HYDROPOWER

- Falling water as a source of energy is known from ancient times.
- It was used to turn water wheels for grinding corn. With industrial development during the 19th century, wooden water wheels were replaced by turbines.
- With the invention of electricity, water turbines were coupled with generators to produce electrical energy.
- In India, the first hydropower station of 130 kW was commissioned during 1897 in the hills of Darjeeling in West Bengal.
- Subsequently, many small hydropower stations were set up utilizing canal falls.
- After independence in 1947, India is marching ahead to develop hydropower as part of multipurpose projects which also provide benefits of irrigation water, industrial and drinking water supply, flood control, and so on.

HYDROPOWER

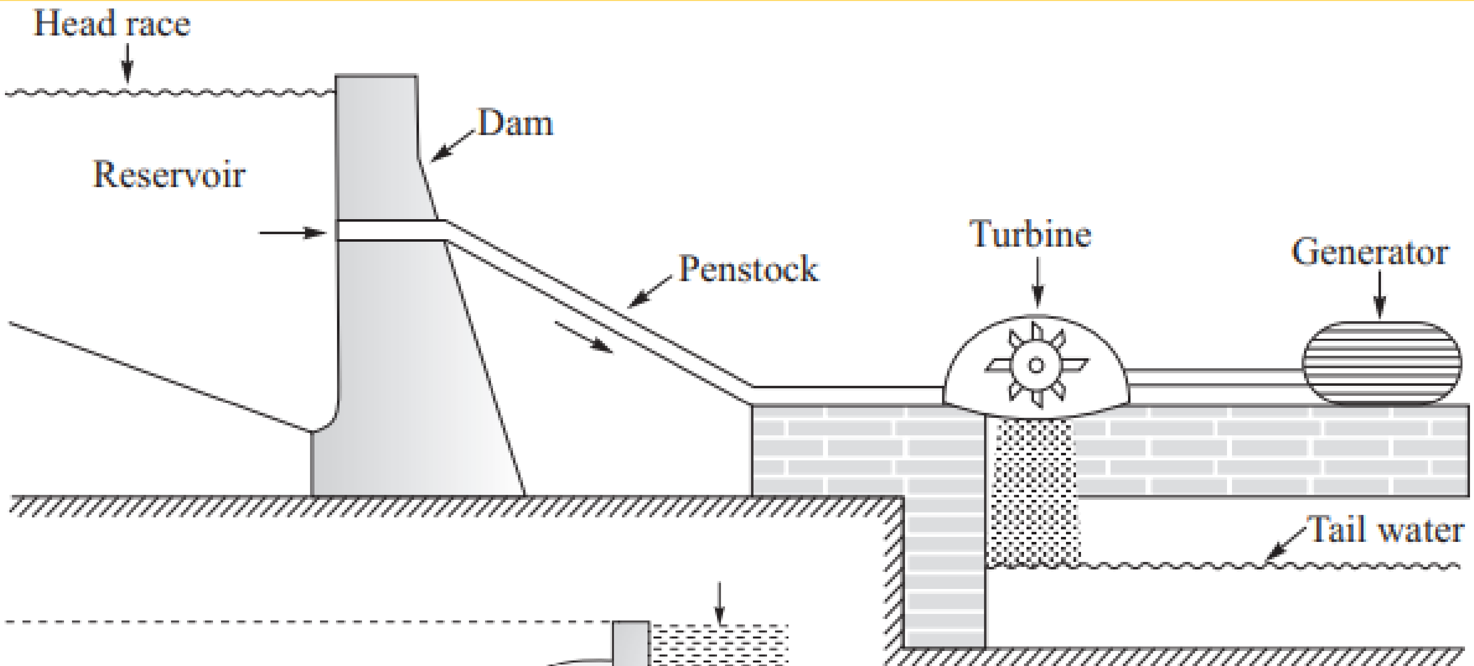
- **Hydropower projects essentially harness energy from flowing or falling water in rivers, rivulets, artificially created storage dams or canals.**
- **Potential energy in water is converted into shaft work utilising a hydraulic prime mover.**
- **Electrical energy is obtained from an electric generator coupled to the shaft of the prime mover.**

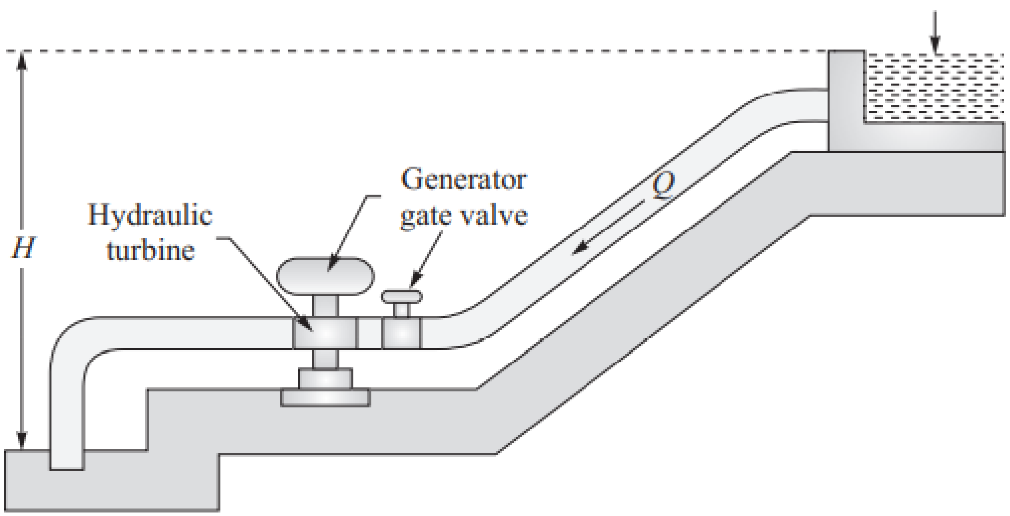
POWER EQUATION

- **The amount of electric power generated (measured in kilowatts) is proportional to the product of net head (metre) and flow in cubic metre per second.**
- **Power generated in kW is expressed by**

$$P = 9.81QH\eta$$

Hydro electrical Power Plant cont.





Hydro electrical Power Plant

Power, P = Potential energy of flowing water in turbine

= mass x gravitational acceleration x head

= m.g.H

But mass = discharge x Density

$= \boldsymbol{Q} \times \boldsymbol{\rho}$

$$\text{P} = \boldsymbol{\rho}\boldsymbol{Q}\text{gH}$$

Newton's Second Law of Motion, Linear Momentum Equation and Impulse Momentum Equation

The fundamental principle of dynamics is Newton's Second Law of Motion which states that "The rate of change of momentum is proportional to the applied force and takes place in the direction of the force".

$$\textbf{Change of momentum} = m.dv$$

$$\textbf{and rate of change of momentum} = m.\frac{d\vartheta}{dt}$$

According to the above law,

Dynamic force applied in x- direction = Rate of change of momentum in x-direction

$$i.e., \quad F_x = m.\frac{d\vartheta_x}{dt}$$

This equation is known as ***linear momentum equation*** and can also be written as

$$F_x dt = m.d\vartheta_x$$

Newton's Second Law of Motion, Linear Momentum Equation and Impulse Momentum Equation cont..

$$F_x dt = m.d\vartheta_x \qquad (1)$$

Impulse of applied force **Resulting change in momentum**

Equation 1 is known as *Impulse-momentum Equation* which states -

"Impulse of dynamic force = resulting change in momentum of body."

$$\boxed{F_x = m.\frac{d\vartheta_x}{dt}}$$

Newton's second law of motion is generally applicable to a system. This may be written as

$$\sum F_x = m.\frac{d\vartheta_x}{dt}$$

Newton's Second Law of Motion, Linear Momentum Equation and Impulse Momentum Equation cont..

$$\sum F_x = m.\frac{d\vartheta_x}{dt}$$

$$\sum F_x = \frac{m}{t}(\vartheta_{x2} - \vartheta_{x1})$$

Since the dimensions of m/t is mass per unit time that is mass flow ρQ

$i.e.,$ $$\sum F_x = \rho Q(\vartheta_{x2} - \vartheta_{x1})$$

Hydro electrical Power Plant cont..

- **Penstock:-** The penstock is used to feed water to the generating machine in powerhouse. Penstock pipes are made of mild steel, fibre glass or PVC depending upon their diameter, thickness and water pressure plus transient pressure arising due to sudden load changes.
- **Tail race:-** A tail race is a water channel, used to drain down the water discharged from the draft tube to the river.

✓ The tail race must maintain a proper tailwater elevation so as to prevent cavitation and inefficient operation of propeller turbine.

✓ From the hydraulic point of view, the water level should be maintained to keep the turbine and the draft tube submerged, otherwise the draft tube vacuum may break and stop the turbine.

CLASSIFICATION OF SMALL HYDROPOWER (SHP) STATIONS

Based on capacity (MNRE Report 2005)

Category	*Unit size*
Micro	Up to 100 kW
Mini	101–1000 kW
Small	1–25 MW

Depending on head

Ultra low head	Below 3 metre
Low head	Above 3 metres and up to 40 metre
Medium/high head	Above 40 metre

- **Field analysis of several small hydro-electric projects revealed a range of suitable net head (m) with water discharge (m^3/s) to generate optimal power.**

Conversion of Hydropower

$$\text{Power, } P = \text{Potential energy of flowing water in turbine}$$

$$= \text{mass} \times \text{coefficient of gravitational acceleration} \times \text{head}$$

$$= m \cdot g \cdot h$$

But

$$m = \text{discharge} \times \text{density}$$

$$= Q \times \rho$$

$$P = \rho Q g H$$

An electric generator is directly coupled to the hydraulic turbine which converts the mechanical energy into electric energy.

