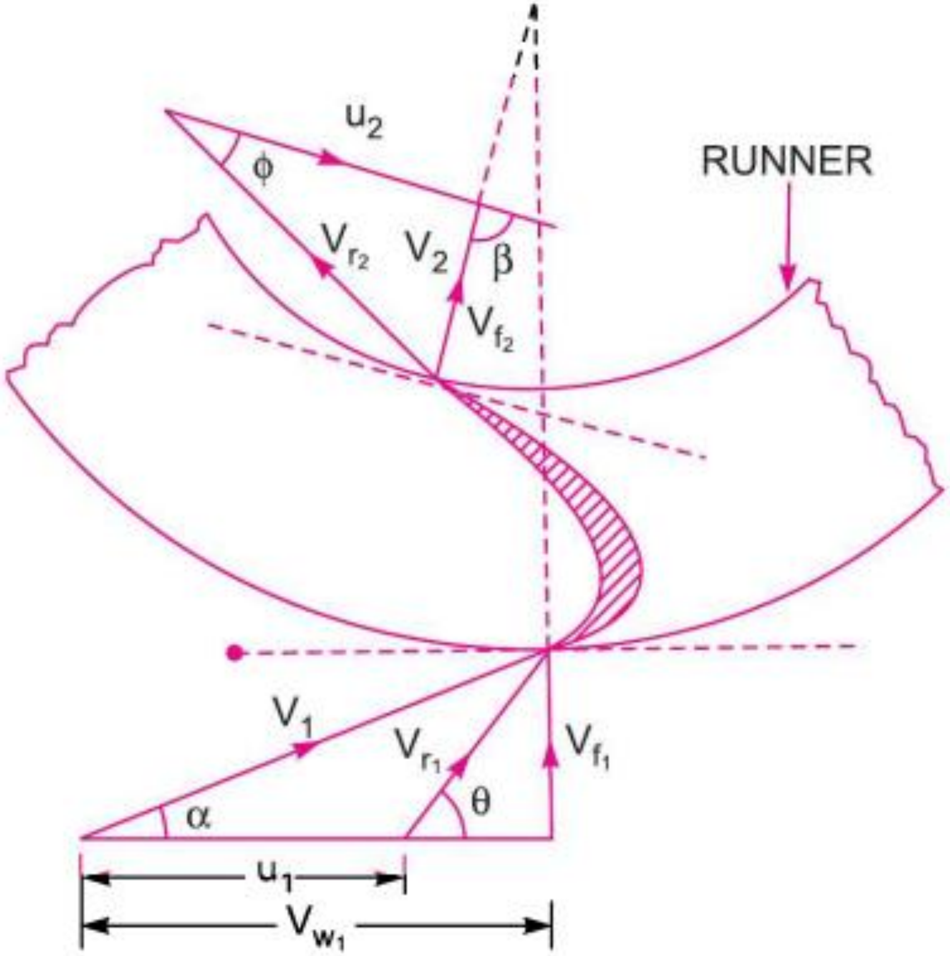
Width at inlet, $B_1 = 200$ mm $= 0.2$ m

Velocity of flow, $V_{f_1} = V_{f_2} = 1.8$ m/s

Guide blade angle, $\alpha = 10°$

Discharge at outlet = Radial

$\therefore$ $\beta = 90°$ and $V_{w_2} = 0$



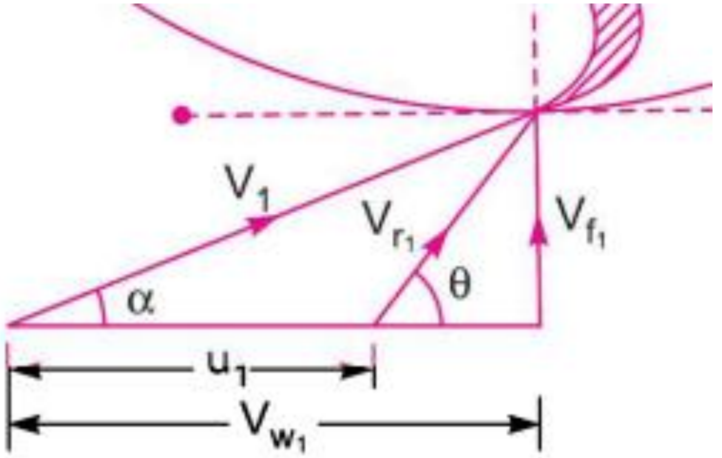
Tangential velocity of wheel at inlet and outlet are :

$$u_1 = \frac{\pi D_1 N}{60} = \frac{\pi \times .9 \times 200}{60} = 9.424 \text{ m/s}$$

$$u_2 = \frac{\pi D_2 N}{60} = \frac{\pi \times .45 \times 200}{60} = 4.712 \text{ m/s.}$$

(*i*) *Absolute velocity of water at inlet of the runner i.e.,* V_1

From inlet velocity triangle,



$$V_1 \sin \alpha = V_{f_1} \qquad V_1 = \frac{V_{f_1}}{\sin \alpha} = \frac{18}{\sin 10^\circ} = \mathbf{10.365\ m/s.\ Ans.}$$

(*ii*) *Velocity of whirl at inlet, i.e.,* V_{w_1}

$$V_{w_1} = V_1 \cos \alpha = 10.365 \times \cos 10^\circ = \mathbf{10.207\ m/s.\ Ans.}$$

(*iii*) *Relative velocity at inlet, i.e.,* V_{r_1}

$$V_{r_1} = \sqrt{V_{r_1}{}^3 + (V_{w_1} - u_1)^2} = \sqrt{1.8^2 + (10.207 - 9.424)^2}$$

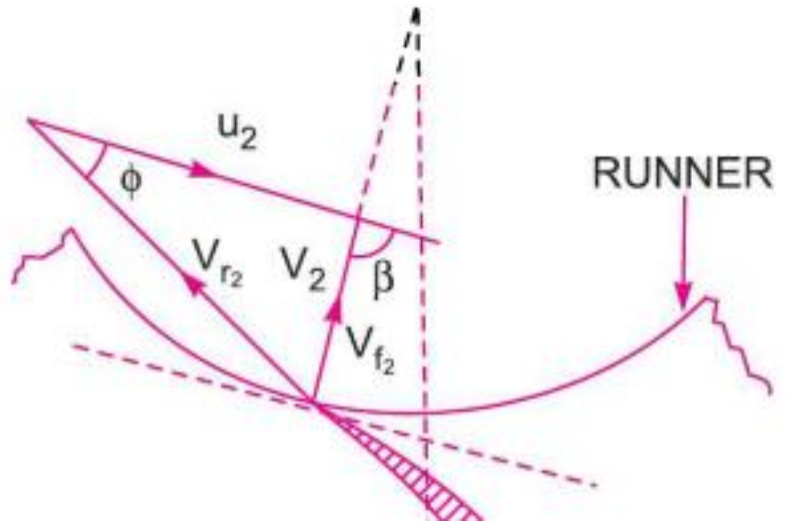
$$= \sqrt{3.24 + .613} = \mathbf{1.963\ m/s.\ Ans.}$$

(*iv*) *The runner blade angles* means the angle θ and φ

$$\tan \theta = \frac{V_{f_1}}{\left(V_{w_1} - u_1\right)} = \frac{1.8}{(10.207 - 9.424)} = 2.298$$

$$\theta = \tan^{-1} 2.298 = \mathbf{66.48^\circ} \text{ or } \mathbf{66^\circ\ 29'.\ Ans.}$$

From outlet velocity triangle, we have



$$\tan \phi = \frac{V_{f_2}}{u_2} = \frac{1.8}{4.712} = \tan 20.9°$$

ϕ = **20.9°** or **20° 54.4′. Ans.**

(v) *Width of runner at outlet, i.e., B_2*

$$\pi D_1 B_1 V_{f_1} = \pi D_2 B_2 V_{f_2} \text{ or } D_1 B_1 = D_2 B_2$$

$$B_2 = \frac{D_1 B_1}{D_2} = \frac{0.90 \times 0.20}{0.45} = 0.40 \text{ m} = \textbf{400 mm. Ans.}$$

(vi) *Mass of water flowing through the runner per second.*

Mass = $\rho \times Q$

$$Q = \pi D_1 B_1 V_{f_1} = \pi \times 0.9 \times 0.20 \times 1.8 = 1.0178 \text{ m}^3\text{/s.}$$

Mass = $\rho \times Q$ = 1000 × 1.0178 kg/s = **1017.8 kg/s. Ans.**

(vii) Head at the inlet of turbine, i.e., H.

$$H - \frac{V_2^2}{2g} = \frac{1}{g}(V_{w_1}u_1 \pm V_{w_2}u_2) = \frac{1}{g}(V_{w_1}u_1)$$

$$H = \frac{1}{g}V_{w_1}u_1 + \frac{V_2^2}{2g} = \frac{1}{9.81} \times 10.207 \times 9.424 + \frac{1.8^2}{2 \times 9.81} \quad (\because V_2 = V_{f_2})$$

$$= 9.805 + 0.165 = \mathbf{9.97\ m.\ Ans.}$$

(viii) Power developed, i.e., $P = \frac{\text{Work done per second on runner}}{1000}$

$$= \frac{\rho Q\,[V_{w_1}u_1]}{1000} = 1000 \times \frac{1.0178 \times 10.207 \times 9.424}{1000} = \mathbf{97.9\ kW.\ Ans.}$$

$$\eta_h = \frac{V_{w_1}u_1}{gH} = \frac{10.207 \times 9.424}{9.81 \times 9.97} = 0.9834 = \mathbf{98.34\%.\ Ans.}$$

Assignment- 5

Problem 18.17 *As inward flow reaction turbine has external and internal diameters as 1.0 m and 0.6 m respectively. The hydraulic efficiency of the turbine is 90% when the head on the turbine is 36 m. The velocity of flow at outlet is 2.5 m/s and discharge at outlet is radial. If the vane angle at outlet is 15° and width of the wheel is 100 mm at inlet and outlet, determine : (i) the guide blade angle, (ii) speed of the turbine, (iii) vane angle of the runner at inlet, (iv) volume flow rate of turbine and (v) power developed.*

Problem 18.18 *An inward flow reaction turbine has an exit diameter of 1 metre and its breadth at inlet is 250 mm. If the velocity of flow at inlet is 2 metres/s, find the mass of water passing through the turbine per second. Assume 10% of the area of flow is blocked by blade thickness. If the speed of the runner is 210 r.p.m. and guide blades make an angle of 10° to the wheel tangent, draw the inlet velocity triangle, and find :*

(i) the runner vane angle at inlet, *(ii) velocity of wheel at inlet,*
(iii) the absolute velocity of water leaving the guide vanes, and
(iv) the relative velocity of water entering the runner blade.

Problem 18.19 *The external and internal diameters of an inward flow reaction turbines are 1.20 m and 0.6 m respectively. The head on the turbine is 22 m and velocity of flow through the runner is constant and equal to 2.5 m/s. The guide blade angle is given as 10° and the runner vanes are radial at inlet. If the discharge at outlet is radial, determine :*

(i) The speed of the turbine, *(ii) The vane angle at outlet of the runner, and*

(iii) Hydraulic efficiency.

