Fluid machinery

Hydraulic machines(General term for all devices that handle fluids)

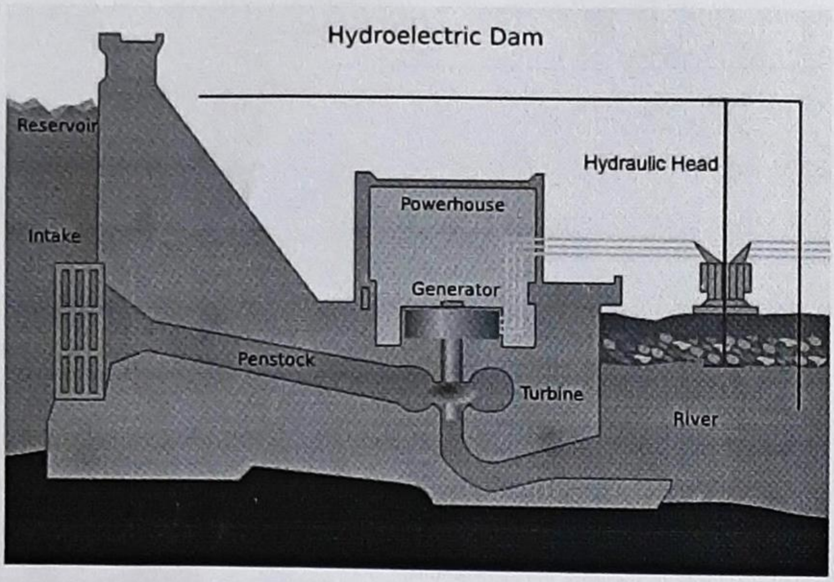
Classifications

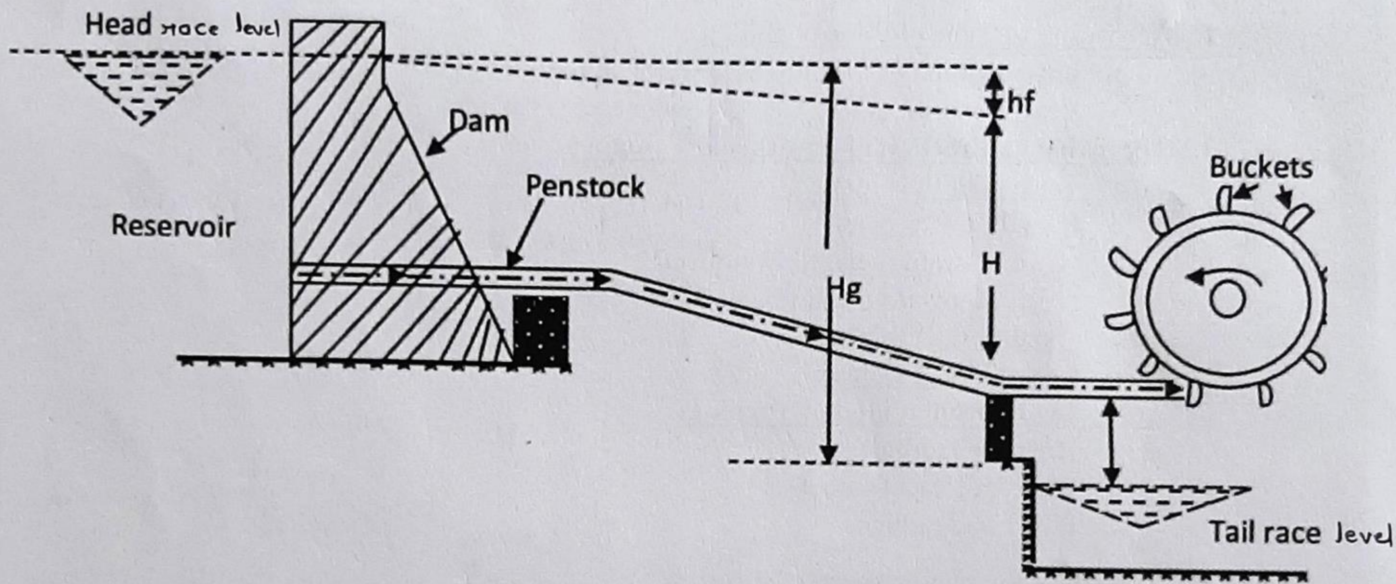
1. Turbomachines.
   Eg, pumps, hydraulic turbines. (also called rotodynamic machines
2. Reciprocating machines
   Eg, Reciprocating machines. (also called positive displacement pumps
3. Water lifting devices
   Eg, jet pump, hydraulic ram, airlift pump
4. Pumps transmitting oils under pressure to operate hydraulic control sys
   Eg, gear pumps

Hydraulic Turbines, Classifications

1. **According to Type of Energy at inlet**
   a. Impulse turbines : If only KE present at inlet
   b. Reaction turbines : If (KE + Pressure energy) at inlet
2. **According to direction of flow through runner**
   a. Tangential flow turbine.
   b. Radial flow turbine.
      i. Inward radial flow turbine.
      ii. Outward radial flow turbine.
   c. Axial flow Turbines.
   d. Mixed flow Turbines.
3. **According to head at inlet of Turbines**
   a. High head turbine.
   b. Medium Head Turbine
   c. Low Head turbine
4. **According to Specific speed of turbine**
   a. High specific speed turbines
   b. Medium Specific speed turbines
   c. low specific speed turbines

Hydropower plant





A hydropower plant with impulse turbine.

Important points for PELTON TURBINES →

1. $\boxed{WP = \dot{m} g H}$

   if Nozzle = 100% efficient

   $WP = \frac{1}{2} \dot{m} V_1^2$

2. $\boxed{RP = \dot{m} \left[V_{w_1} + V_{w_2} \right] U}$ watt.

   $[\because U_1 = U_2 = U]$

3. Mass flow rate

   $\boxed{\dot{m} = \rho a V_1}$

   [V_1 → and Not V_{r_1}; because a series of vanes are there]

4. Jet velocity.

   $\boxed{V_1 = C_v \sqrt{2 g H}}$

   C_v → Coeff. of Velocity.