Water head in hydraulic systems

- **Gross head:** It is the difference in level from the upper surface of water at the highest usable point to the lowest level at the discharge side of the turbine when no water is flowing.
- **Net head:** It is head of water available for doing work on the turbine. It is the gross head less the hydraulic losses occurred in carrying water to the entrance of the turbine.
- **Rated head:** It is the head at which the turbine produces the rated output at the rated speed.

Water head in hydraulic systems cont..

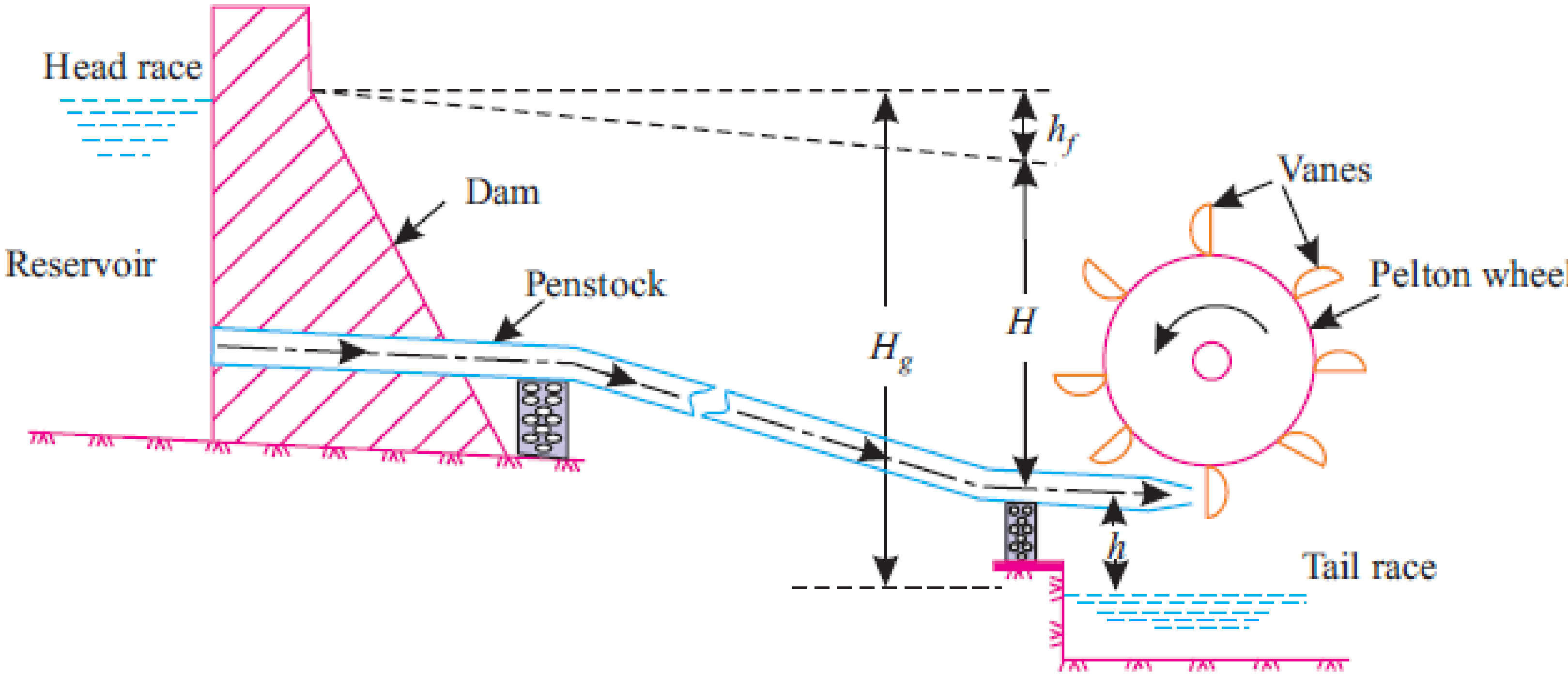


Figure: Layout of hydroelectric power plant using an impulse turbine (Pelton wheel)

Definition of Head and Efficiency cont..

1. Gross head. The gross (total) head is the difference between the water level at the reservoir (also known as the *head race*) and the water level at the tail race. It is denoted by H_g.

2. Net or effective head. The head available at the inlet of the turbine is known as net or effective head. It is denoted by H and is given by:

$$H = H_g - h_f - h$$

where, h_f = Total loss of head between the head race and entrance of the turbine

Definition of Head and Efficiency cont..

$$= \frac{4fLV^2}{D \times 2g}$$ (L = length of penstock, D = diameter of penstock,

V = velocity of flow in penstock), and

h = Height of nozzle above the tail race.

3. Efficiencies. The following are the important *efficiencies of turbine* :

(*i*) Hydraulic efficiency (η_h). It is defined as the *ratio of power developed by the runner to the power supplied by the jet at entrance to the turbine.*

Mathematically,

$$\eta_h = \frac{\text{Power developed by the runner}}{\text{Power supplied at the inlet of turbine}}$$

Work done by the jet on the runner

$$= \frac{\rho Q_a (V_{w1} \pm V_{w2}) u}{wQ_aH} = \frac{\left(\frac{w}{g}\right) Q_a (V_{w1} \pm V_{w2}) u}{wQ_aH}$$

$$= \frac{(V_{w1} \pm V_{w2}) u}{gH} = \frac{H_r}{H}$$

Definition of Head and Efficiency cont..

where, V_{w1}, V_{w2} = Velocities of whirl at inlet and outlet respectively,

u = Tangential velocity of vane,

H = Net head on the turbine, and

Q_a = Actual flow rate to turbine runner (bucket).

The parameter, $H_r = \frac{1}{g}(V_{w1} + V_{w2})\,u$ represents the energy transfer per unit weight of water and is referred to as the '*runner head*' or '*Euler head*'.

$$H - H_r = \Delta H = \text{Hydraulic losses within the turbine.}$$

(*ii*) Mechanical efficiency (η_m). It is defined as the *ratio of the power obtained from the shaft of the turbine to the power developed by the runner.* These two powers differ by the amount of mechanical losses, *viz.,*bearing friction, etc.

Mathematically,
$$\eta_h = \frac{\text{Power available at the turbine shaft}}{\text{Power developed by turbine runner}} = \frac{\text{Shaft power}}{\text{Bucket power}}$$

Definition of Head and Efficiency cont..

$$= \frac{P}{wQ_a\left(\frac{V_{w1} + V_{w2}}{g}\right)u} = \frac{P}{wQ_a H_r}$$

Values of mechanical efficiency for a Pelton wheel usually lie between *97 to 99 percent depending on size and capacity of the unit.*

(*iii*) Volumetric efficiency (η_v). The volumetric efficiency is the *ratio of the volume of water actually striking the runner to the volume of water supplied by the jet to the turbine.* That is,

$$\eta_v = \frac{\text{Volume of water actually striking the runner } (Q_a)}{\text{Total water supplied by the jet to the turbine } (Q)}$$

For Pelton turbines, $\eta_v \simeq 0.97$ to 0.99.

(*iv*) Overall efficiency (η_o). It is defined as the *ratio of power available at the turbine shaft to the power supplied by the water jet.* That is

$$\eta_0 = \frac{\text{Power available at the turbine shaft}}{\text{Power available from the water jet}} = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{wQH}$$

(where, Q = the total discharge in m^3/s supplied by the jet.)

The values of overall efficiency for a Pelton wheel lie between 0.85 to 0.90.

Definition of Head and Efficiency cont..

The individual efficiencies may be combined to give,

$$\eta_0 = \eta_h \times \eta_m \times \eta_v$$

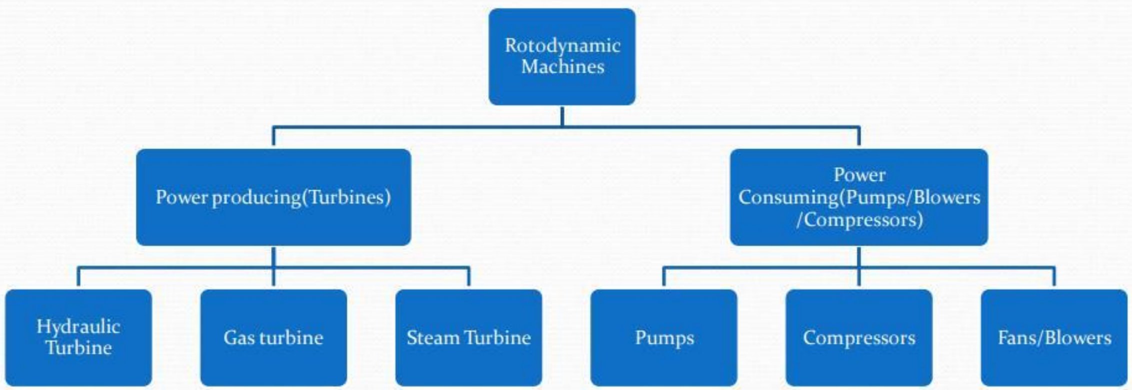
$$= \frac{H_r}{H} \times \frac{P}{wQ_a H_r} \times \frac{Q_a}{Q} = \frac{P}{wQH},$$ which is the same as defined vide eqn.