PART –IV

Degree of Reaction (R):

$$R = \frac{\text{Contribution of Pressure energy Head into (Runner power)}}{\text{Contribution of Kinetic energy + Contribution of Pressure energy Head into (Runner power)}}$$

$$\boldsymbol{R = \frac{Change\ in\ pressure\ inside\ the\ runner}{Change\ in\ total\ energy\ inside\ the\ runner}}$$

Fundamental equation for hydrodynamic machines

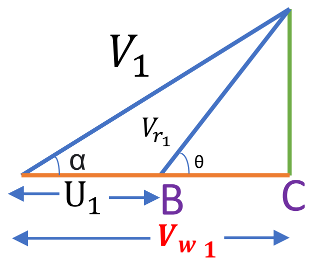
Or

Energy transfers per unit weight to the runner

Or

Total energy change inside the runner per unit weight

$$\boldsymbol{H_e = \frac{1}{g}\left[V_{W_1} U_1 \pm V_{W_2} U_2\right]}$$



$$V_{w_1} = U_1 + BC$$

$$V_{w_1} = U_1 + V_{r_1} \cos \theta$$

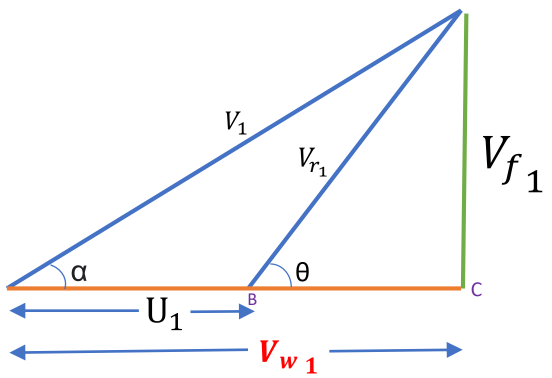
$$V_{w_1} = U_1 + \sqrt{V_{r_1}^2 - V_{f_1}^2}$$

$$(V_{w_1} - U_1)^2 = V_{r_1}^2 - V_1^2 + V_{w_1}^2$$

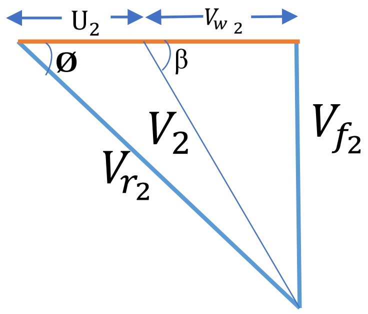
$$V_{w_1}^2 + U_1^2 + 2.V_{w_1}.U_1 = V_{r_1}^2 - V_1^2 + V_{w_1}^2$$

$$V_{w_1}^2 + U_1^2 + 2.V_{w_1}.U_1 = V_{r_1}^2 - V_1^2 + V_{w_1}^2$$

$$\boxed{V_{w_1}.U_1 = \frac{1}{2}\left[U_1^2 - V_{r_1}^2 + V_1^2\right]}$$



From outlet velocity triangle:



$$V_{w_2} + U_2 = V_{r_2} \cos \Theta$$

$$V_{w_2} = V_{r_2} \cos \Theta - U_2$$

$$V_{w_2} = \sqrt{{V_{r_2}}^2 - {V_{f_2}}^2} - U_2$$

$$V_{w_2} = \sqrt{{V_{r_2}}^2 - (V_2 - V_{w_2})^2} - U_2$$

$$(V_{w_2} + U_2)^2 = {V_{r_2}}^2 - {V_2}^2 + {V_{w_2}}^2$$

$${V_{w_2}}^2 + {U_2}^2 + 2.V_{w_2}.U_2 = {V_{r_2}}^2 - {V_2}^2 + {V_{w_2}}^2$$

$${V_{w_2}}^2 + {U_2}^2 + 2.V_{w_2}.U_2 = {V_{r_2}}^2 - {V_2}^2 + {V_{w_2}}^2$$

$$V_{w_2}.U_2 = \frac{1}{2}\left[{V_{r_2}}^2 - {V_2}^2 - {U_2}^2\right]$$

$$H_e = \frac{1}{g}[V_{W_1} U_1 \pm V_{W_2} U_2]$$

$$H_e = \frac{1}{2g}[U_1{}^2 - V_{r_1}^2 + V_1^2 \pm V_{r_2}{}^2 - V_2{}^2 - U_2{}^2]$$

$$H_e = \frac{1}{2g}[U_1{}^2 - V_{r_1}^2 + V_1^2 + V_{r_2}{}^2 - V_2{}^2 - U_2{}^2]$$

$$H_e = \frac{1}{2g}\left[\left(V_1^2 - V_2{}^2\right) + (U_1{}^2 - U_2{}^2) + (V_{r_2}{}^2 - V_{r_1}^2)\right]$$

$$H_e = \frac{(V_1^2 - V_2{}^2)}{2g} + \frac{(U_1{}^2 - U_2{}^2)}{2g} + \frac{(V_{r_2}{}^2 - V_{r_1}^2)}{2g}$$

Change in kinetic energy per unit weight inside the runner + Change in energy per unit weight due to centrifugal action + Change in static pressure energy per unit weight $= H_e$

Change in pressure inside the runner $\frac{(U_1{}^2-U_2{}^2)}{2g}+\frac{(V_{r_2}{}^2-V_{r_1}^2)}{2g}$

$$\mathbf{R} = \frac{\frac{(U_1{}^2-U_2{}^2)}{2g}+\frac{(V_{r2}{}^2-V_{r1}^2)}{2g}}{\frac{(V_1^2-V_2{}^2)}{2g}+\frac{(U_1{}^2-U_2{}^2)}{2g}+\frac{(V_{r2}{}^2-V_{r1}^2)}{2g}}$$

$$\mathbf{R} = \frac{\frac{(U_1{}^2-U_2{}^2)}{}+\frac{(V_{r2}{}^2-V_{r1}^2)}{}}{\frac{(V_1^2-V_2{}^2)}{}+\frac{(U_1{}^2-U_2{}^2)}{}+\frac{(V_{r2}{}^2-V_{r1}^2)}{}}$$

$$R = \frac{(U_1{}^2-U_2{}^2)+(V_{r_2}{}^2-V_{r_1}^2)}{(V_1^2-V_2{}^2)+(U_1{}^2-U_2{}^2)+(V_{r_2}{}^2-V_{r_1}^2)}$$

$$R = \frac{(V_1^2-V_2{}^2)+(U_1{}^2-U_2{}^2)+(V_{r_2}{}^2-V_{r_1}^2)-(V_1^2-V_2{}^2)}{(V_1^2-V_2{}^2)+(U_1{}^2-U_2{}^2)+(V_{r_2}{}^2-V_{r_1}^2)}$$

$$R = 1 - \frac{(V_1^2-V_2{}^2)}{(V_1^2-V_2{}^2)+(U_1{}^2-U_2{}^2)+(V_{r_2}{}^2-V_{r_1}^2)}$$

$$2gH_e = \left(\boldsymbol{V_1^2} - \boldsymbol{V_2}^{\mathbf{2}}\right) + \left(\boldsymbol{U_1}^{\mathbf{2}} - \boldsymbol{U_2}^{\mathbf{2}}\right) + \left(\boldsymbol{V_{r_2}}^{\mathbf{2}} - \boldsymbol{V_{r_1}^2}\right)$$

$$\text{Based on } H_e = \frac{1}{2g}\left[U_1{}^2 - V_{r_1}^{\ 2} + V_1^2 \pm V_{r_2}{}^2 - V_2{}^2 - U_2{}^2\right]$$

$$R = 1 - \frac{\left(\boldsymbol{V_1^2} - \boldsymbol{V_2}^{\mathbf{2}}\right)}{2gH_e}$$

1)Pelton wheel (Degree of reaction)

$U_1=U_2$ $V_{r_1} = V_{r_2}$

$$R = 1- \frac{(V_1^2 - V_2{}^2)}{(V_1^2 - V_2{}^2)}$$

$$R = 1-1 = 0$$

2) Actual reaction turbine

Radial distance $\beta = 90$; $V_{w_2} = 0$; $V_2 = V_{f_2}$

$V_{f_1} = V_{f_2}$

$$H_e = \frac{1}{g}[V_{w_1} U_1]$$

$\text{Tan}\,\alpha = \frac{V_{f_1}}{V_{w_1}}$ $\qquad$ $\text{Cot}\,\alpha = \frac{V_{w_1}}{V_{f_1}}$

$V_{w_1} = V_{f_1} \text{Cot}\,\alpha$

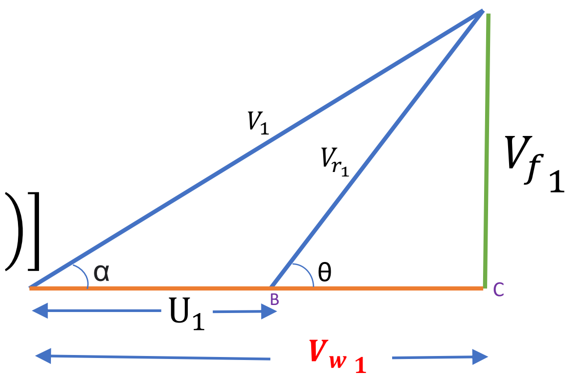
$U_1 = V_{w_1} - BC$

$U_1 = V_{w_1} - V_{f_1} \text{Cot}\,\alpha$

$U_1 = V_{f_1} \text{Cot}\,\alpha - V_{f_1} \text{Cot}\,\theta$

$$H_e = \frac{1}{g}[V_{w_1} U_1]$$

$$H_e = \frac{1}{g}\left[V_{f_1} \text{Cot}\,\alpha \; (V_{f_1} \text{Cot}\,\alpha - V_{f_1} \text{Cot}\,\theta)\right]$$



$$H_e = \frac{1}{g}\left[V_{f_1} \text{Cot}^2\,\alpha - \text{Cot}\,\alpha . \text{Cot}\,\theta\,)\right]$$

$V_1^2 - V_2{}^2 = V_{f_1} \text{Cosec}^2\,\alpha - V_{f_2}{}^2$

$V_1^2 - V_2{}^2 = V_{f_1}{}^2 (\text{Cosec}^2\,\alpha - 1\,)$

$V_1^2 - V_2{}^2 = V_{f_1}{}^2 (\text{Cot}^2\,\alpha)$

$$R = 1 - \frac{V_{f_1}{}^2 (\text{Cot}^2\,\alpha)}{\frac{1}{g}\left[V_{f_1} \text{Cot}\,\alpha \; (V_{f_1} \text{Cot}\,\alpha - V_{f_1} \text{Cot}\,\theta\,)\right]}$$

$$R = 1 - \frac{(\text{Cot}^2\,\alpha)}{[\text{Cot}\,\alpha \; (\text{Cot}\,\alpha - \text{Cot}\,\theta\,)]}$$

Problem 18.27 *A Kaplan turbine working under a head of 20 m develops 11772 kW shaft power. The outer diameter of the runner is 3.5 m and hub diameter is 1.75 m. The guide blade angle at the extreme edge of the runner is 35°. The hydraulic and overall efficiencies of the turbines are 88% and 84% respectively. If the velocity of whirl is zero at outlet, determine :*

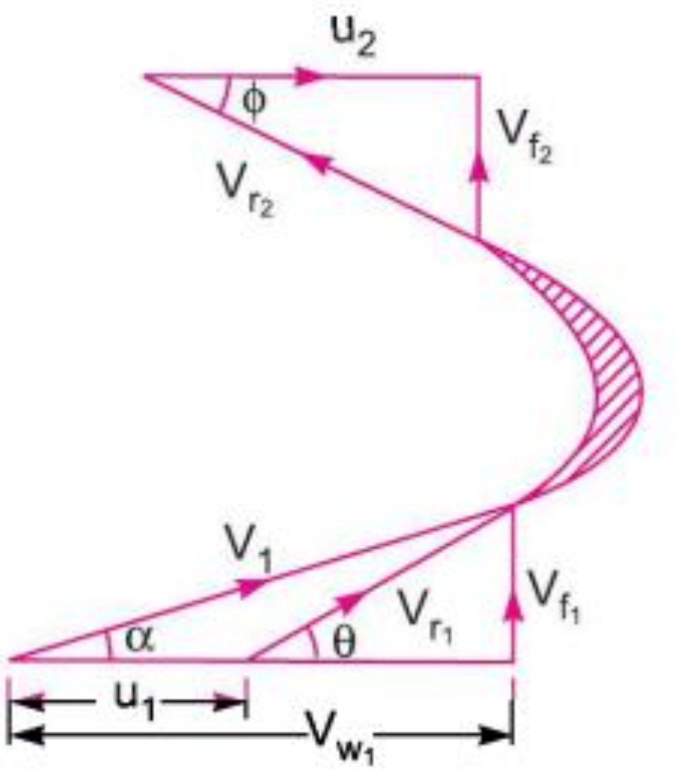
(i) Runner vane angles at inlet and outlet at the extreme edge of the runner, and

(ii) Speed of the turbine.