5. Speed Ratio: Speed ratio is always defined at inlet.

   $\boxed{\text{Speed ratio} = \frac{U_1}{\sqrt{2gH}} = \frac{U_1}{V_1}}$

6. $U_1 = U_2 = U$

   (A) $\boxed{U = \frac{\pi D N}{60}}$. [D → mean dia of runner]

7. No. of Buckets. (Z), Taygun relation.

   $\boxed{Z = 15 + 0.5 m}$. [m → Jet ratio]

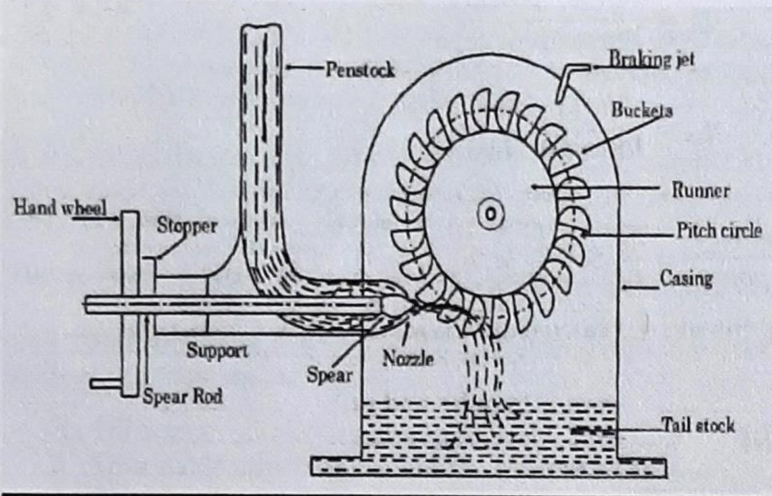
8. Jet ratio: $\boxed{m = \frac{D}{d}}$ [d → dia. of Jet]

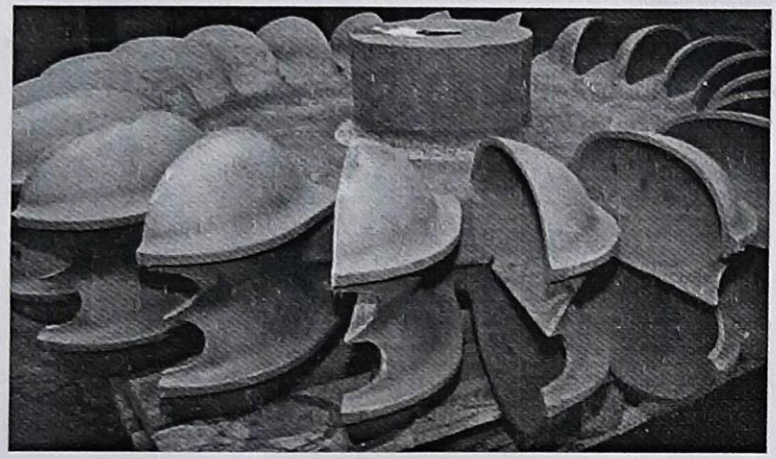
9. depth of Bucket = 1.2d.

10. width of bucket = 5d.

11. Angle of deflection (ϕ) → 160° ~ 170°.

Impulse turbines construction details (Eg. Pelton turbine/pelton wheel)





Main Components

1. **Nozzle & flow regulating arrangement.** → Nozzle is fitted with spear to control quantity of water flowing.
2. **Runer with Buckets.:** Circular disc which has a number of buckets attached on its periphery. Each bucket is divided into two symmetrical parts.
3. **Casing**: Provided to prevent splashing of water, and has no hydraulic funciton.
4. **Braking jet: Due to inertia** Runner keeps on rotating even after nozzle is closed. Braking jet is used to stop the moving runner . it is achieved by using a small nozzle on the back of vanes to stop the runner.

Working:- Water comes through penstock from storage reservoir ; at the inlet of Nozzle: The energy of coming water is converted into kinetic energy as it passed through nozzle. As water leaves Nozzle ; it comes out in form of a Jet; This Jet of water strikes on vanes mounted on the runner and then leaves runner. A very high force is exerted by water on the vanes ; thus it produces Impulse on vanes. [also reason why these turbines are called Impulse turbines]

Definition of Heads of Turbines

1. **Gross Head (H_G):** The Difference between the head race level and tail race level when no water is running is called Gross head.(It is the head under which hydroelectric powerplant is working)

$$H_G = Head\ race\ level - Tail\ race\ level$$

Gross head is not used to calculate the efficiency of the turbine.

2. **Net head (H) :** It is defined as the head available at the inlet of the turbine.

$$H = H_G - h_f$$

$$h_f = \frac{flv^2}{2gd}$$

Gross head is not used to calculate the efficiency of the turbine.

Different types of efficiency of turbines

1. **Volumetic efficiency (η_v):**

$$\eta_v = \frac{Volume\ per\ second\ striking\ runner}{Volume\ per\ second\ coming\ from\ the\ penstock}$$

2. **Hydraulic efficiency** (η_h):

$$\eta_h = \frac{Runner\ power}{Water\ power}$$

3. **Mechanical Efficiency** (η_m):

$$\eta_m = \frac{Shaft\ power}{Runner\ power}$$

4. **Overall efficiency**(η or η_o):

$$\eta_o = \frac{Shaft\ power}{Water\ power} = \frac{SP}{RP} \times \frac{RP}{WP} = \eta_m \times \eta_h$$

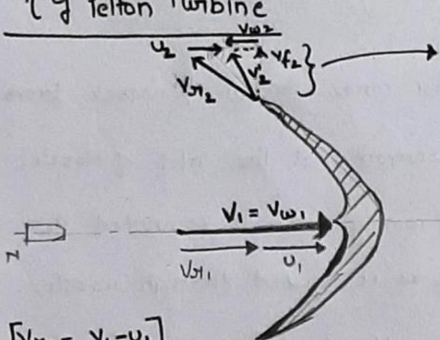
Water Power: $\boxed{WP = \dot{m}\, gH}$ → for both Impulse turbine & Reaction turbine.

For Pelton wheel $RP = \dot{m}\, [V_{w1} + V_{w2}]U$

For Reaction turbines $RP = \dot{m}\, [V_{w1}U_1 + V_{w2}\, U_2]$

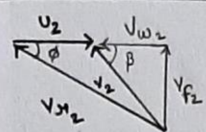
Shaft power : It is the shaft horse power or break horse power.

η of Pelton Turbine



$[V_{r1} = V_1 - U_1]$

Exit velocity Δ; for impulse turbine.