If η_g is the efficiency of a generator, then power output of hydrounit (turbine + hydrogenerators)

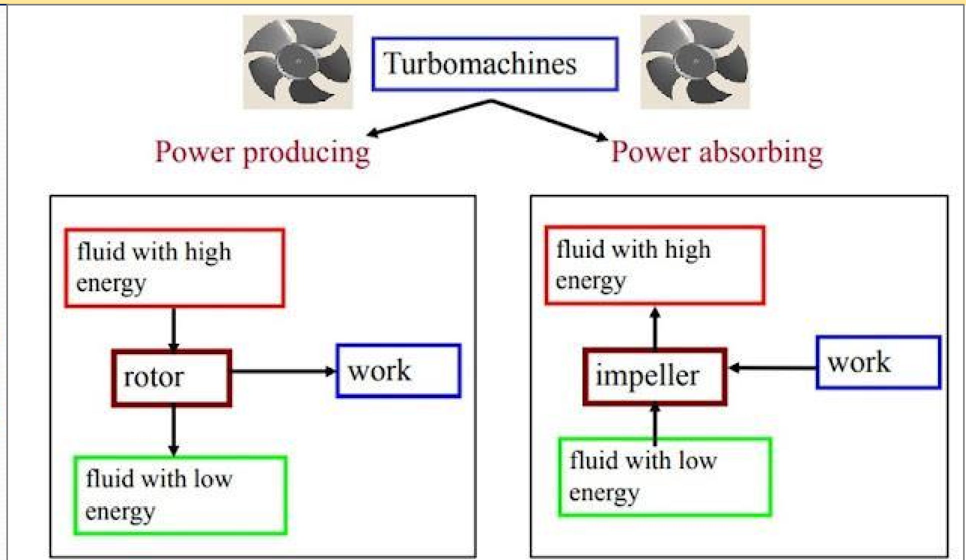
$$= (wQH) \times \eta_0 \times \eta_g$$

The product $\eta_0 \times \eta_g$ is known as *hydroelectric plant efficiency.*

Types of Rotodynamic Machines

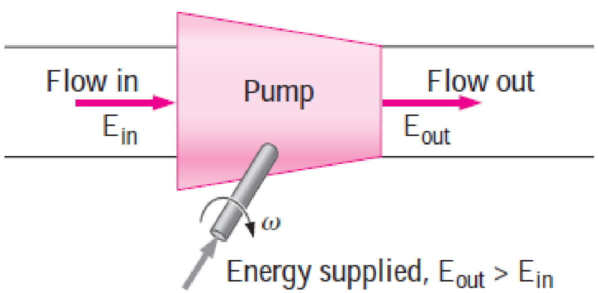


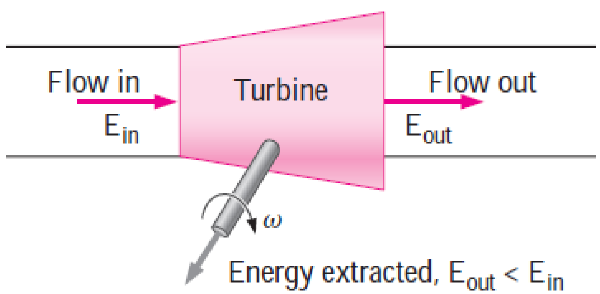
Turbine Input: Stored energy of water
Turbine output: Mechanical Energy
Pump Input: Mechanical energy
Pump Output: Stored energy of water



Turbine: The work is done by the fluid on the rotor.

Pump, Compressor, Fan, and Blower: The work is done by the rotor on the fluid element.

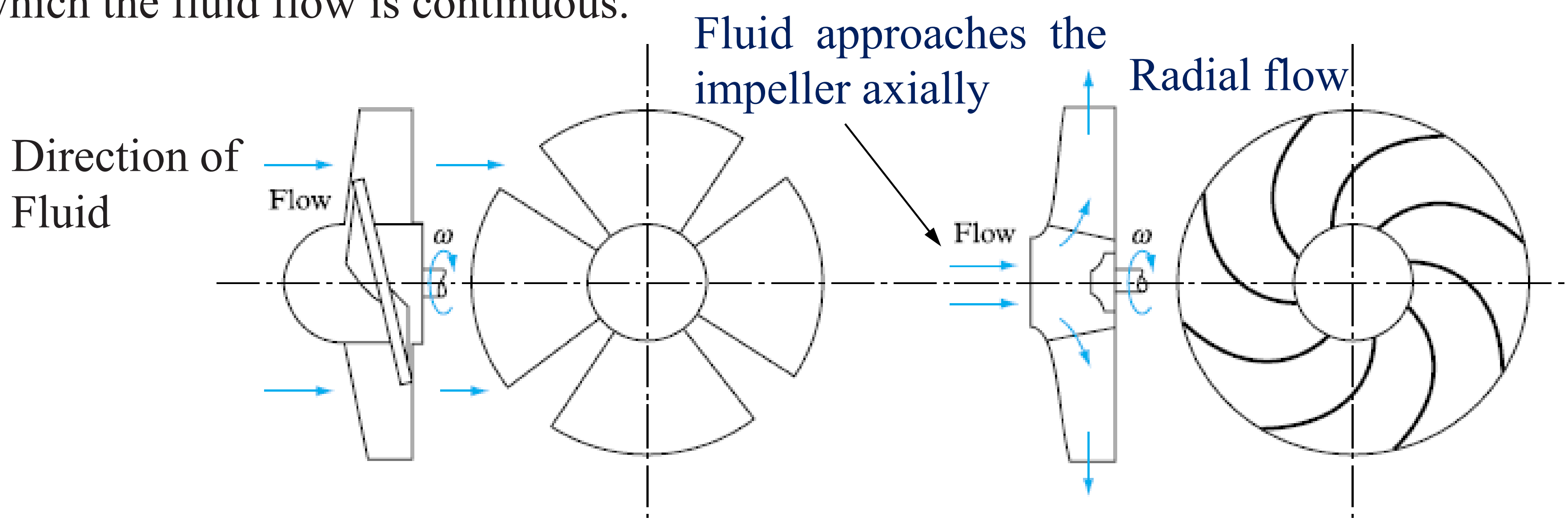




(a) A pump supplies energy to a fluid, while **(b) A turbine extracts energy from a fluid**

Flow Through Rotodynamic Machines

All rotodynamic machines, as previously stated, have a *rotating part called the impeller*, through which the fluid flow is continuous.



(a) Axial flow impeller (b) Centrifugal impeller

- Flow to be perpendicular to the impeller and, hence, along its axis of rotation, as shown in Machines of this kind are called **axial flow machines.**
- In **centrifugal machines (sometimes called 'radial flow'),** although the fluid approaches the impeller axially, it turns at the machine's inlet so that the flow through the impeller is in the plane of the impeller rotation.

Flow Through Rotodynamic Machines cont..

- **Mixed flow machines** constitute a third category. They derive their name from the fact that the **flow through their impellers is partly axial and partly radial**.
- Shows a mixed flow fan impeller from the discharge side.

(b)

All impellers consist of a supporting disc or cylinder and blades attached to it.

Figure: A mixed flow fan impeller.
(Courtesy of Airscrew-Howden Ltd)

(b) A centrifugal pump impeller (shrouded).
(Courtesy of Worthington-Simpson Ltd)

Flow Through Rotodynamic Machines cont..

- Mixed flow machines :-They derive their name from the fact that the flow through their impellers is partly axial and partly radial.
- Shows a mixed flow fan impeller from the discharge side.
- It should be noted that the hub is conical; thus the direction of flow leaving the impeller is somewhere between the axial and radial.

(c) A centrifugal pump impeller (unshrouded). (Courtesy of Worthington-Simpson Ltd)

Classification of turbines

The hydraulic turbines are *classified* as follows :

1. According to the head and quantity of water available.
2. According to the name of the originator.
3. According to the action of water on moving blades.
4. According to the direction of flow of water in the runner.
5. According to the disposition of the turbine shaft.
6. According to the specific speed N.

Classification of turbines cont.

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

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

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

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

2. According to the name of the originator :

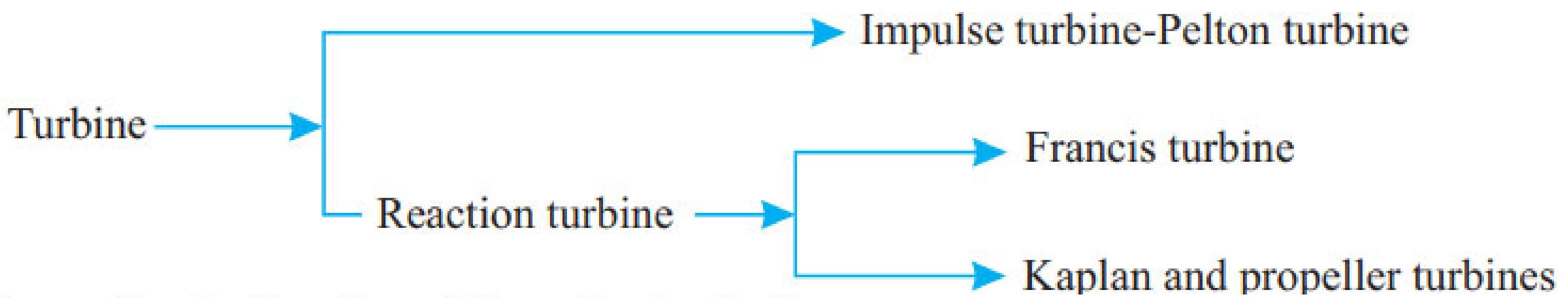
(*i*) *Pelton turbine* ... named after Lester Allen Pelton of California (U.S.A.). It is an impulse type of turbine and is used for *high head and low discharge*.