Head, $H = 20$ m

Shaft power, S.P. = 11772 kW

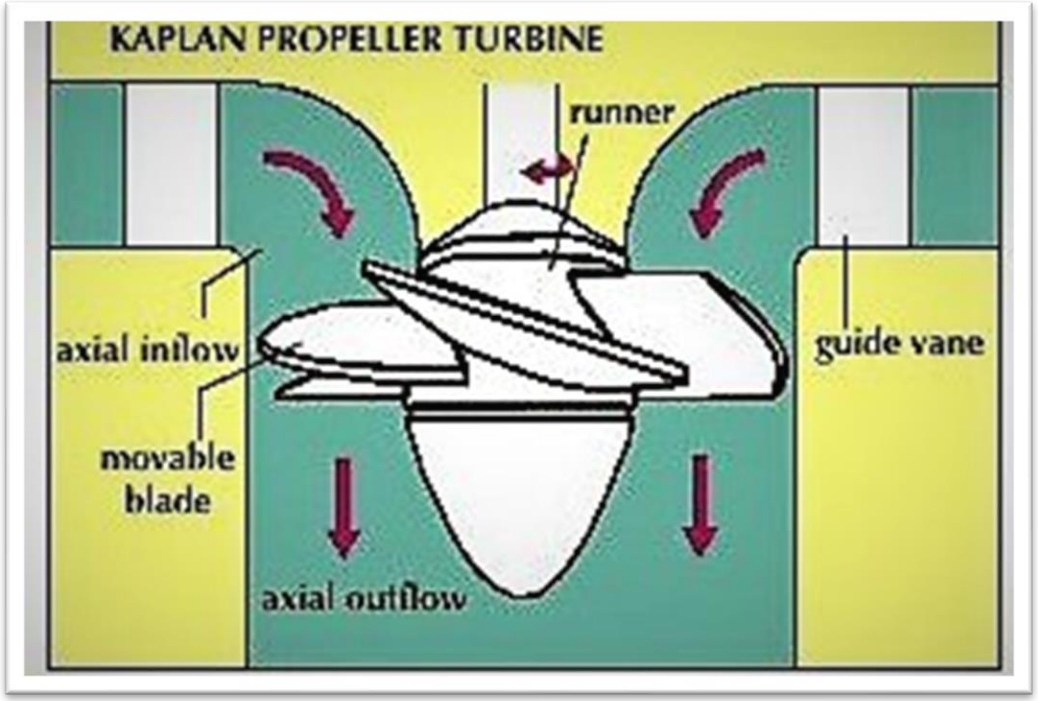
Outer dia. of runner, $D_o = 3.5$ m



PART –V

AXIAL FLOW REACTION TURBINE :

If the water flows parallel to the axis of the rotation of the shaft, the turbine is known as axial flow turbine.



And if the head at the inlet of the turbine is the sum of **pressure energy** and **kinetic energy** and during the flow of water through runner a part of **pressure energy** is converted into Kinetic energy, the turbine is known as **reaction turbine**.

AXIAL FLOW REACTION TURBINE

1. Propeller Turbine
2. Kaplan Turbine

- When the vanes are fixed to the hub and they are not adjustable, the turbine is known as propeller turbine
- if the vanes on the hub are adjustable, the turbine is known as a Kaplan Turbine
- The runner of Kaplan turbine resembles with propeller of ship , That is why Kaplan turbine is also called as Propeller Turbine.
- This turbine is suitable where a large quantity of water at low head is available.

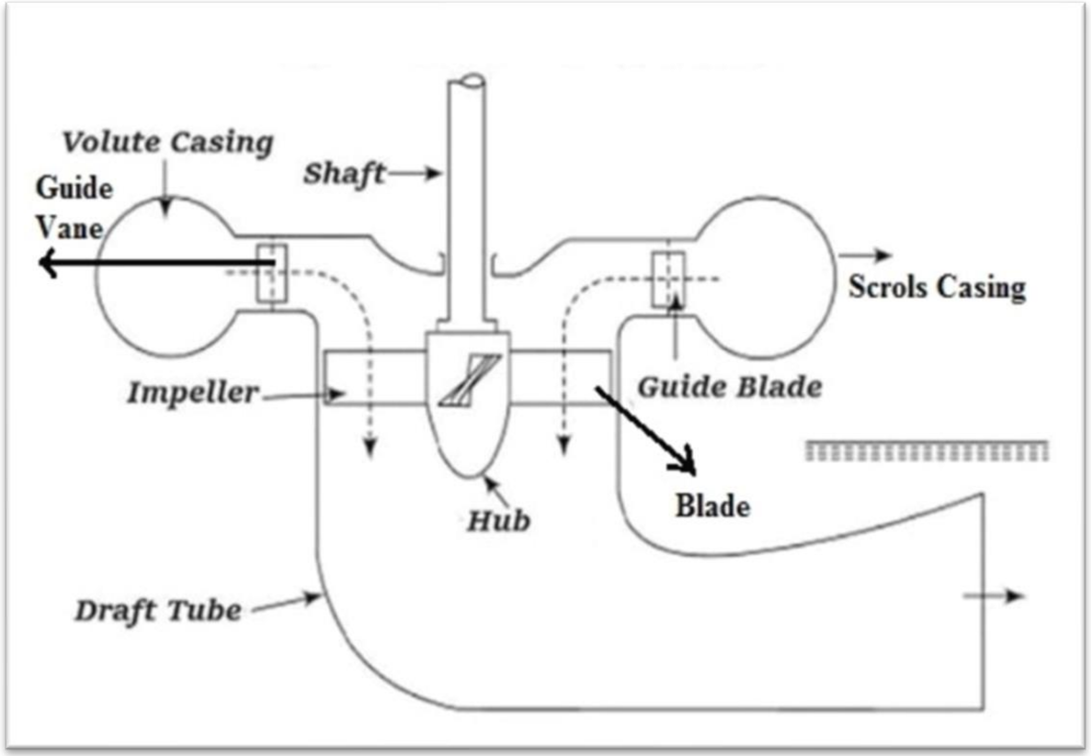
The propeller turbines have the following favorable characteristics:

- Relatively small dimensions combined with **high rotational speed**
- large **overloading** capacity.
- The comparatively high efficiencies at partial loads and the ability of overloading is obtained by a coordinated regulation of the guide vanes and the runner blades to obtain optimal efficiency for all operations.

- Kaplan turbines have adjustable runner blades, that offers significant advantage to give high efficiency even in the range of partial load, and there is little drop in efficiency due to head variation or load

Kaplan turbine

- Kaplan turbine is an axial flow reaction turbine. The water flows through the runner of the turbine in an axial direction and the energy at the inlet of the turbine is the sum of kinetic and pressure energy .



- In an axial flow reaction turbine the shaft is vertical. The lower end of the **shaft is larger** and is known as '**hub**' or '**boss**'. It is on this hub that the vanes are attached.

- Kaplan turbine is best suited where large quantity of low head water is available. Kaplan Turbine is named after V. Kaplan, the Australian Engineer.

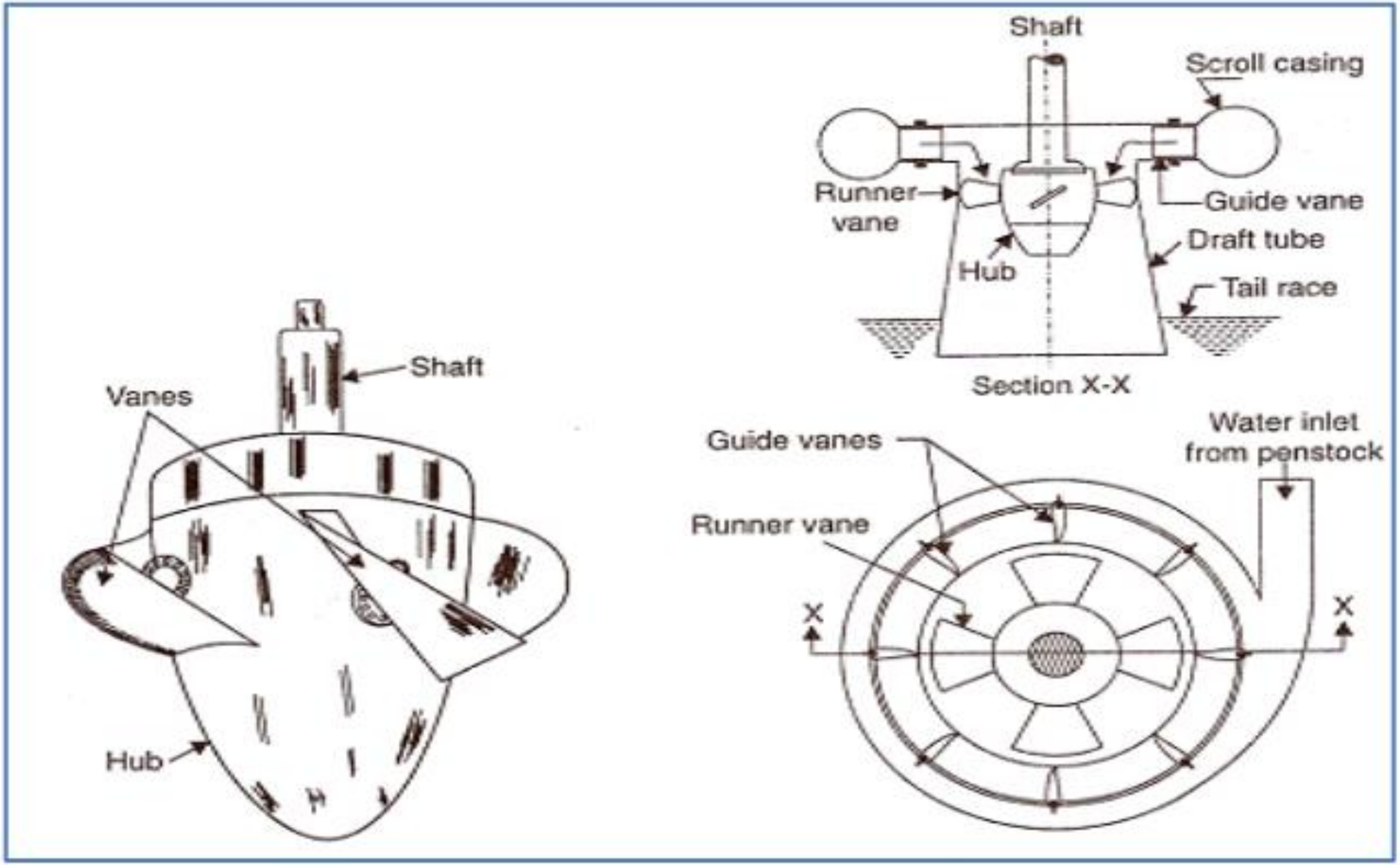
- Kaplan turbines are now widely used throughout the world in **high-flow, low-head power production.**