(*) Exit velocity triangles are similar on both upper & lower sides;
Because of symmetry; analysis done on one side only.

① Assume Smooth surface

$\therefore$ • $V_{r1} = V_{r2}$; & $U_1 = U_2$.

② Nozzle 100% efficient.

$\therefore \left[WP = \dot{m} gH = \frac{1}{2}\dot{m} V_1^2\right]$ —— (a)

Now; Runner power $= F_x \cdot U_1 = \dot{m}\,[V_{w1} + V_{w2}]\,U_1$.

$\left[V_{w1} = V_1 ,\ V_{w2} = V_{r2}\cos\phi - U_2 \right.$ also $V_{w2} = V_{r1}\cos\phi - U_1$

$\because V_{r1} = V_{r2}$ $\quad \because U_1 = U_2$.

also we know

(*) $V_{r1} = V_1 - U_1$ •

⇒ We get

$$RP = \dot{m}\ \left[(V_1) + [(V_1 - U_1)\cos\phi - U_1]\right] U_1$$

$$\Rightarrow \left[RP = \dot{m}\,(V_1 - U_1)\,[1 + \cos\phi]\,U_1\right] \text{—— (b)}$$

Now $\eta_h = \frac{RP}{WP} = \frac{\cancel{\dot{m}}\,[V_1 - U_1]\,[1 + \cos\phi]\,U_1}{\frac{1}{2}\cancel{\dot{m}}\,V_1^2} \Rightarrow$

$$\boxed{\eta_h = \frac{2U_1\,(V_1 - U_1)\,[1 + \cos\phi]}{V_1^2}} \text{—— (1)}$$

Note. $WP = \frac{1}{2}\dot{m}V_1^2$ iff; nozzle is 100% efficient; else take $WP = \dot{m} gH$

Differentiate 1 wrt U_1 and equate to zero.

$$\frac{d\eta}{dU_1} = 0 \Rightarrow \text{ we get } U_1 = V_1/2.$$

Put $U_1 = V_1/2$ in ①.

$$\eta = \frac{2 \times \frac{V_1}{2}\,[V_1 - V_1/2]\,[1 + \cos\phi]}{V_1^2} \Rightarrow \eta = 98.29\%$$

max efficiency of Pelton turbine.

Governing in Pelton turbine

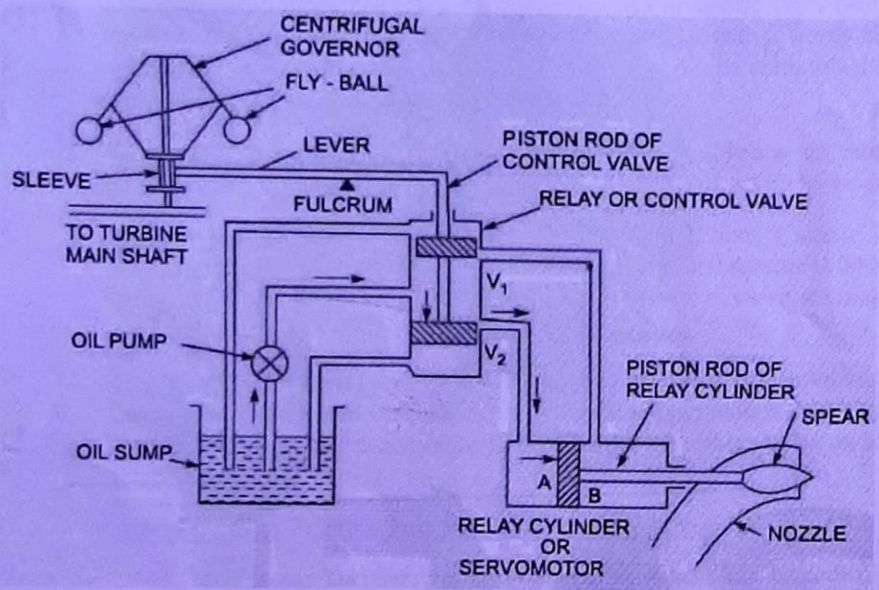
Governing of turbines is the operation to keep spped of turbines constant under all conditions. This is done automatically by the device called governor. Governor regulates the rate of flow through turbine according to the changing load conditions on the turbine.

Necessity of Governing : Since Turbine is directly coupled with a generator which must run at constant speed under all fluctuating conditions, frequency of power generation by a generator of constant number of poles under all varying condtions must be constant.

This is possible only if spped of generator under all loading conditions is same.

Governing of Pelton Wheel : In Pelton wheel governing is done by means of oil pressure governor which consists of following parts.

1. Oil Sump.
2. Gear pump also called oil pump. It is driven by power from turbine shaft.
3. The servomotor also called relay cylinder.
4. Control valve,Distribution valve, relay valve.
5. Centrifugal governor, Pendulum. It is driven by belt or gear from turbine shaft.
6. Pipes connecting oil sump with control valve and control valve servomotor.
7. Spear rod.



Reaction Turbines (working) At inlet of the turbine water has both Kinetic energy and pressure energy, This is achieved by making water coming from penstock enter inlet of a casing, this casing is full of water at all instants.

Inside the casing there is a stator which is fixed to the casing and having a series of guide vanes. The function of the guide vanes is to direct water at a particular angle to the moving vanes.

Moving vanes are mounted on the runner.

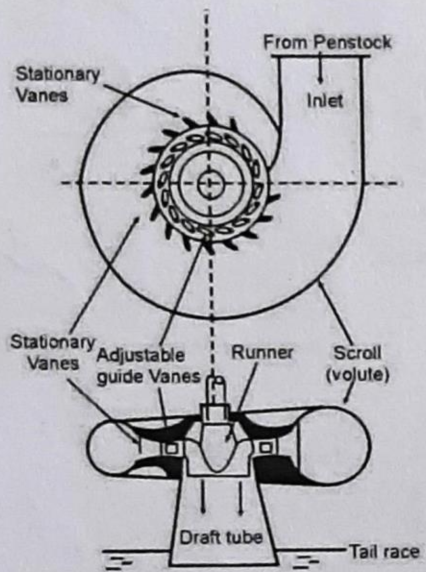
At inlet of casing water has both KE and Pressure energy, and both energies decrease along the vanes.(as this energy of water is tranffered to vanes/runner.)