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

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

Classification of turbines cont.

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



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

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

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

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

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

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

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

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

Classification of turbines cont.

5. According to the disposition of the turbine shaft :

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

6. According to specific speed :

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

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

where,

N = The normal working speed,

P = Power output of the turbine, and

H = The net or effective head in metres.

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

The following table gives the comparison between the impulse and reaction turbines with regard to their operation and application.

Specific speed of turbines cont.

The ‘specific speed’ is a figure which gives a fundamental basis of comparison between turbines of different types. It may be defined as the speed at which the turbine would run (at its desired efficiency) under unit head so as to produce unit power. The specific speed is calculated as

$$\text{specific speed, } n_s = \frac{n\sqrt{P}}{H^{5/4}}$$

where

n_s = specific speed
n = speed of turbine in rpm
P = output of turbine
H = head of water on turbine.

The specific speed depends on the turbine type and design. The ranges of n_s are given

Specific speed of turbines cont.

Table Specific speed range for different turbines

Type of turbine	*Name*	*Specific speed, n_s*
Impulse	Pelton	10–50
Reaction (mixed flow)	Francis	60–300
Propeller	Kaplan	300–1000
	Bulb	>1000

It infers that high-head operational turbines have a low value of specific speed while low-head turbines have a high value of n_s.

Specific speed of turbines cont.

It is required to develop 15,000 kW at 214 rpm under a head of 100 metre with a single runner. What type of turbine should be installed?

Solution

$$n_s = \frac{n\sqrt{P}}{H^{5/4}}$$

$$= \frac{214\sqrt{15000}}{100^{5/4}}$$

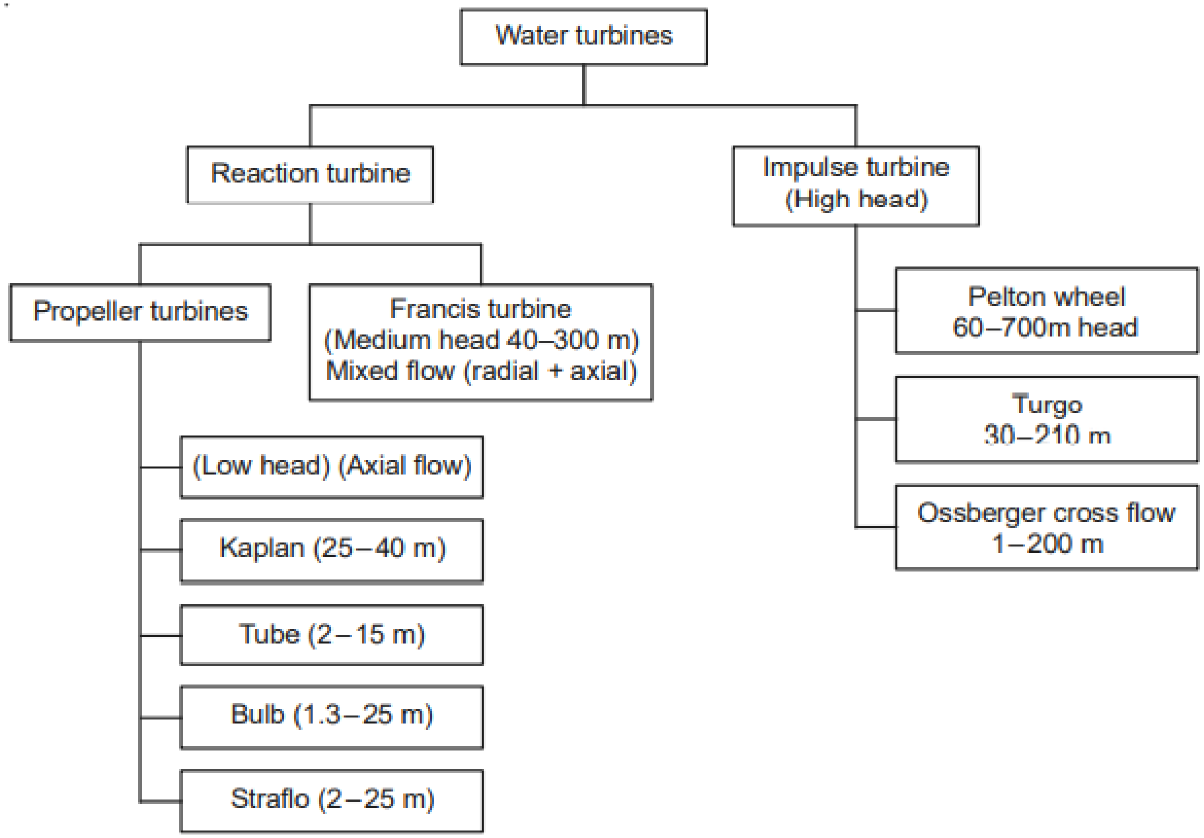
or $$n_s = 83$$

Hence, a reaction turbine should be used.

Specific speed of turbines cont.

Q. Find the specific speed when 150 kW power is to be generated under a head of 100 m at 300 rpm. Also, suggest the type of turbine to be used based on specific speed.

Classification of water turbines



- **Water turbines are classified based on the action of flowing water on turbine blades, the existing head and the quantity of water available, the direction of water flow on turbine blades, and the name of the inventor.**

Turbine Types

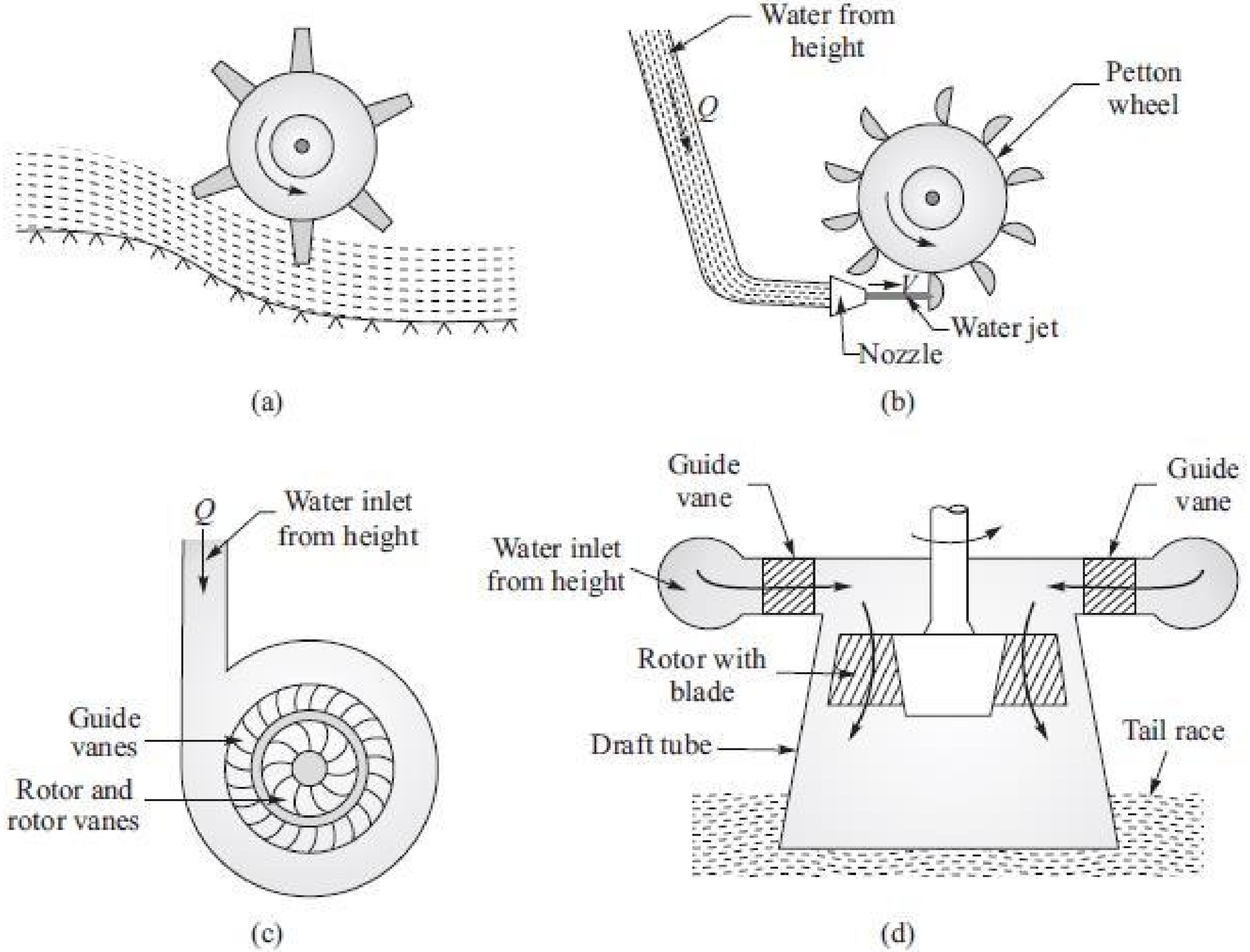


Figure Types of hydraulic turbines. (a) Water wheel, (b) Impulse turbine, (c) Reaction turbine (Francis) and (d) Reaction turbine (Kaplan).

Reaction Turbine cont..

Francis turbine blades are joined to two rims 1 and 2 as shown in Figure (a) and are especially shaped [Figure (b)] to ensure maximum extraction of energy from water.