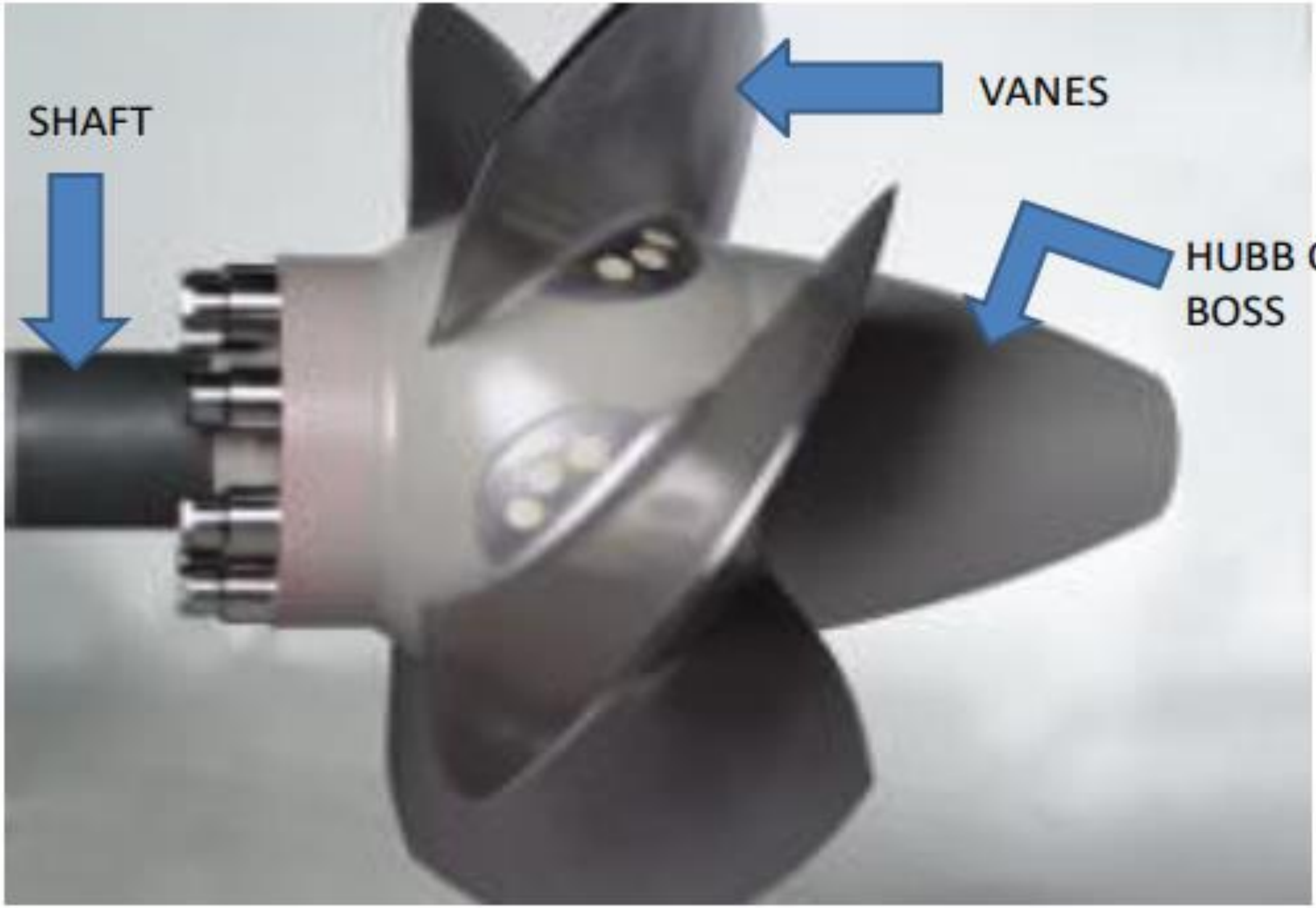
The main parts of a Kaplan Turbine are:

1. Scroll Casing
2. Guide vane Mechanism
3. Hub with Vanes
4. Draft Tube

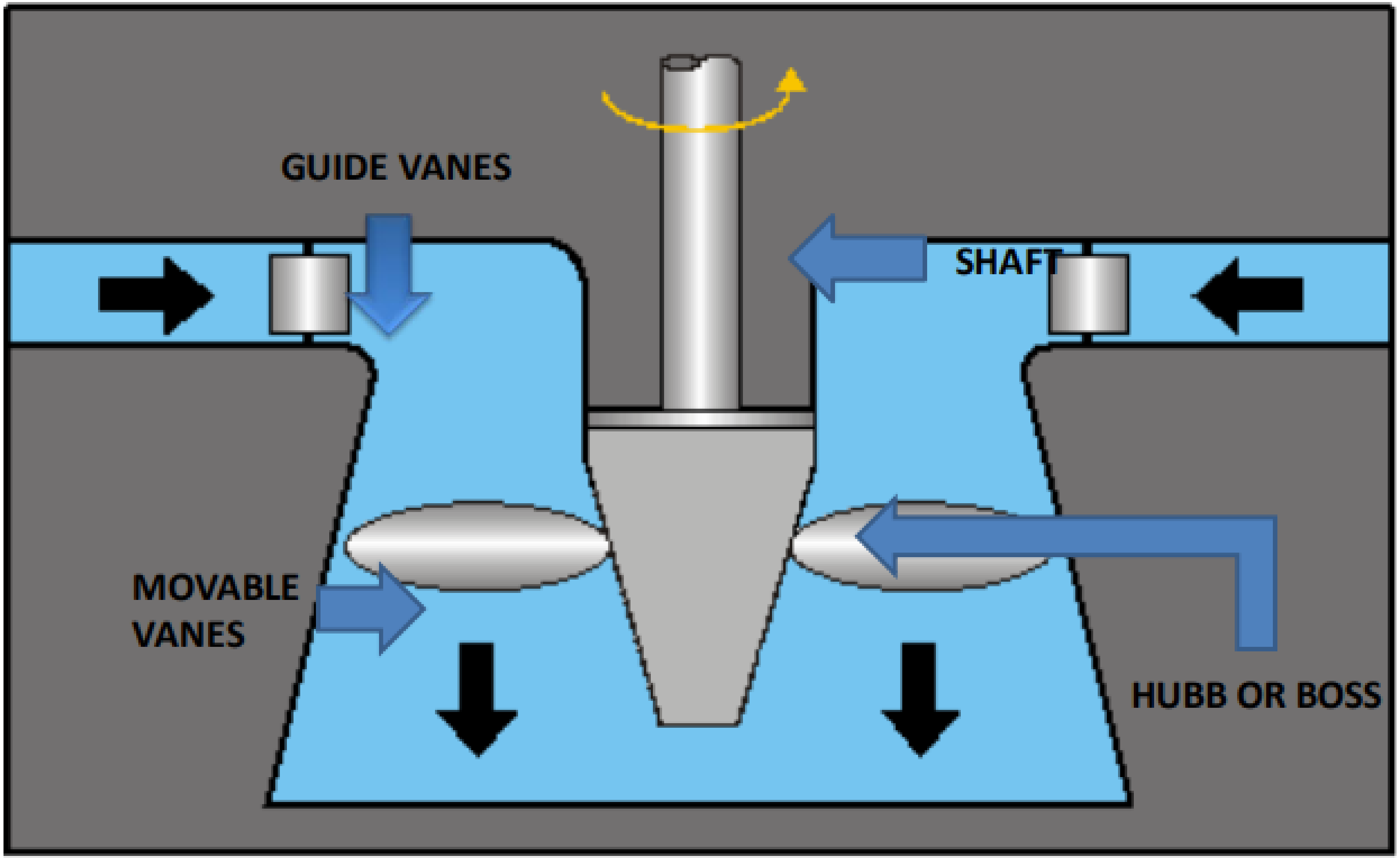
Working principle :

- The water enters the turbine through the guide vanes which are aligned such as to give the flow a **suitable degree of swirl**. The flow from guide vanes pass through the curved passage which forces the radial flow to axial direction.
- The axial flow of water with a component of swirl applies force on the blades of the rotar and looses its momentum, both **linear and angular**, producing torque and rotation (their product is power) in the shaft. The scheme for production of hydroelectricity by Kaplan Turbine is same as that for Francis Turbine.