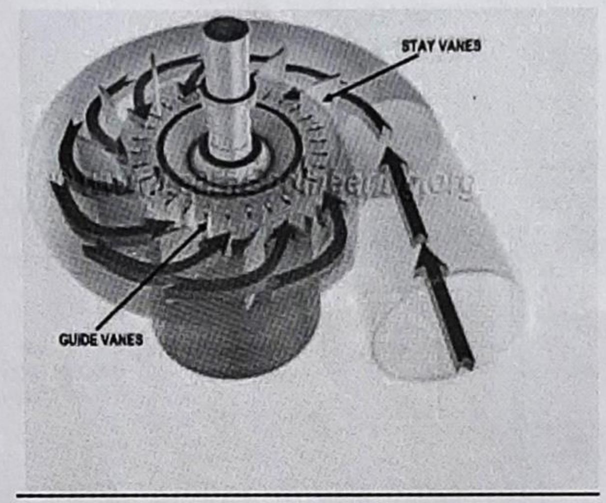
When water comes and strikes on the blades, the blades turn in the direction of striking water, a force of high magnitude is appliedby water on the vanes which produces impulse action.

Also during flow over the vane, there is pressure drop due to the shape of the vane, that means vane exerts a force on wate, as a consequence a reactive force is also applied by water on the vane (Newton's 3rd Law)

Thus the turbines are called Impulse rreaction turbines or Reaction turbines.

Francis turbine construction details.





- **Water head required 40 to 600 m.**
- **It is a Inward Radial flow reaction turbine.**
- **Guide vanes can be adjusted but Vanes attached to runner cannot be adjusted.**

Working of Francis turbine:

Casing: water from the penstock enters the scroll casing(spiral casing) which completely surrounds the runner. The purpose of the casing is to provide an even distribution of water around the circumference of the turbine runner, maintaining almost uniform velocity of water.

In order to keep the velocity of water uniform throughout its path around runner, cross-sectional area of the casing is gradually decreased(ie. Cross-sectional area of casing is max at entry and min at the tip.) .

Guide mechanism : Guide vanes or wicket gates are fixed between two rings in form of a wheel, known as guide wheel.

Guide vanes have a section known as aerofoil section, it is such that it allows water to pass over it without forming eddies & minimum frictional loss.

Each guide vane can be adjusted to a desired angle to control flow.

Reaction pressure : There is pressure difference between guide vanes and runner, which is also called reaction pressure, & is responsible for the movement of the runner. The existence of this reaction pressure is the reason Francis turbine is also called reaction turbine.

▶ Main Components

1. **Spiral casing/Scroll casing**: The spiral casing around the runner of the turbine is known as the volute casing or scroll case. The cross-sectional area of this casing decreases uniformly along the circumference to keep the fluid velocity constant in magnitude along its path towards the guide vane. This is so because the rate of flow along the fluid path in the volute decreases due to continuous entry of the fluid to the runner through the openings of the guide vanes or stay vanes.
2. **Guide and stay vanes**: The primary function of the guide and stay vanes is to convert the pressure energy of the fluid into the momentum energy. It also serves to direct the flow at design angles to the runner blades.
3. **Runner blades**: Runner blades are the heart of any turbine. These are the centers where the fluid strikes and the tangential force of the impact causes the shaft of the turbine to rotate, producing torque. Close attention in design of blade angles at inlet and outlet is necessary, as these are major parameters affecting power production
4. **Draft tube**: The draft tube is a conduit that connects the runner exit to the tail race where the water is discharged from the turbine. Its primary function is to reduce the velocity of discharged water to minimize the loss of kinetic energy at the outlet. This permits the turbine to be set above the tail water without appreciable drop of available head.

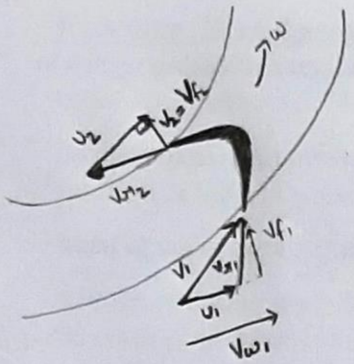
Advantages of Francis Tubines over Pelton Wheel.

1. In Francis Turbines variation in operation head can be controlled more easily.
2. Operating head can be Utilized even when variation in tail water level is relatively large.
3. Mechanical efficiency of Pelton wheel decreases faster with wear as compared to francis turbines.
4. Size of runner, generator, powerhouse is relatively small & economical.

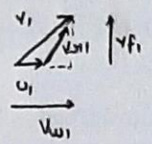
Disadvantages of Francis turbines over pelton wheel

1. Water which is not very clean can cause very rapid wear in high head francis turbine.
2. Overhaul and inspection is much more difficult.
3. Cavitation is an ever present danger.
4. Water hammer effect is more troublesome in francis turbine.
5. If Francis turbine run below 50% head for long time, it will loose efficiency and cavitation danger will become more serious.

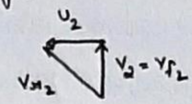
Francis Turbine → Inward Radial flow reaction turbine .



Inlet velocity triangle →



outlet velocity triangle →



} ∵ Inward radial flow reaction turbines have radial discharge at exit .

∴ $\beta = 90^\circ$

$V_{w_2} = 0$.

Work done and efficiency of Francis Turbines -

① $[H = H_G - h_f]$, ② $\left[H = \begin{Bmatrix}\text{Total energy available}\\ \text{at exit from penstock}\end{Bmatrix} - \begin{Bmatrix}\text{Total energy at exit}\\ \text{from draft tube}\end{Bmatrix}\right] = \left[\frac{p}{\rho g} + \frac{v^2}{2g} + z\right]_{penstock} - \left[\frac{p}{\rho g} + \frac{v^2}{2g} + z\right]_{draft\ tube}$

③ If draft tube exit is at [redacted] Tail race level.

$$H = \left[\frac{p}{\rho g} + \frac{v^2}{2g} + z\right]_{Penstock} - \left[\frac{V_d^2}{2g}\right]$$ [Here; V_d = velocity at exit of draft tube]

(4) If V_d is too small and can be Neglected .

$$H = \left[\frac{p}{\rho g} + \frac{v^2}{2g} + z\right]_{penstock} .$$

★ work done at Runner / Runner power ; $RP = \dot{m}\,[V_{w_1}U_1 \pm V_{w_2}U_2]$

but for radial flow reaction turbines; with Inward flow $V_{w_2} = 0$.

$$\boxed{\therefore\ [RP]_{francis} = \dot{m}\,V_{w_1}U_1 = \rho Q\,V_{w_1}U_1}$$

[Hydraulic efficiency η_h] $\boxed{\eta_h = \frac{RP}{WP} = \frac{\dot{m}\,V_{w_1}U_1}{\dot{m}\,g\,H} = \frac{V_{w_1}U_1}{gH}}$

★ But if velocity of whirl at exit is not zero ; [ie if $V_{w_2} \neq 0$]

$$\boxed{\eta_h = \frac{V_{w_1}U_1 \pm V_{w_2}U_2}{gH}}$$ ★ only if $V_{w_2} \neq 0$; given.