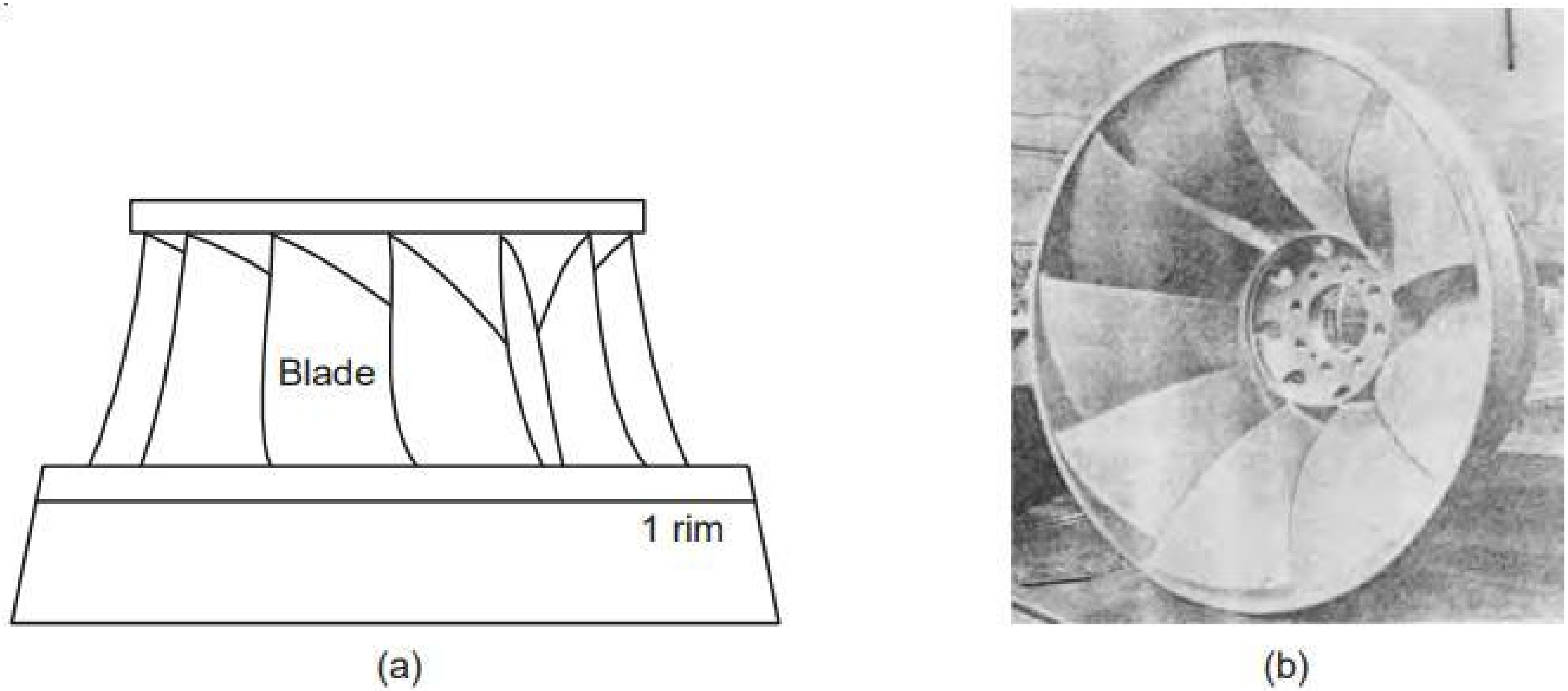


Figure: Francis turbine: (a) front view and (b) bottom view

Reaction Turbine cont..

The major parts of a Francis turbine system are:

1. Penstock pipe from high water level to scroll casing.

2. Scroll casing provided around turbine welded with penstock on upper side and draft tube on lower side.

3. Guide vanes installed on pivots to control water entering the runner.

4. Turbine wheel with blades, i.e., a runner.

5. Draft tube.

Reaction Turbine cont..

- Guide vanes are arranged on pivots around the turbine, and their degree of opening controls the quantity of water entering the turbine and consequently the power output can be adjusted.
- The runner of a Francis turbine consists of a number of fixed curved blades, arranged evenly along the circumference of the runner.
- Water under pressure enters the runner from the guide vanes towards the centre in radial direction and discharges out of the runner axially. Francis turbine is thus an inward mixed flow (radial + axial) type.
- Water completely fills the passages between the blades. Energy partly in the kinetic form and partly in the pressure form is imparted to the runner to rotate it as shown in Figure (a).

Reaction Turbine cont..

- **Guide vanes are arranged on pivots around the turbine, and their degree of opening controls the quantity of water entering the turbine and consequently the power output can be adjusted.**
- **The draft tube is an outflow bend and an upper taper pipe fabricated of steel plates.**
- **It enables the turbine to be installed above the tail race level without losing the head below the runner. Water leaving the runner at certain velocity at low pressure possesses kinetic energy.**

Francis Turbine-Reaction Turbine cont..

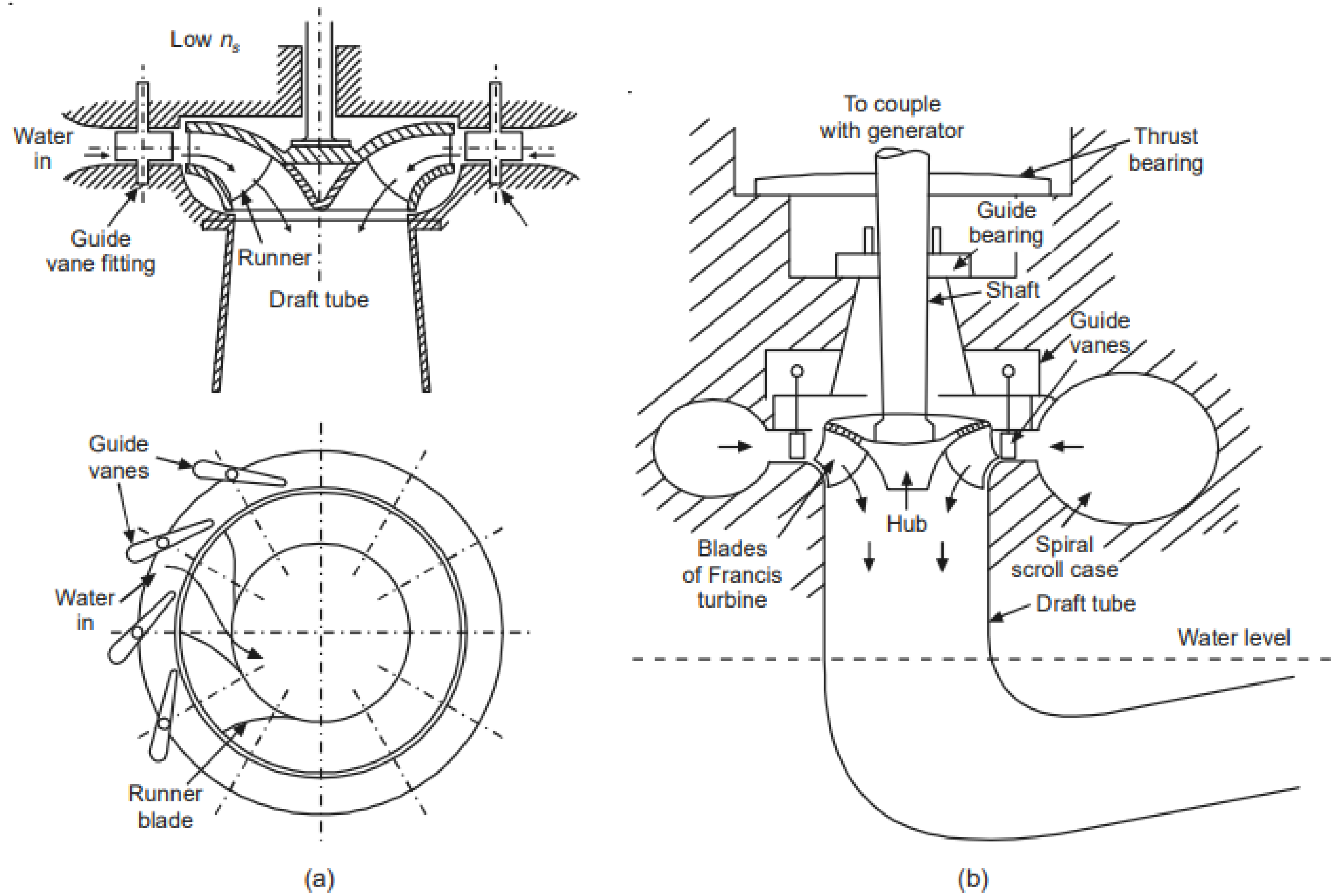
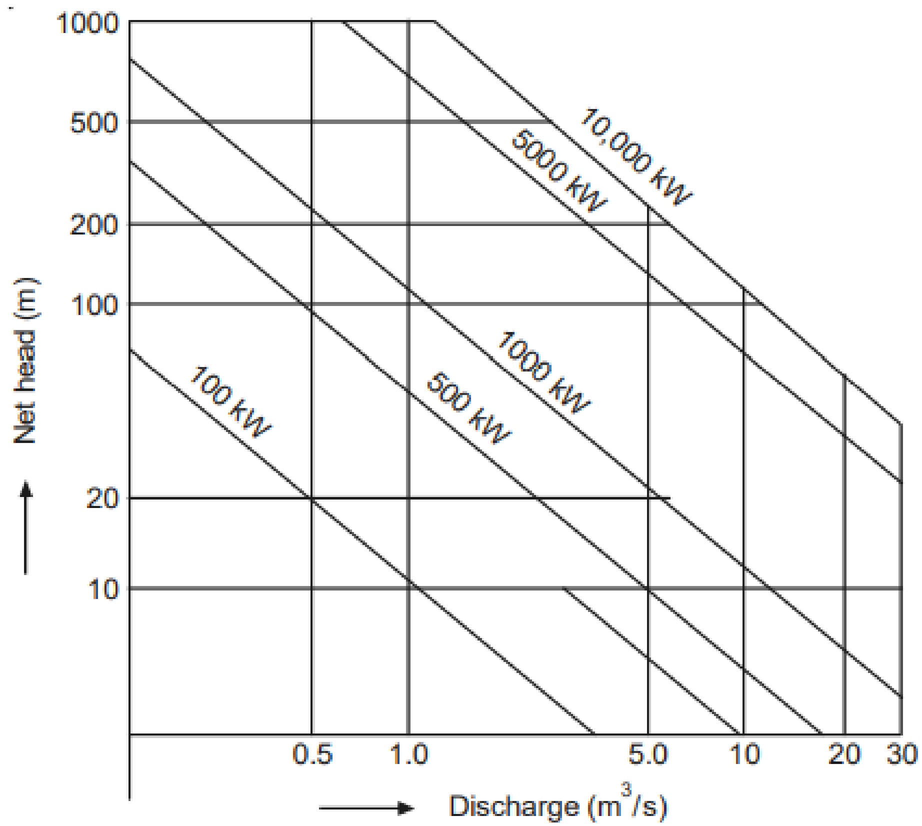