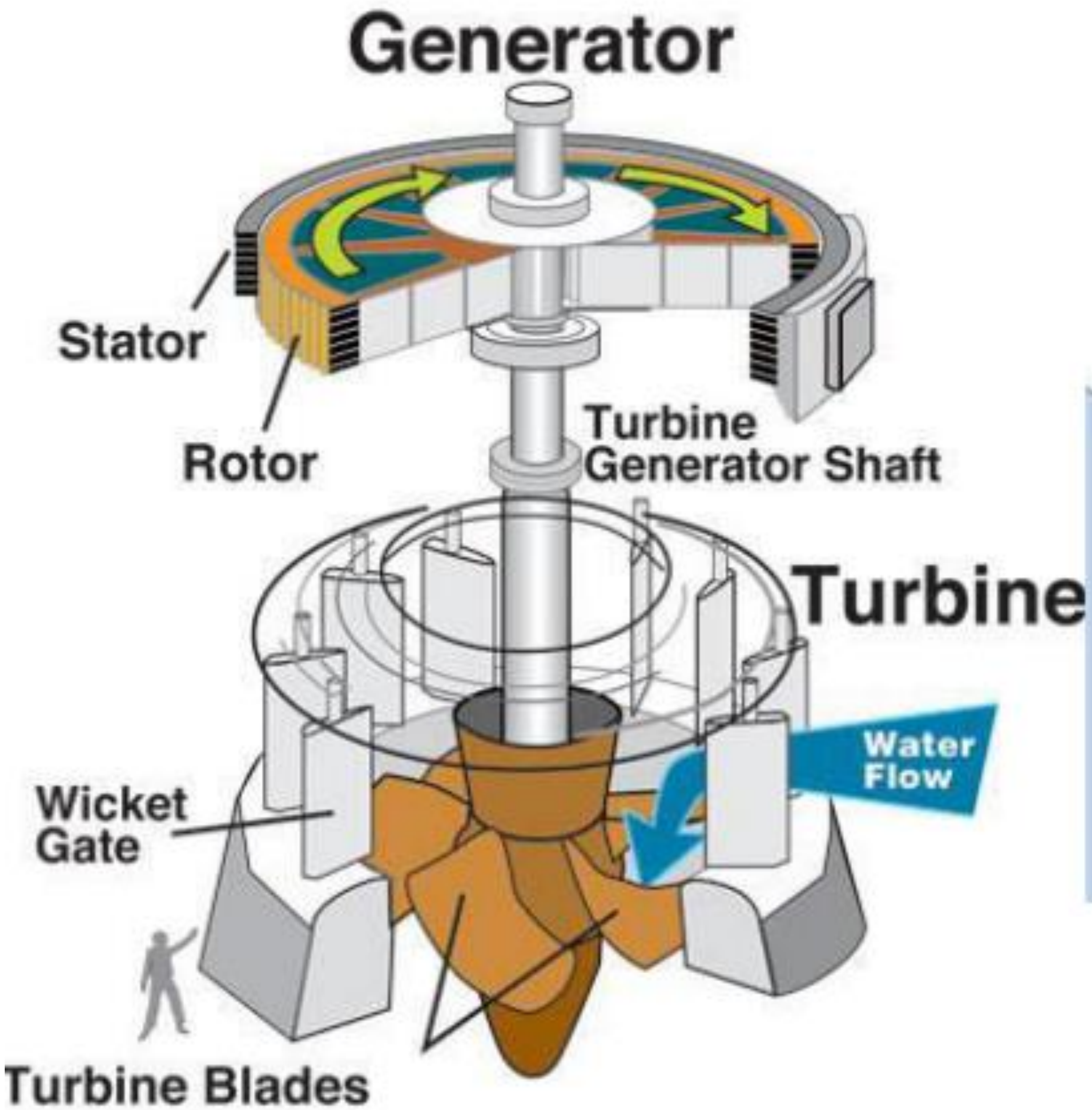

Shaft
Vanes
Hub
Shaft
Scroll casing
Runner vane
Guide vane
Draft tube
Hub
Tail race
Section X-X
Guide vanes
Water inlet from penstock
Runner vane
X
X

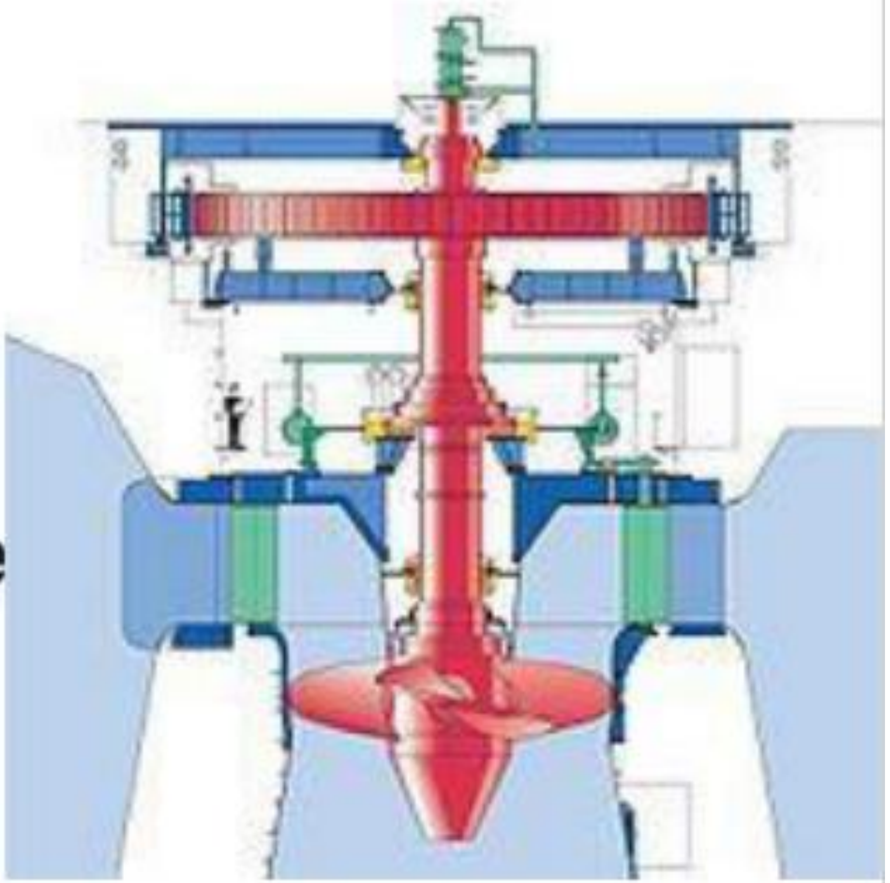


VANES
SHAFT
HUBB OR
BOSS


GUIDE VANES
SHAFT
MOVABLE
VANES
HUBB OR BOSS

Kaplan Turbine





Comparison of the turbines

	Pelton	**Francis**	**Kaplan**
Energy at inlet	Impulse	Reaction	Reaction
Head	High	Medium	Low
Flow Direction	Tangentially	Mixed flow (**Radial entry axial Outlet**)	Axial flow
Discharge required	Low	Medium	High
Specific Speed	Low	Medium	High

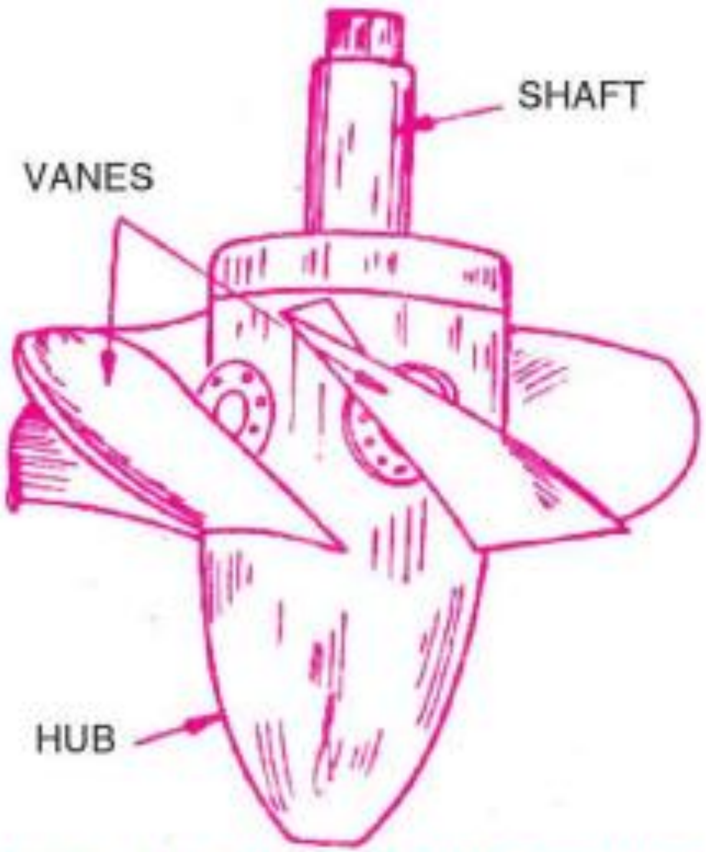


Fig. 18.25 *Kaplan turbine runner.*

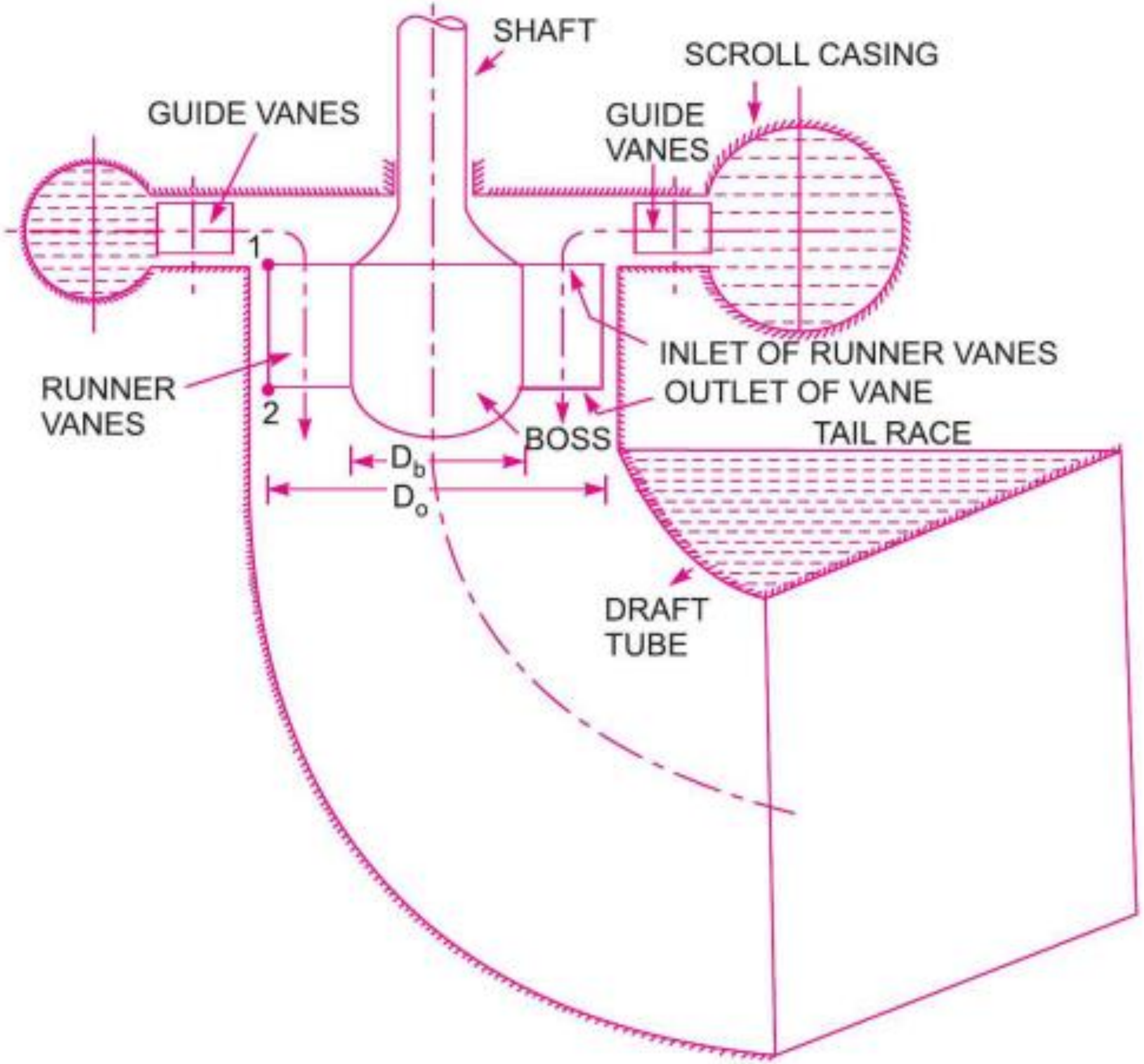


Fig. 18.26 *Main components of Kaplan turbine.*

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

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

D_0 = Outer diameter of the runner

D_b = Diameter of hub

V_{f_1} = velocity of flow at the inlet

Some important points for the Kaplan or propeller turbine

1. The Peripheral velocity at the inlet and outlet

$$U_1 = U_2 = \frac{\pi D_0 N}{60}$$

2. Velocity of flow at the inlet and outlet are equal

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

3. Area of the flow at inlet = Area of the flow at the outlet

$$\frac{\pi}{4}(D_0^2 - D_0^2)$$

Types of Draft tube :

It is conical diverging tube fitted at runner exit to convert the Kinetic energy into pressure energy .it always increases the efficiency of turbine .