Imp points wrt Francis Turbines.

1. ratio of width to dia = $\frac{B_1}{D_1}$

2. Flow ratio; $k_f = \frac{V_{f_1}}{\sqrt{2gH}}$ $\left[\frac{\text{velocity of flow at inlet}}{\text{theoretical Jet velocity}}\right]$

3. Speed ratio; $k_s = \frac{U_1}{\sqrt{2gH}}$ $\left[\frac{\text{Peripheral speed at inlet}}{\text{Theoretical Jet velocity}}\right]$

4. Mass flow rate.

$(\dot{m})_{ideal} = \rho(\pi D_1)B_1V_{f_1} = \rho(\pi D_1)B_1V_{f_2}$.

$(\dot{m})_{actual} = \rho(\pi D_1 - nt)B_1V_{f_1}$

5. $RP = \dot{m}\,[V_{w_1}U_1 + V_{w_2}U_2]$ [if $V_{w_2} \neq 0$]

for inward radial flow with radial discharge.

$\boxed{RP = \dot{m}\,V_{w_1}U_1}$

6. $\boxed{U_1 = \frac{\pi D_1 N}{60}}$, $\boxed{U_2 = \frac{\pi D_2 N}{60}}$. ★ $\boxed{U_1 \neq U_2}$

7. Degree of Reaction.

$$\boxed{R = 1 - \frac{V_1^2 - V_2^2}{2g\left(\frac{RP}{\dot{m}g}\right)}}$$

8. Francis Turbine : Inward radial flow reaction turbine with radial discharge.

$\boxed{\beta = 90^\circ}$ $\boxed{V_{w_2} = 0}$

Degree of Reaction (R) :→ It is defined as ratio of Pressure energy change inside a runner to the total energy change inside the runner.

$$\boxed{R = \frac{\text{change of Pressure energy inside the runner}}{\text{change of Total energy inside the runner}}}$$

$$\frac{RP}{\dot{m}g} = \frac{V_{w_1}U_1 + V_{w_2}U_2}{g} \text{ meter.} \quad \text{——— (1)}$$

At inlet -

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

$$\Rightarrow V_{w_1}^2 + U_1^2 - 2V_{w_1}U_1 = V_{r_1}^2 - [V_1^2 - V_{w_1}^2] \Rightarrow \underline{V_{w_1}U_1} = \frac{V_1^2 + U_1^2 - V_{r_1}^2}{2} \quad \text{——— (2)}$$

At outlet -

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

$$(V_{w_2} + U_2)^2 = (V_{r_2}^2 - V_{f_2}^2)$$

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

$$\rightarrow \underline{V_{w_2}U_2} = \frac{V_{r_2}^2 - U_2^2 - V_2^2}{2} \quad \text{——— (3)}$$

Put values from (2) & (3) in (1).

$$\frac{RP}{\dot{m}g} = \underbrace{\frac{V_1^2 - V_2^2}{2g}}_{\text{contribution of KE}} + \underbrace{\frac{U_1^2 - U_2^2}{2g} + \frac{V_{r_2}^2 - V_{r_1}^2}{2g}}_{\text{contribution of Pressure energy.}}$$

Degree of Reaction,

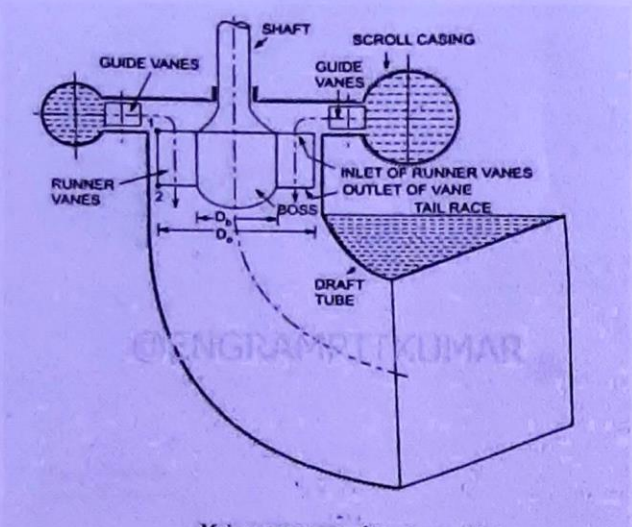
$$R = \frac{\frac{U_1^2 - U_2^2}{2g} + \frac{V_{r_2}^2 - V_{r_1}^2}{2g}}{\frac{RP}{\dot{m}g}} = \frac{\frac{RP}{\dot{m}g} - \frac{V_1^2 - V_2^2}{2g}}{\frac{RP}{\dot{m}g}}$$

from

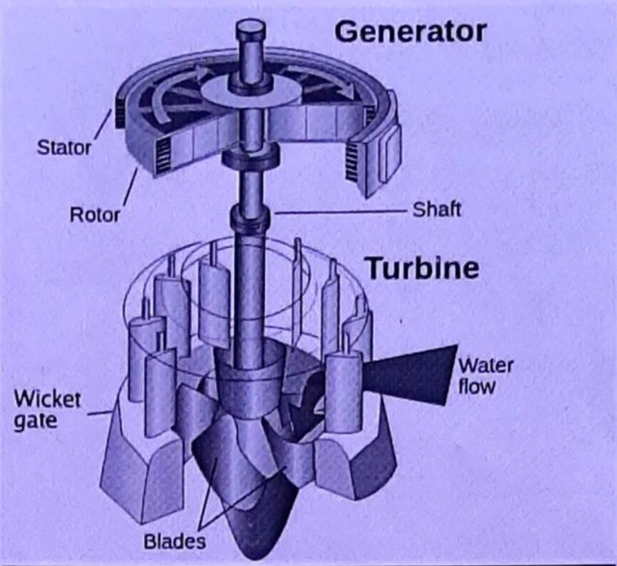
$$\rightarrow \boxed{R = 1 - \frac{V_1^2 - V_2^2}{2g\left[\frac{RP}{\dot{m}g}\right]}}$$

Kaplan Turbines: Are Axial flow reaction turbines, ie. Water flows axially. Or water flows parallel to the axis of rotation of the Shaft.