Figure: (a) Flow of water through the guide vanes and runner of Francis turbine, and (b) cross section of Francis turbine.

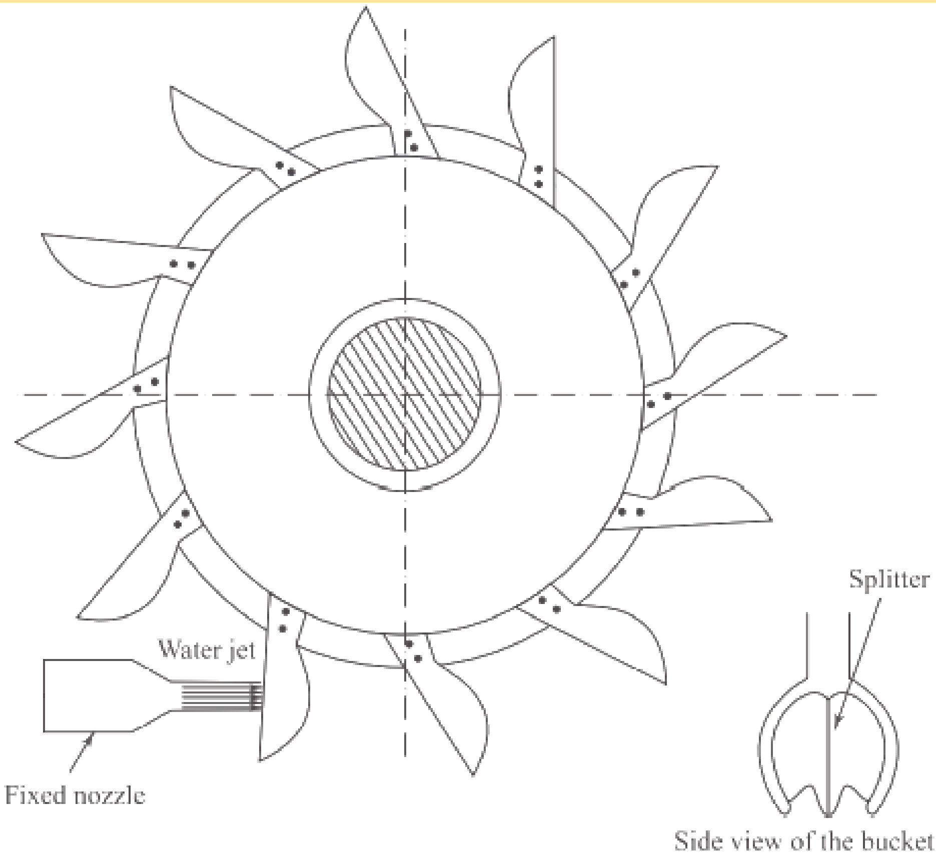
Graph for hydropower units—net head (m) v_s discharge (m^3/s)—to generate power



Classification of water turbines- Impulse

- Turbines are subdivided into impulse and reaction machines.
- In the impulse turbines, the total head available is first converted into the kinetic energy. This is usually accomplished in one or more nozzles.
- The jets issuing from the nozzles strike vanes attached to the periphery of a rotating wheel.
- Because of the rate of change of angular momentum and the motion of the vanes, work is done on the runner (impeller) by the fluid and, thus, energy is transferred.
- Since the fluid energy which is reduced on passing through the runner is entirely kinetic, it follows that the absolute velocity at outlet is smaller than the absolute velocity at inlet (jet velocity).
- Furthermore, the fluid pressure is atmospheric throughout and the relative velocity is constant except for a slight reduction due to friction.

Impulse Hydraulic Turbine: The Pelton Wheel



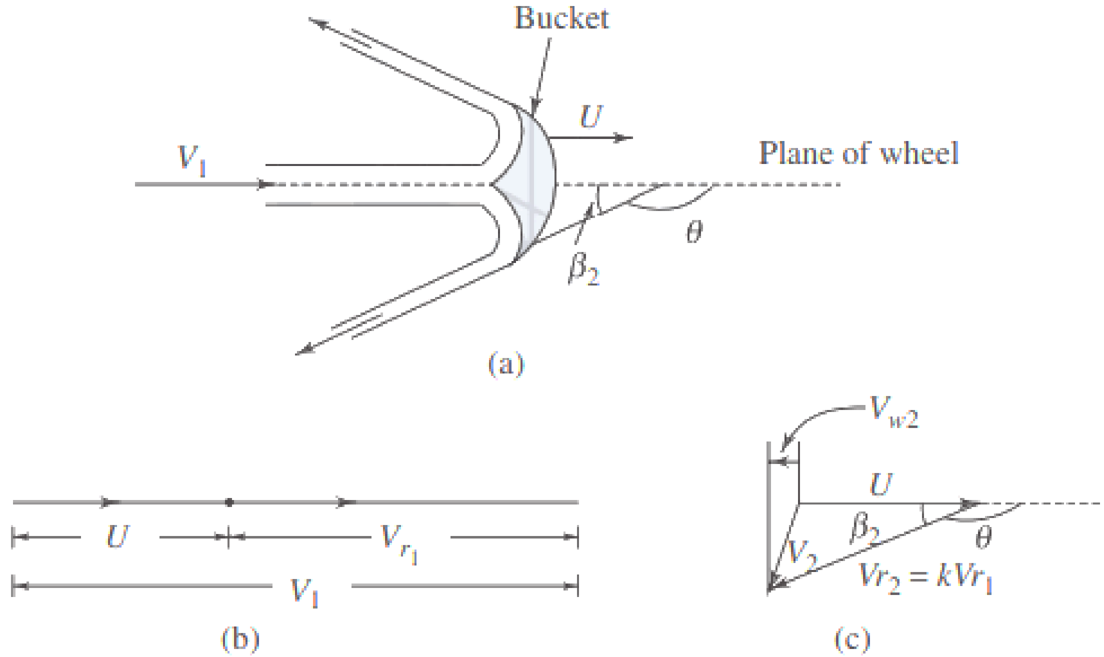


Figure (a): Flow along the bucket of a pelton wheel
(b): Inlet velocity triangle
(c): Outlet velocity triangle

- **Suited for high heads.**
- **The rotor consists of a large circular disc or wheel on which a number of spoon-shaped buckets are spaced uniformly.**

PERFORMANCE CHARACTERISTICS OF HYDRAULIC TURBINES

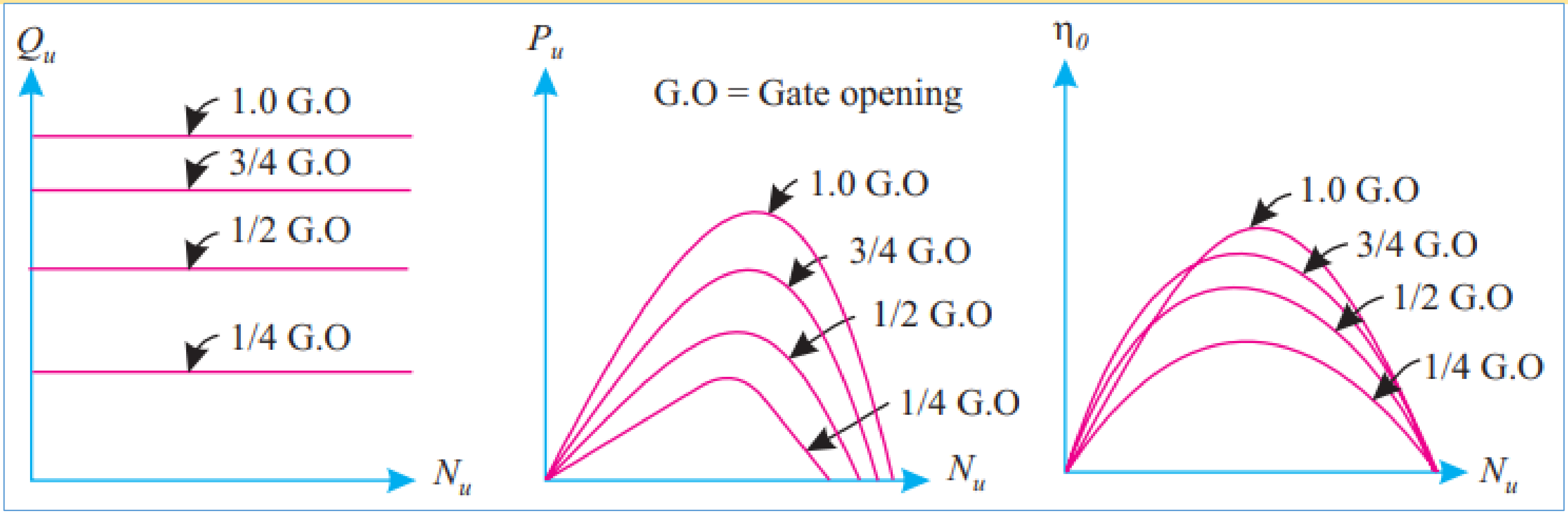
The turbines are normally designed for specific values of head, speed, discharge, power and efficiency (known as the *designed conditions*). But oftenly turbines may be required to operate under conditions different from those for which these have been designed. Thus, to know about their exact behaviour under varying conditions it becomes necessary to conduct tests either on the actual turbines at the site or on their small scale models in a research laboratory. The results so obtained are usually represented graphically and the curves obtained are known as "*Characteristic curves*". These curves are usually plotted in terms of unit quantities (for sake of convenience). The characteristic curves are of the following types :