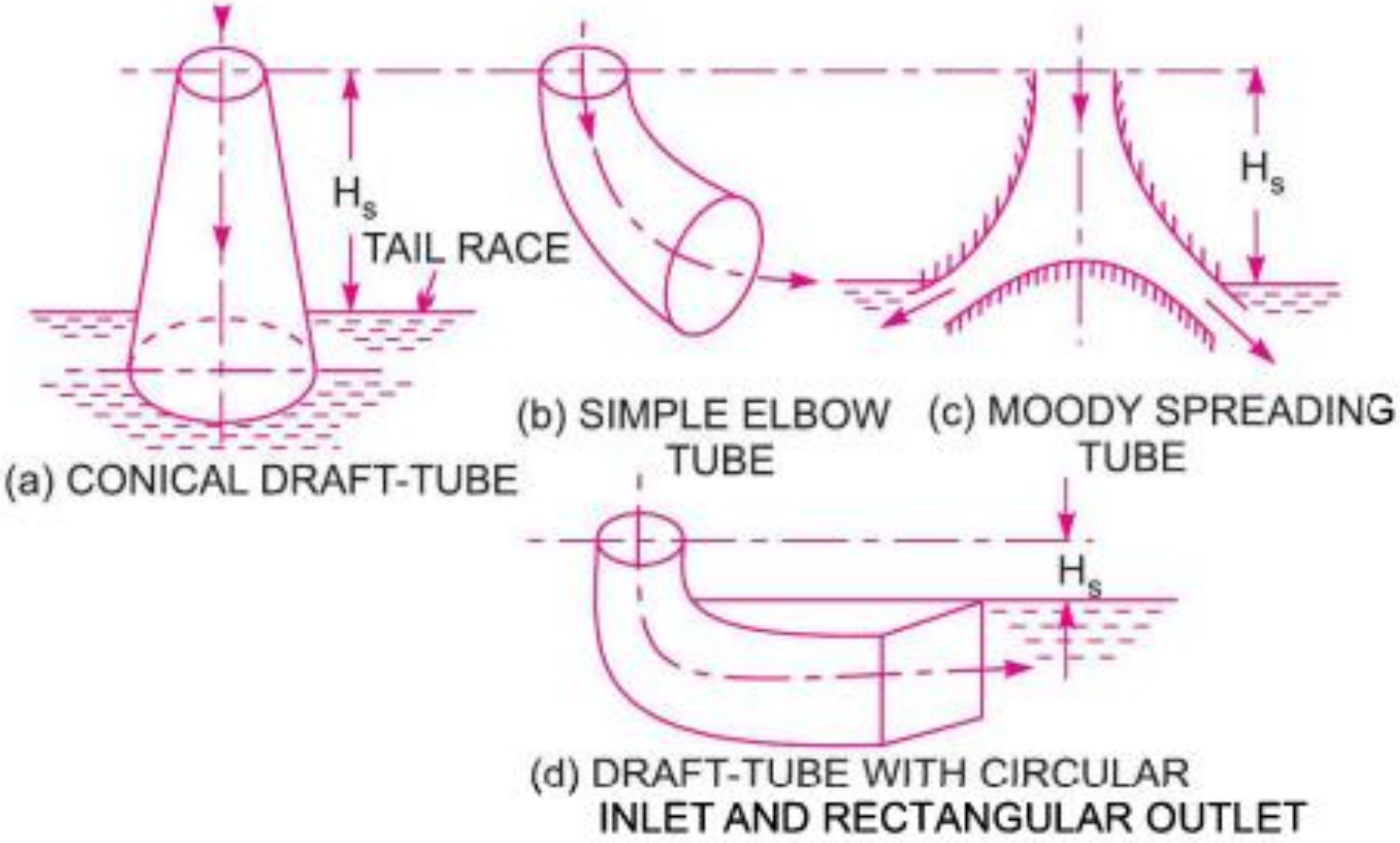
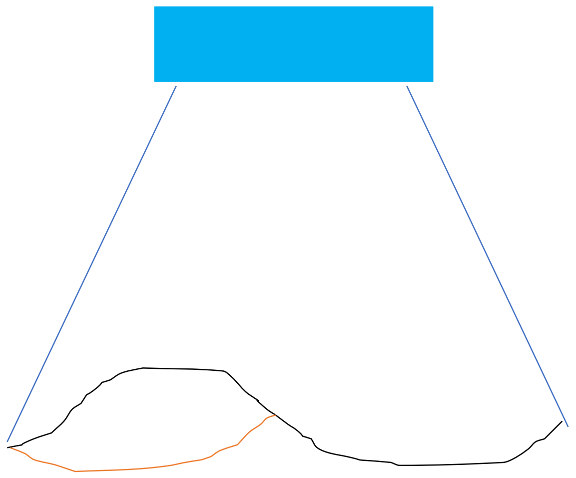


Fig. 18.32 *Types of draft-tubes.*

Draft Tube :

- The draft-tube is a pipe of gradually increasing area which connects the outlet of the runner to the tailrace.
- 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 while the other end is sub-merged below the level of water in the tail race



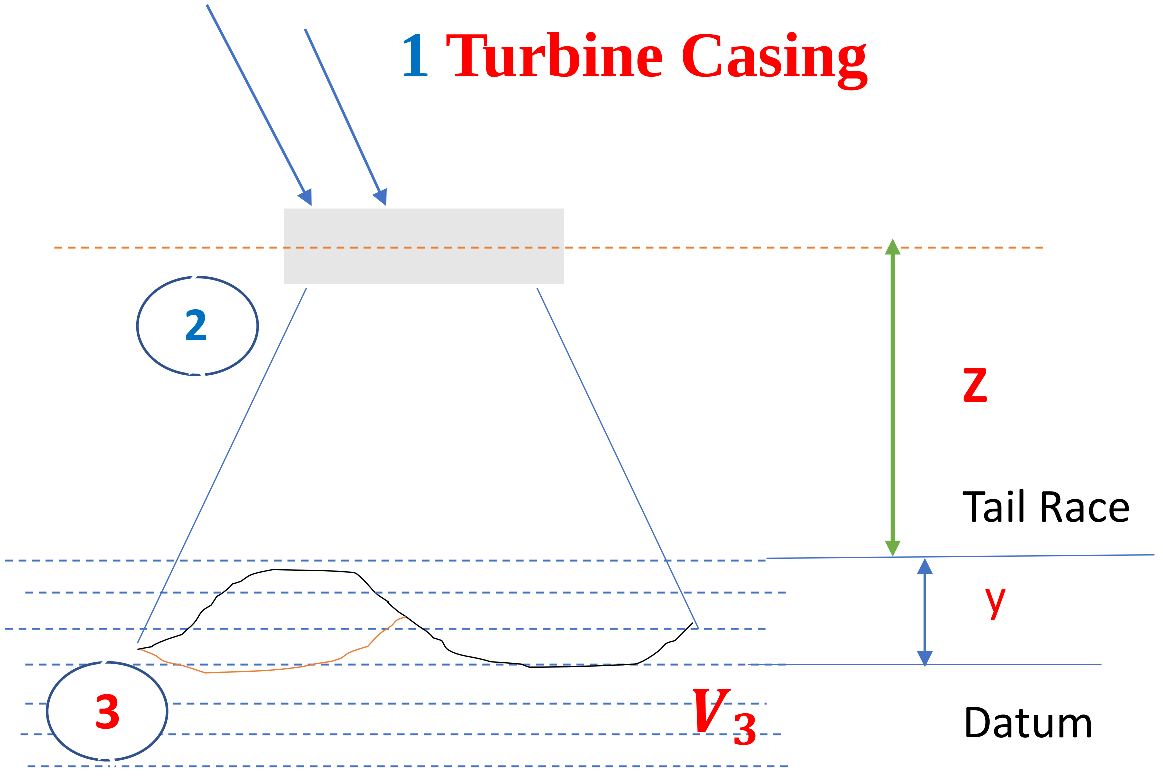
The draft-tube, in addition to serve a passage for water discharge, has the following two purposes also :

1. It permits a negative head to be established at the outlet of the runner and thereby 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.
2. It converts a large proportion of the kinetic energy **(V_2^2/2g)** rejected at the outlet of the turbine into useful pressure energy. Without the draft tube, the kinetic energy rejected at the outlet of the turbine will go waste to the tail race.
3. Increase Net head on turbine
4. Turbine can placed above the tail race
5. Converts Large portion of the Kinetic energy into pressure energy

- 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 a draft-tube, the Kinetic energy &) rejected at the outlet of the runner will go waste to the tail race.

Conical draft turbine	Most efficient (90 %)	Low Specific speed turbine
Simple Elbow Tube	Efficiency 60 %	Take less space
Moody sprating tube	More efficient (85%)	Reduce Whirl velocity (V_{W_2} = 0)
Draft tube with Circular inlet and rectangular outlet	Efficiency (80 %)	Takes Less space



Applying Bernoulli's equation between 2 and 3

$$\frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z + y = \frac{P_3}{\rho g} + \frac{V_3^2}{2g} + 0 + h_s$$

$$\frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z + y = \frac{P_3}{\rho g} + \frac{V_3^2}{2g} + 0 + h_s$$

$$\frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z + y = \frac{P_a}{\rho g} + y + \frac{V_3^2}{2g} + 0 + h_f$$

$$\frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z + \cancel{y} = \frac{P_a}{\rho g} + \cancel{y} + \frac{V_3^2}{2g} + 0 + h_f$$

$$\frac{P_2}{\rho g} = \frac{P_a}{\rho g} + \frac{V_3^2}{2g} - \frac{V_2^2}{2g} - Z + h_f$$

$$\frac{P_2}{\rho g} = \frac{P_a}{\rho g} - \left[Z + \frac{V_2^2 - V_3^2}{2g} - h_f\right]$$

Absolute pressure

Less than atmospheric pressure

Gauge pressure

$$\frac{P_2}{\rho g} = -\left[Z + \frac{V_2^2 - V_3^2}{2g} - h_f\right]$$

To avoid cavitation $V_3 < V_2$ ← To compensate pressure increase

Efficiency of the Draft tube

$$\eta_d = \frac{\text{Net gain in pressure head}}{\text{Velocity head at the enterence of the draft tube}}$$

$$\eta_d = \frac{\frac{V_2^2 - V_3^2}{2g} - h_f}{\frac{V_2^2}{2g}}$$

Angle of convergence ---- 3^0 *to* 5^0

PART –VI

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 the symbol N,.

The specific speed is used in comparing the different types of turbines as every type of turbine has **different specific speed**.

In **M.K.S. units**, unit power is taken as **one horse power** and **unit head** as **one meter**.