Kaplan turbine construction details

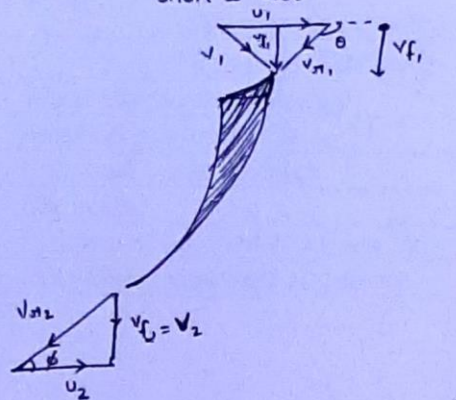


Main components of Kaplan turbine.

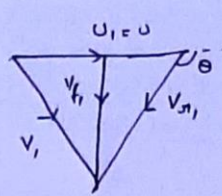


- Water head required 10–70 metres.
- It is an Inward Radial flow reaction turbine.
- Kaplan turbine is a propeller-type Water turbine and has **adjustable blades**.
- Shaft of an axial flow reaction turbines is vertical, lower end of the shaft is made larger - & is known as "Hub" or "Boss", Vanes are fixed on the hub and it acts as runner for axial flow reaction turbines.
- Various parts like Spiral casing, Stay vanes, guide vanes, Draft tube etc are same as for mixed flow/Radial flow turbines. **BUT** for Axial turbines water enters the runner in axial direction and leaves axially.
  - ▶ Pressure at the inlet of blade is greater than Pressure at the exit of the blade.
  - ▶ Energy transfer is due to reaction effect.
  - ▶ In axial flow reaction turbines number of blades is fewer and loading per blade is larger. ∴ smaller contact area causes lower frictional loss compared to mixed flow turbines.

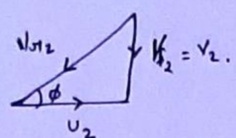
Kaplan turbine - Kaplan turbine runner blade is twisted with blade angle being greater at outer tip than at hub.



Inlet velocity triangle -



outlet velocity triangle :—



Imp points -

(1) $n = \dfrac{D_b}{D_o}$

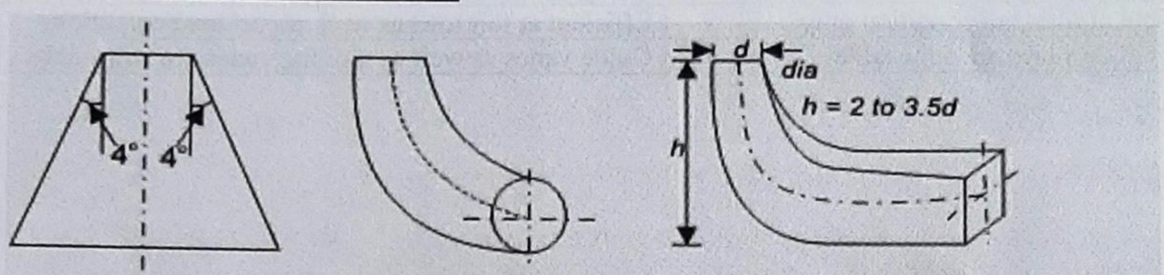
(2) $Q = \dfrac{\pi}{4} (D_o^2 - D_b^2) V_f = \dfrac{\pi}{4} (D_o^2 - D_b^2) C_f \sqrt{2gH}$ $[C_f \approx 0.70]$

(3) Expression for work done & η of Kaplan turbines is similar to Francis turbine

Differences Between Francis and Kaplan turbines		
	Francis Turbine	**Kaplan Turbine**
1	Water enters runner Radially	Water enters runner axially
2	Numbers is blades is 16 to 24	Numbers of blades is 3 to 8
3	Frictional losses are high	Frictional loss is low
4	Big in size	Compact in Size
5	Efficient at full load condition only	Efficient at full load as well as part load conditions
6	Only Guide vanes are adjustable	Guide vanes as well as moving vanes are adjustable

Draft Tube.

Different types of draft tubes



(a) Straight type (b) Simple elbow type (c) Elbow type with varying cross-section

1. **Straight type**. It is usually employed for low specific speed, vertical shaft Francis turbine. The cone angle is restricted to 8^0 to avoid the losses due to separation. The tube must discharge sufficiently low under tail water level. The maximum efficiency of this type of draft tube is 90%. This type of draft tube improves speed regulation of falling load.
2. **Simple Elbow**. The vertical length of the draft tube should be made small in order to keep down the cost of excavation, particularly in rock. The exit diameter of draft tube should be as large as possible to recover kinetic energy at runner's outlet. The cone angle of the tube is again fixed from the consideration of losses due to flow separation. Therefore, the draft tube must be bent to keep its definite length
3. **Elbow type with varying cross section**. . Sometimes, the transition from a circular section in the vertical portion to a rectangular section in the horizontal part is incorporated in the design to have a higher efficiency of the draft tube. The horizontal portion of the draft tube is generally inclined upwards to lead the water gradually to the level of the tail race and to prevent entry of air from the exit end

Benefits of Draft Tube.

1. Easy maintenance of turbine is possible.
2. Efficiency (η) of turbines is increased by utilizing kinetic head at the exit of Runner.
3. Permits negative suction head to be established at the runner exit.
4. Converts large portion of the velocity energy rejected at the runner into useful pressure energy.

- Draft tube must always run airtight
- Its lower end must always be submerged below level of water at tail race.

Imp.