1. Main or constant head characteristic curves.
2. Operating or constant speed characteristic curves.
3. Constant efficiency or iso-efficiency or Muschel curves.

Main or Constant Head Characteristic Curves

- *Head and gate opening are maintained constant.*
- *Speed is varied* by allowing a variable quantity of water to flow through the inlet opening.
- The brake power (P) is then measured mechanically by means of a dynamometer.
- The overall efficiency and unit quantities are then calculated by using the basic data; these are then plotted *against unit speed as abscissa.*

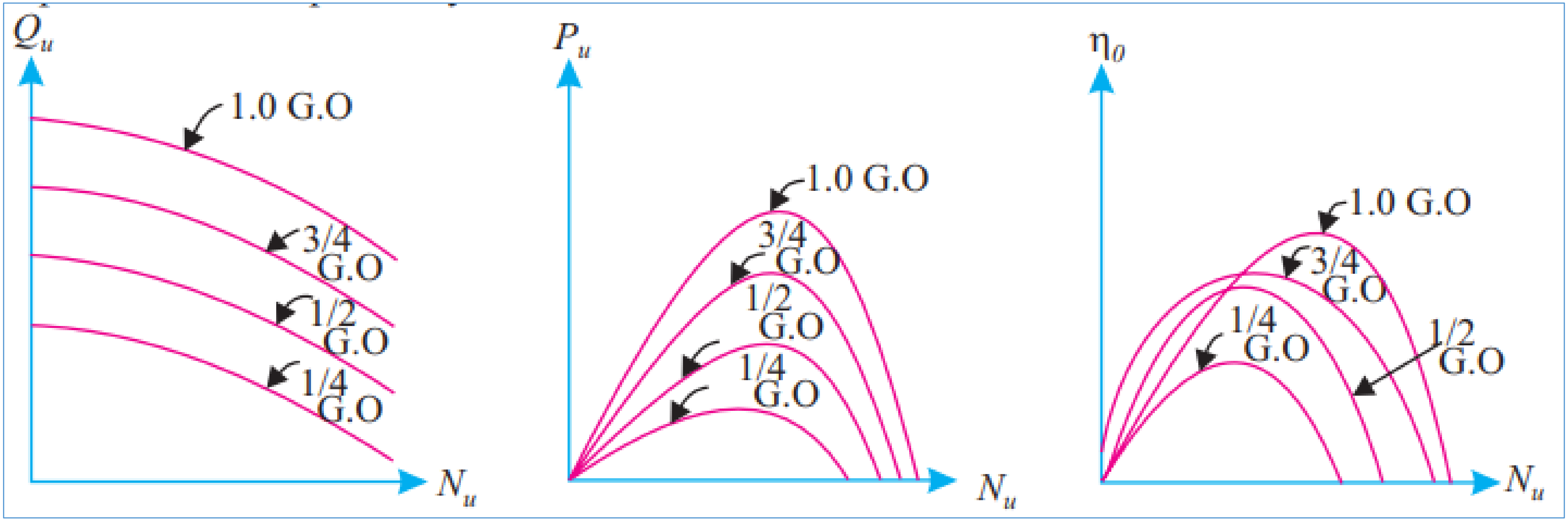
Main characteristic curves of Pelton wheel.



The main characteristic curves yield the following information :

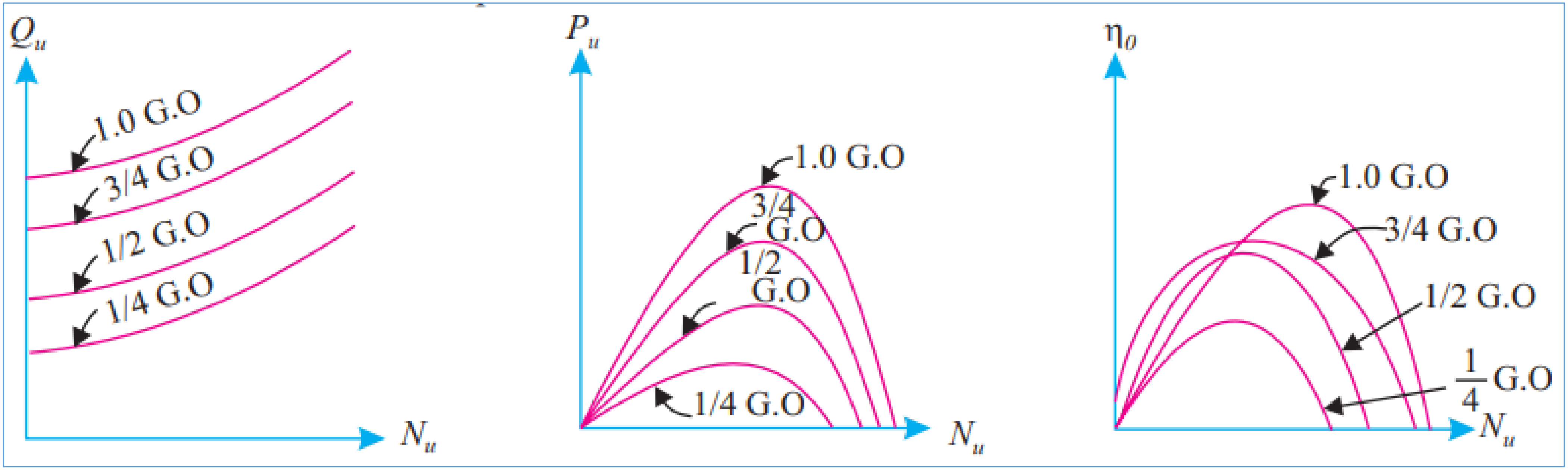
- The discharge Q_u for a *Pelton wheel* depends only upon the gate opening and is independent of N_u; the curves for Q_u are horizontal.
- The curves between Q_u and N_u for a *Francis turbine are falling curves*. This is due to the fact that a *centrifugal head develops which* acts outwards and *opposes* the external head causing flow, eventually decreasing the discharge as the speed increases.
- The curves between Q_u and N_u for a *Kaplan turbine* are *rising curves*; the discharge increases with the increase in speed.

Main characteristic curves of Francis turbine.



- The curves between Q_u and N_u for a *Francis turbine are falling curves*. This is due to the fact that a *centrifugal head develops which* acts outwards and *opposes* the external head causing flow, eventually decreasing the discharge as the speed increases.

Main characteristic curves of Kaplan turbine.



- The curves between P_u and N_u and those between η_0 and N_u indicate that at a particular speed the efficiency is maximum.

The maximum efficiency for a *Pelton wheel* usually occurs at the *same speed for all gate openings; this speed usually corresponds to a speed ratio of 0.45 . However, the maximum efficiency for a reaction turbine usually occurs at different speeds for different gate openings.*

Operating or Constant Speed Characteristic Curves

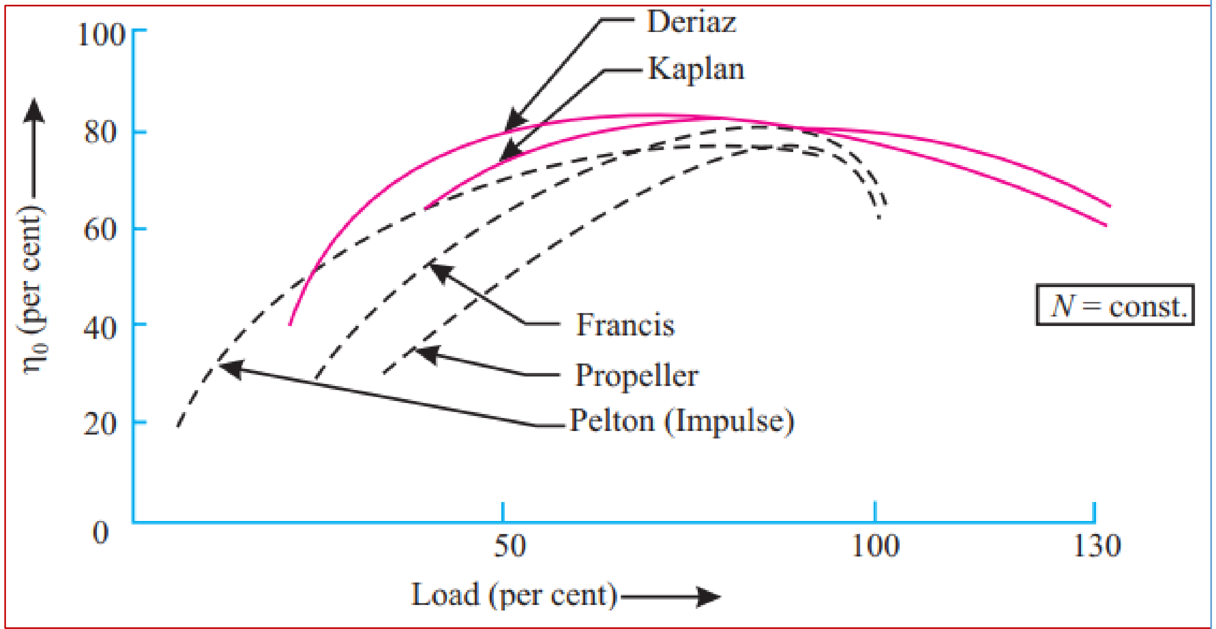
These curves are obtained as follows :