But **in S.I. units**, unit power is taken as **one kilowatt** and **unit head** as **one meter.**

$$\eta_0 = \text{Overall Efficiency} = \frac{\text{Shaft Power}}{\text{Runner Power}}$$

$$= \frac{\textbf{Powert Developed}}{\frac{\rho \times g \times Q \times H}{1000}} = \frac{P}{\frac{\rho \times g \times Q \times H}{1000}}$$

H = Head under which the turbine is working

Q = Discharge through turbine

P =Power developed or Shaft power

Power developed or shaft power (p) $= \eta_0 \times \frac{\rho \times g \times Q \times H}{1000}$

$$\mathbf{p} = \eta_0 \times \frac{\rho \times g \times Q \times H}{1000}$$

$$P \propto Q \times H$$

The absolute velocity and tangential velocity and Head on the turbine are related as

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

So $U \propto \sqrt{H}$

But tangential velocity is given as

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

$$U \propto DN$$

$\sqrt{H} \propto DN$ or $D \propto \frac{\sqrt{H}}{N}$

D = Diameter of the actual turbine

N = Speed of the actual turbine

U = Tangential velocity of the turbine

N_s = Specific speed of the turbine

V = Absolute velocity of water

The discharge through turbine is given by

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

$$\text{Area} \propto B \times D \qquad \text{Velocity} \propto \sqrt{H}$$

B =Width

$$\propto D^2$$

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

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

From this →

$$Q \propto \left[\frac{\sqrt{H}}{N}\right]^2 \times \sqrt{H}$$

$$\propto \frac{H}{N^2} \times \sqrt{H}$$

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

$P \propto Q \times H$

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

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

$$P = K\frac{H^{\frac{5}{2}}}{N^2}$$

Where **k** is proportionality constant

If p =1, H =1, the speed N= specific speed N_S ,Substituting these values in the above equation we get

$$P = K\frac{H^{\frac{5}{2}}}{{N_S}^2}$$

$$1 = K\frac{1^{\frac{5}{2}}}{{N_s}^2} \quad \textbf{or} \quad K = {N_s}^2$$

$$P = {N_s}^2\frac{H^{\frac{5}{2}}}{N^2}$$

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

Significance of specific speed:

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

S. No	Specific speed		Types of turbine
	(M.K.S)	(S.I)	
1.	10 to 35	8.5 to 30	Pelton wheel with single jet
2.	35 to 60	30 to 51	Pelton wheel with two or more jets
3.	60 to 300	51 to 225	Francis turbine
4.	300 to 1000	255 to 860	Kaplan & Propeller turbine

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Unit Quantity:

Unit Quantity defines when turbine operated under unit head

This parameter will help us to find out speed (N)

Discharge (Q), Power (P) for the turbine same turbine at the different, different head conditions

Unit Speed: (N_U)

$U \alpha D.N$ D can be taken as a constant

$N \alpha \sqrt{H}$

$$\frac{N}{\sqrt{H}} = K = \text{constant}$$

Definition – H= 1 m; N = N_U

$$\frac{N_U}{\sqrt{1}} = k \;\; ; K = N_U$$

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

Unit Discharge (Q_U):

$$Q_U \; \alpha \; D^2 \sqrt{H}$$

$$Q \; \alpha \; \sqrt{H}$$

$$\frac{Q}{\sqrt{H}} = k = \text{constant}$$

Definition H = 1 meter

$$Q = Q_U$$

$$\boldsymbol{\frac{Q_1}{\sqrt{H}_1} = Q_U = \frac{Q_2}{\sqrt{H}_2}}$$

Unit power: (P_U)

P_U α Q.H

P_U α $\sqrt{H}$ .H

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

Definition H = 1 meter ,P =P_U

$$\boxed{\frac{P_1}{H_1^{3/2}} = P_U = \frac{P_2}{H_2^{3/2}}}$$

Model Prototype

Head Co efficient

U α D.N α $\sqrt{H}$

$\sqrt{H}$ α D.N

H α D^2N^2

$$\left(\frac{H}{D^2N^2}\right)_{Model} = Constant = \left(\frac{\mathrm{H}}{D^2N^2}\right)_{Prototype}$$

Discharge co-officiant:

$$\mathbf{Q}\ \boldsymbol{\alpha}\ \boldsymbol{D^2}\sqrt{\boldsymbol{H}}$$

$$\mathrm{Q}\ \alpha\ D^2 . D . N$$

$$\mathrm{Q}\ \alpha\ D^3\mathrm{N}$$

$$\left(\frac{\mathrm{Q}}{D^3\mathrm{N}}\right)\text{Model} = \text{Constant} = \left(\frac{\mathrm{Q}}{D^3\mathrm{N}}\right)\ \text{Prototype}$$

Power Co officiant:

P α Q.H

P α D^3N.D^2N^2

P α D^5N^3

$[\frac{P}{D^5N^3}]$model = constant = $[\frac{P}{D^5N^3}]$ prototype

Specific speed:

$$\frac{N\sqrt{P}}{H^{5/4}} prototype = constant = \frac{N\sqrt{P}}{H^{5/4}} model$$

Characteristics curves of Hydraulic turbines

Characteristic curves of a hydraulic turbine are the curves, with the help of which the exact behavior 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 a turbine are :

1. Speed (N)
2. Power (P)
3. Head (H)
4. Discharge (Q)
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 the other four 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.

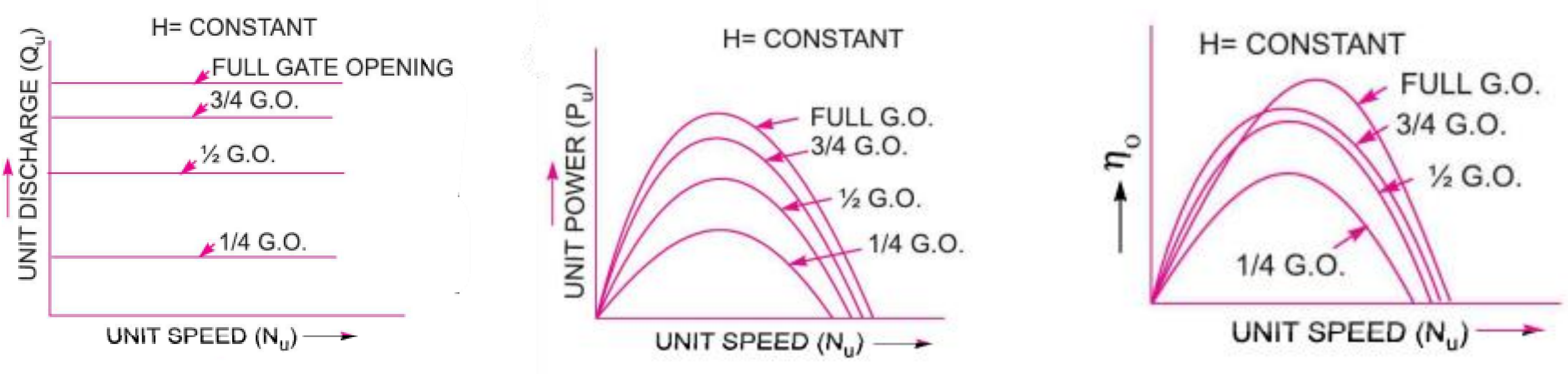
1. Main Characteristic Curves or Constant Head Curves.

2. Operating Characteristic Curves or Constant Speed Curves.

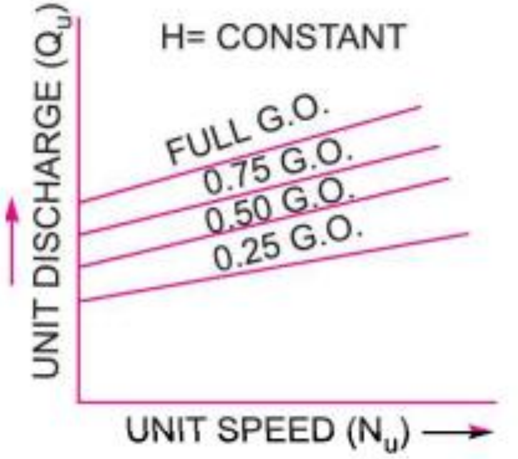
3. Muschel Curves or Constant Efficiency Curves.

1. Main Characteristic Curves or Constant Head Curves.

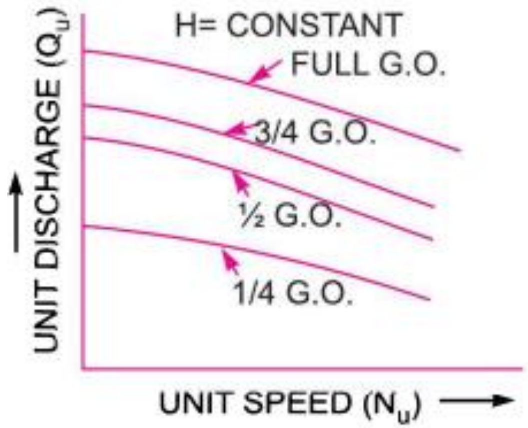
- Main characteristic curves are obtained by maintaining a constant head and a constant gate opening (G.O.) on the turbine.
- The speed of the turbine is varied by changing load on the turbine.
- For each value of the speed, the corresponding values of the power (P) and discharge (Q) are obtained. Then the overall efficiency (η_0) for each value of the speed is calculated.
- From these readings the values of unit speed (N), unit power (P) and unit discharge (Q) are determined.



Main Characteristic curves for a Pelton wheel

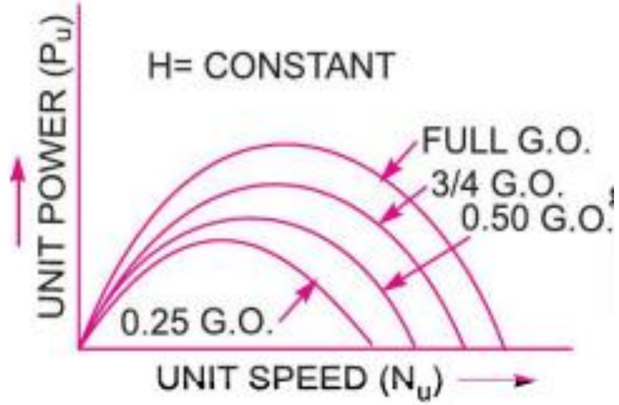


(a) FOR KAPLAN TURBINE

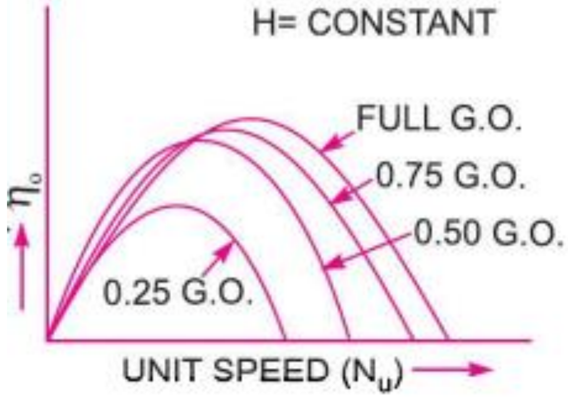


(b) FOR FRANCIS TURBINE

(a) FOR KAPLAN TURBINE



(b) FOR FRANCIS TURBINE



Operating Characteristic Curves or Constant Speed Curves.

Operating characteristic curves are plotted when the speed on the turbine is constant.