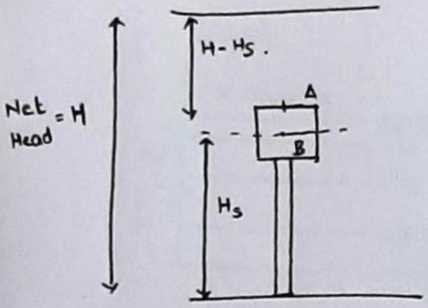
1. $$\frac{P_2}{\rho g} = 10.3 - \left[\frac{V_2^2 - V_3^2}{2g} + H_s - h_f \right].$$

2. $$\frac{P_2}{\rho g} < \frac{P_{atm}}{\rho g}.$$

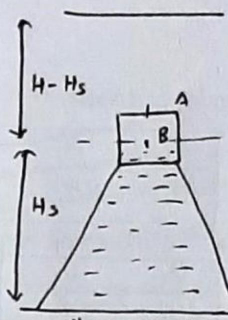
3. efficiency of draft tube; $$\eta_{draft\ tube} = \frac{\text{Contribution of kinetic energy into Pressure head}}{\text{kinetic head at inlet}} = \frac{\frac{V_2^2 - V_3^2}{2g} - h_f}{\frac{V_2^2}{2g}}.$$

4. To avoid Cavitation, $$\frac{P_2}{\rho g} > \frac{P_{vapour}}{\rho g}.$$

Draft Tube Analysis.



without draft tube



with Draft tube

[Recovery of Head at Exit; because of used of Draft tube.]

Inlet Head = $H - H_s$

outlet Head = 0.

$\therefore$ working Head = $(H - H_s) - 0$

$= H - H_s$.

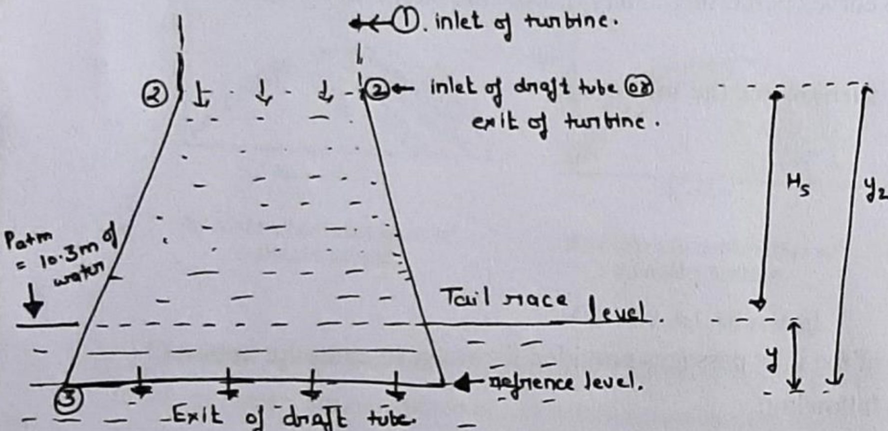
Head at inlet of turbine = $H - H_s$.

Head at outlet of turbine = $-H_s$.

$\therefore$ working Head = $(H - H_s) - (-H_s)$

working Head $= \underline{\underline{H}}$.

Analysis.



(a) $h_f \rightarrow$ loss of energy in draft tube.

(b) y = distance of bottom of draft tube from tail race level.

(c) $P_{atm} \rightarrow$ atmospheric pressure at surface of tail race

(d) $y_2 - y = H_s \rightarrow$ distance btw runner exit and tail race water level.

H_s is called $\boxed{\text{Static Suction Head}}$ of the draft tube.

(e) $\frac{V_2^2 - V_3^2}{2g} \rightarrow$ dynamic head; $\boxed{\text{dynamic suction head}}$ of draft tube.

(f) $\frac{P_3}{\rho g} = \frac{P_{atm}}{\rho g} + y$.

applying bernoulli's eqn btw point (2) & (3)

$$\frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 = \frac{P_3}{\rho g} + \frac{V_3^2}{2g} + z_3 + h_f.$$

$$\frac{P_2}{\rho g} + \frac{V_2^2}{2g} + (H_s + \cancel{y}) = [10.3 + \cancel{y}] + \frac{V_3^2}{2g} + 0 + h_f.$$

$$\Rightarrow \frac{P_2}{\rho g} = 10.3 + \left[\frac{V_3^2 - V_2^2}{2g}\right] + h_f - H_s$$

$$\Rightarrow \boxed{\frac{P_2}{\rho g} = 10.3 - \left[\frac{V_2^2 - V_3^2}{2g} + H_s - h_f\right]}$$

→ ① $\left[10.3 = \frac{P_{atm}}{\rho g}\right]$

→ ② $\frac{P_2}{\rho g}$ is lower than $\frac{P_{atm}}{\rho g}$; i.e it is lower than atmospheric pressure

also to avoid vapourization. $\boxed{\frac{P_2}{\rho g} > \frac{P_v}{\rho g}}$

where; $P_v \rightarrow$ vapour pressure. ① $\frac{P_v}{\rho g} = 2.4$ m of water.

Unit Quantities

1. **Unit Speed. (Nu)** : It is the speed of turbine under unit head.

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

2. **Unit discharge (Qu) :** It is the discharge to turbine under unit head

$$\boxed{\frac{Q_1}{\sqrt{H_1}} = \frac{Q_2}{\sqrt{H_2}}}$$

3. **Unit Power (Pu) :** It is the power developed by the turbine under unit head.

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

4. **Specific Speed:** It is speed of geometrically similar turbine developing unit shaft power under unit head.

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

Characteristic curves

Characteristic Curves of a Turbine:

These are curves which are characteristic of a particular turbine which help us in studying the performance of the turbine under various conditions. These curves pertaining to any turbine are supplied by its manufacturers, based on actual tests.

The data that must be obtained in testing a turbine are the following:

1. The speed of the turbine N
2. The discharge Q
3. The net head H
4. The power developed P
5. The overall efficiency η_0
6. Gate opening (this refers to the percentage of the inlet passages provided for water to enter the turbine).

The characteristic curves obtained are the following:

(i) Constant head curves or main characteristic curves

(ii) Constant speed curves or operating characteristic curves

(iii) Constant efficiency curves, or Muschel curves.