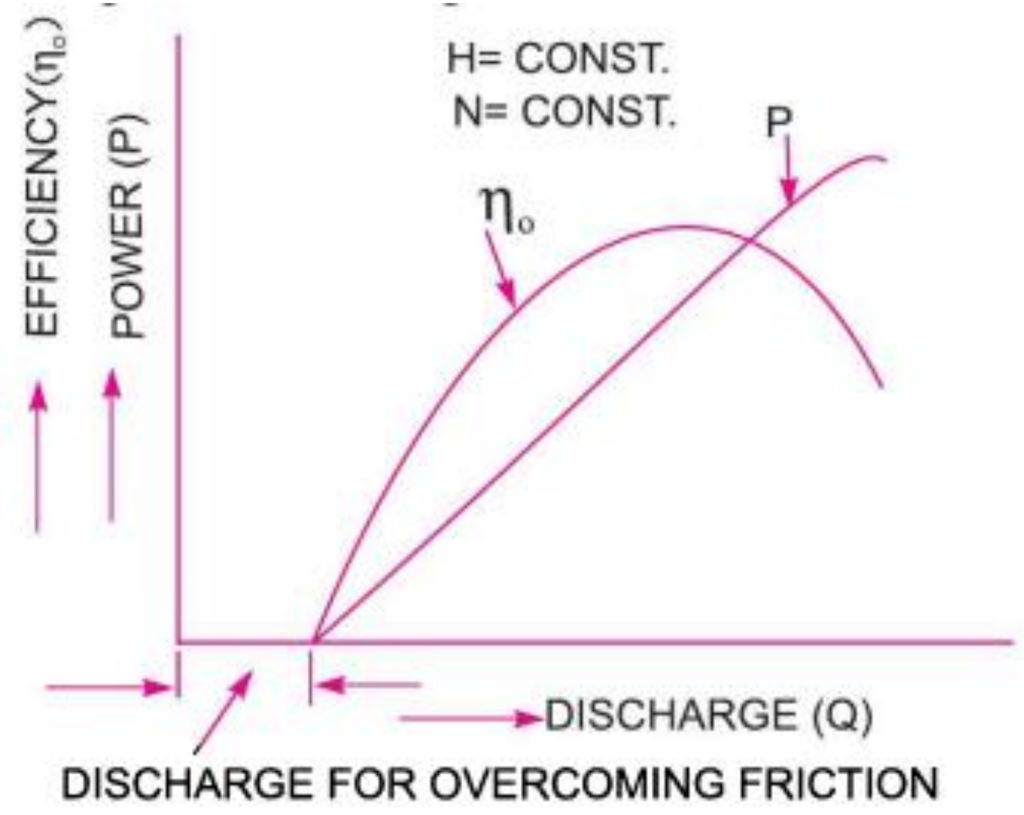
In case of turbines, the head s generally constant.

There are three independent parameters namely N, H and Q.

For operating characteristics N and H are constant and hence the variation of power and efficiency with respect to discharge Q are plotted.

The **power curve** for turbines shall not pass through the origin because certain amount of discharge is needed to produce power to overcome initial friction.

Hence the power and efficiency curves will be slightly away from the origin on the x-axis, as to overcome initial friction certain amount of discharge will be required. Figure shows the variation of power and efficiency with respect to discharge.



Operating characteristic curves.

Constant Efficiency Curves or Muschel Curves or Iso-Efficiency Curves.

- These curves are obtained from the **speed vs. efficiency** and **speed vs. discharge** curves for different gate openings.
- For a given efficiency from the N_u **vs.** η_0**,** curves, there are two speeds.
- From the N_u **vs. Qu** curves, corresponding to two values of speeds there are two values of discharge.
- Hence for a given efficiency there are two values of discharge for a particular gate opening. This means for a given efficiency there are two values of speeds and two values of the discharge for a given gate opening.

Constant Efficiency Curves or Muschel Curves or Iso-Efficiency Curves.

If the efficiency is maximum there is only one value. These **two values of speed** and **two values of discharge** corresponding to a particular gate opening are plotted as shown in Fig.

- The procedure is repeated for different gate openings and the curves Q vs. N are plotted. The points having the same efficiencies are joined. The curves having same efficiency are called **iso- efficiency curves**. These curves are helpful for determining the zone of constant efficiency and for predicating the performance of the turbine at various efficiencies.

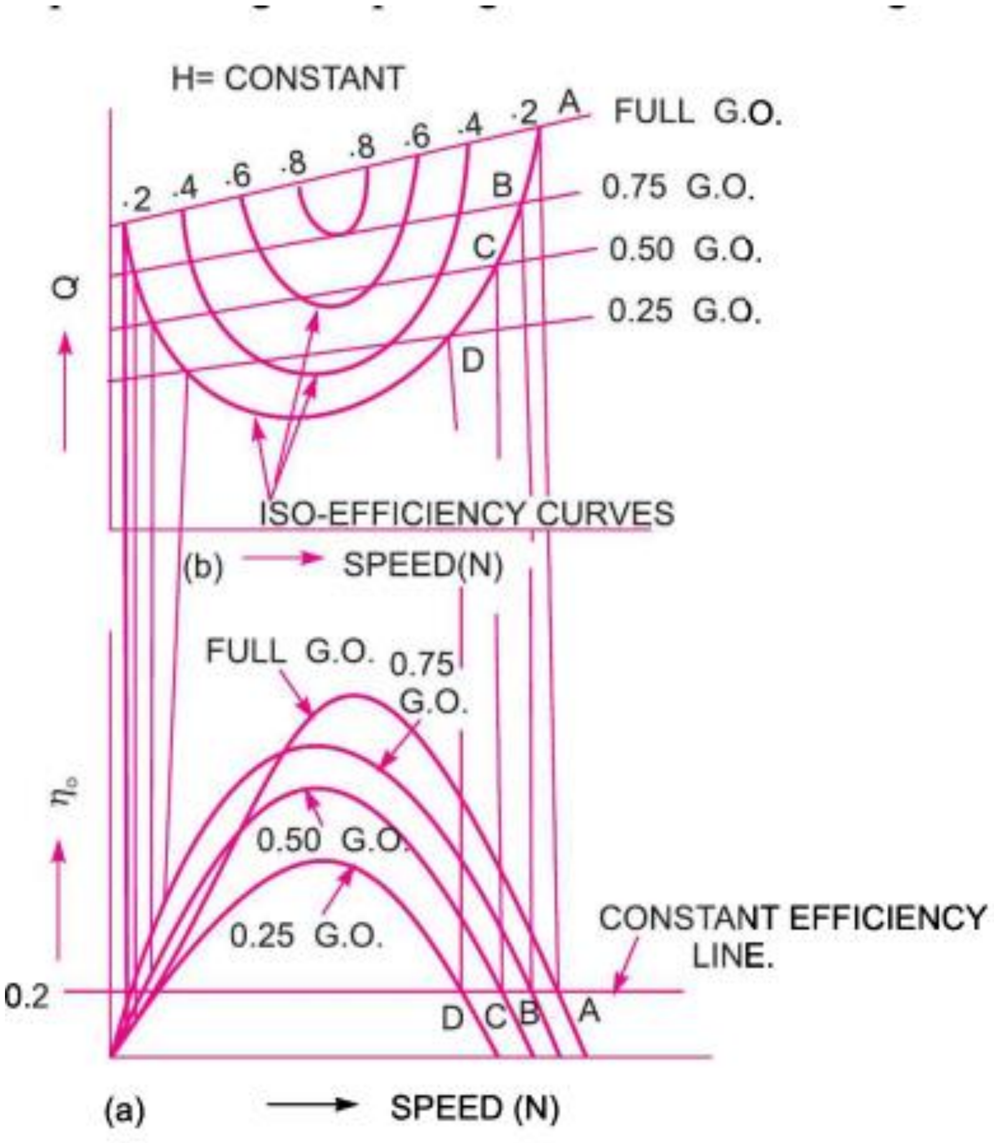


Fig. 18.38 *Constant efficiency curve.*

For plotting the iso-efficiency curves, horizontal lines representing the same efficiency are drawn on the

η_0 - **speed curves.**

The points at which these lines cut the efficiency curves at various gate 0.2 openings are transferred to the corresponding **Q~ speed curves.**

The points having the same efficiency are then joined by a smooth curves. These smooth curves represents the **Iso-efficiency curve.**

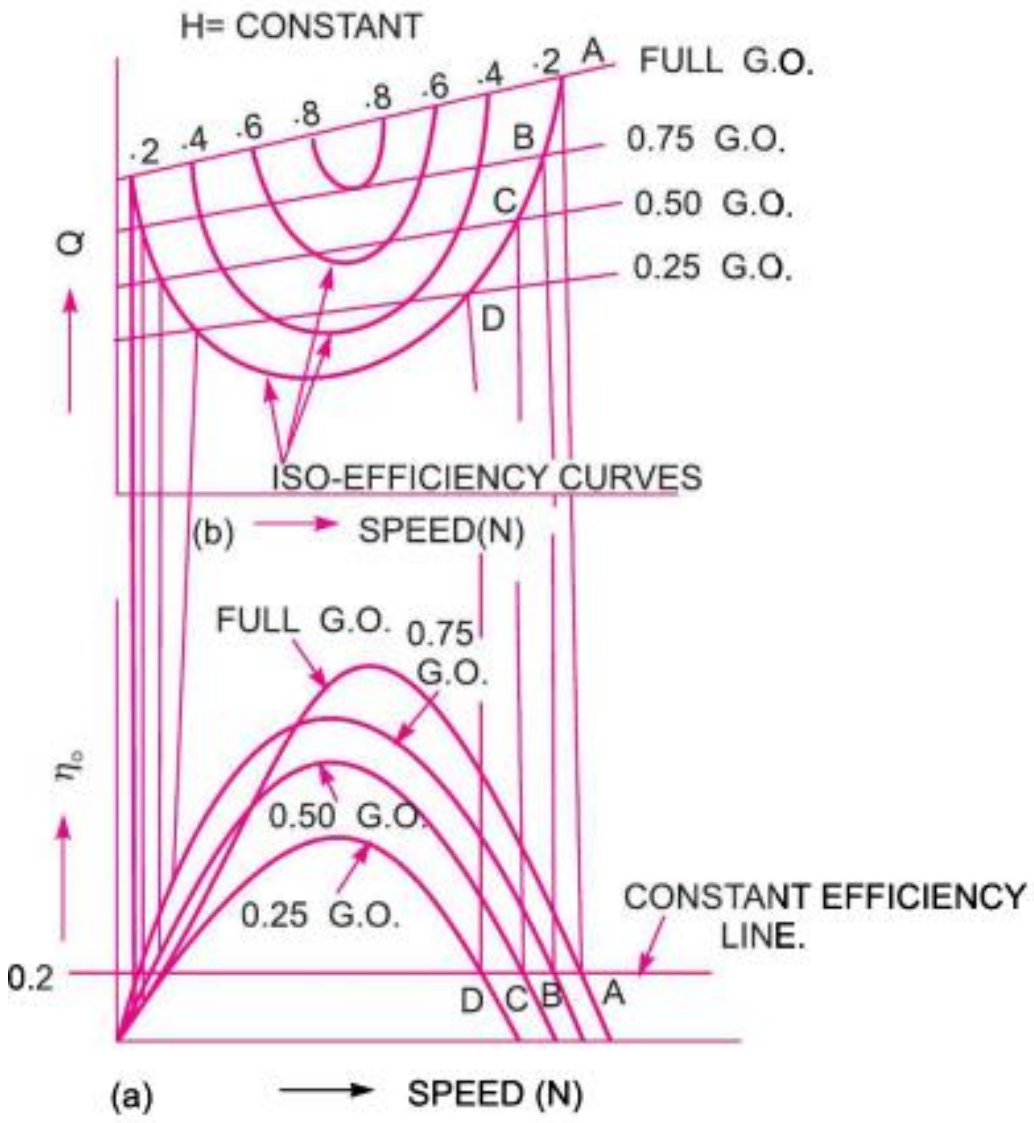


Fig. 18.38 *Constant efficiency curve.*