(i) Constant Head Curves or Main Characteristic Curves:

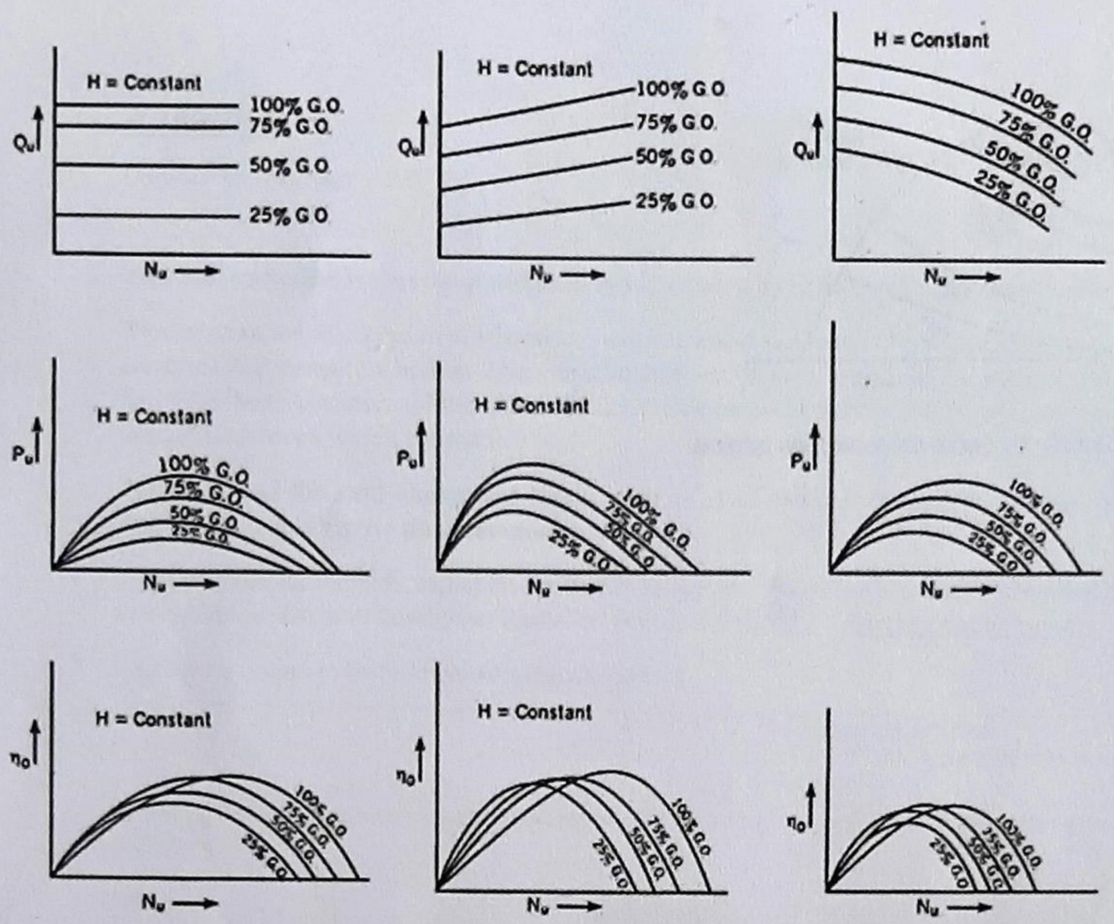
Maintaining a constant head, the speed of the turbine is varied by admitting different rates of flow by adjusting the percentage of gate opening. The power P developed is measured mechanically. From each test, the unit power P_u, the unit speed N_u, the unit quantity Q_u and the overall efficiency η_0 are determined.

The characteristic curves drawn are:

(a) Unit quantity vs unit speed

(b) Unit power vs unit speed

(c) Overall efficiency vs unit speed



(a) Main characteristics of a pelton wheel.

(b) Main characteristics of a kaplan turbine.

(c) Shows the main characteristic curves of a Francis turbine.

Fig. 23.1. (a), (b) and (c).

ii) Constant Speed Curves or Operating Characteristic Curves:

In this case tests are conducted at a constant speed varying the head H and suitably adjusting the discharge Q. The power developed P is measured mechanically. The overall efficiency is aimed at its maximum value.

The curves drawn are

$$P \ vs \ Q$$
$$\eta_0 \ vs \ Q$$
$$\eta_0 \ vs \ P_u$$
$$\eta_{0max} \ vs\% \text{ of full load.}$$

(iii) Constant Efficiency Curves (Muschel Curves):

These curves are plotted from data which can be obtained from the constant head and constant speed curves. The object of obtaining this curve is to determine the zone of constant efficiency so that we can always run the turbine with maximum efficiency.

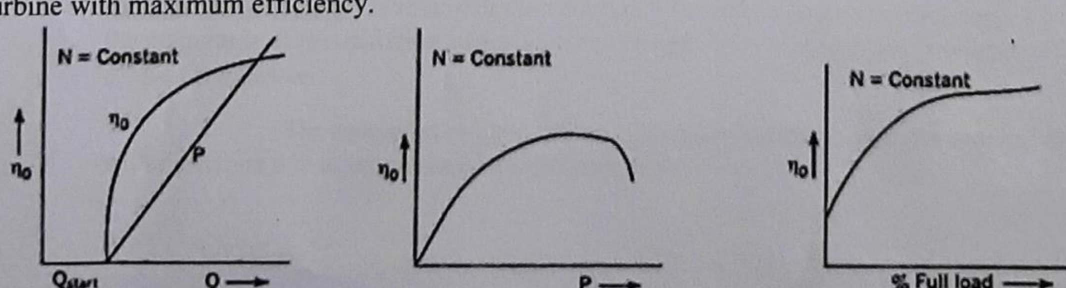


Fig. 23.2. Operating characteristics of a turbine.

16

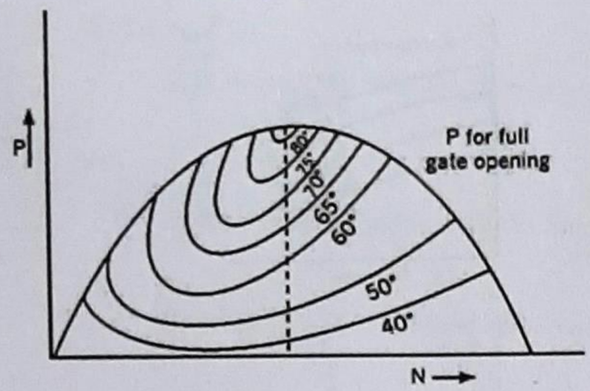


Fig. 23.3. Constant efficiency curve for a reaction turbine.