(*a*) Percentage of full load *v*/s overall efficiency (η_0) curves :

- For each gate opening speed is kept constant. The constant speed is attained by regulating the gate opening thereby varying the discharge flowing through the turbine as the load varies; the head may or may not remain constant.
- The brake power (P) is measured mechanically by means of a dynamometer.
- The overall efficiency (η_0) is then calculated from the measured values of discharge, head and power.
- Further knowing the total load capacity of the turbine the percentage of full load is computed from the measured power and a plot of η_0 *v/s* percentage of full load is prepared.

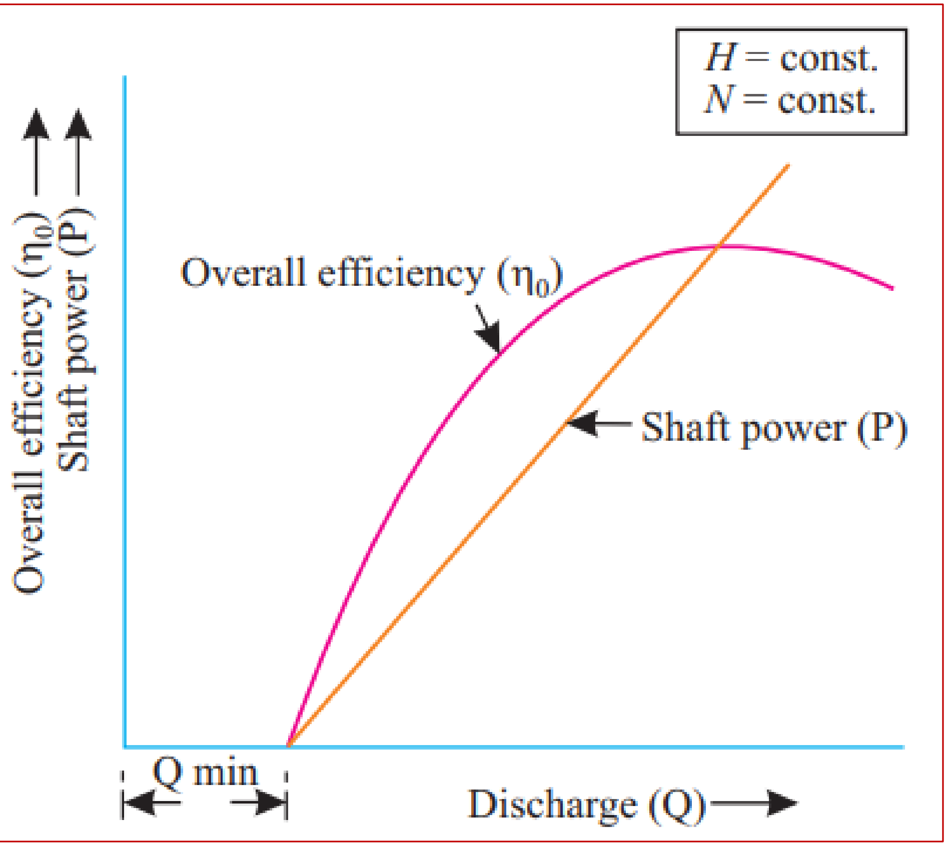
(*a*) Percentage of full load *v/s* overall efficiency (η_0) curves :

Fig. the graphs plotted between *percentage of full load v/s* η_0 for different types of turbines. The following *points are worth noting* :



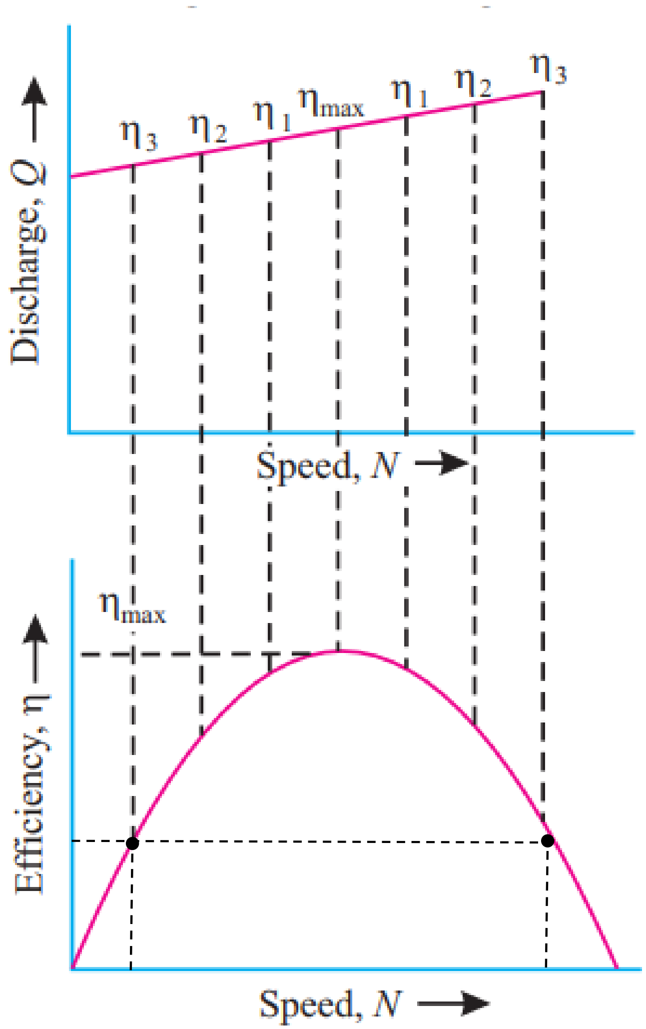
- As the percentage full load increases η_0 also increases (In other words, at reduced loads η_0 is also less).
- At 100 per cent full load η_0 is near about the maximum efficiency in all cases.
- The Kaplan, the Deriaz and the Pelton wheel maintain a high efficiency over a longer range of *part load* as compared with either the Francis or the fixed blade propeller turbine.
- The maximum overall efficiency of all the turbines is almost the same (about 85%).

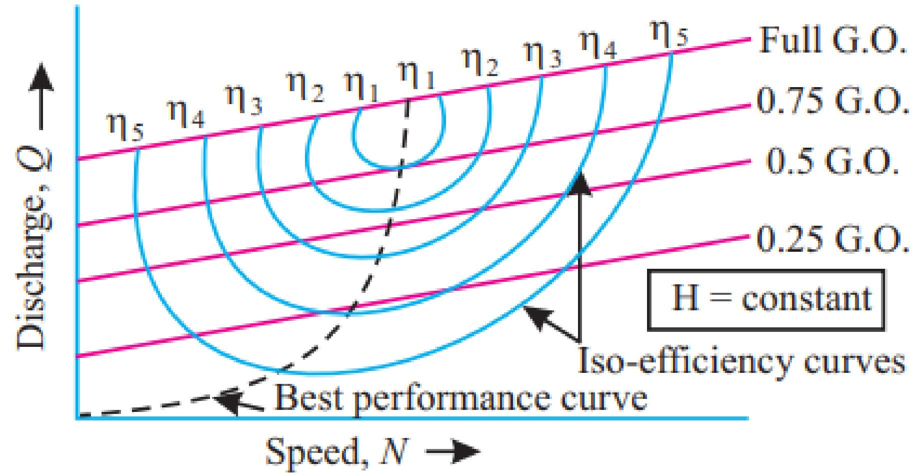
(*b*) Overall efficiency (η_0) and output (shaft) power (P) v/s discharge (Q) curves:



- Shaft power or output power (P) is a straight line, since $P \propto Q$ if H (head) is constant.
- η_0 *v/s* discharge (Q) graph is curvilinear and η_0 increases with Q and remains *nearly* constant beyond a particular value of discharge.

Constant efficiency or iso-efficiency or Muschel curves





Constant efficiency or iso-efficiency or Muschel curves

As η–N curve is of parabolic nature, there exits two speeds for one value of efficiency except for maximum efficiency which occurs at one speed only. Corresponding to these values of speeds there are also two values of discharge for each value of efficiency (Q-N curve). Hence on Q-N curve we can plot two points for each value of efficiency and one point for maximum efficiency. By adopting this procedure for different gate openings or heads we can get number of Q-N curves and we can plot on them efficiency points (as described above). The points denoting the same efficiency can now be joined to get constant iso-efficiency curves or Muschel curves (The German word 'Muschel' means shell, indicating shape of curve). The diagram showing these curves is also called Hill diagram (since it looks like top view of a hill). In actual practice unit speed and unit discharge are taken along the co-ordinate axes.

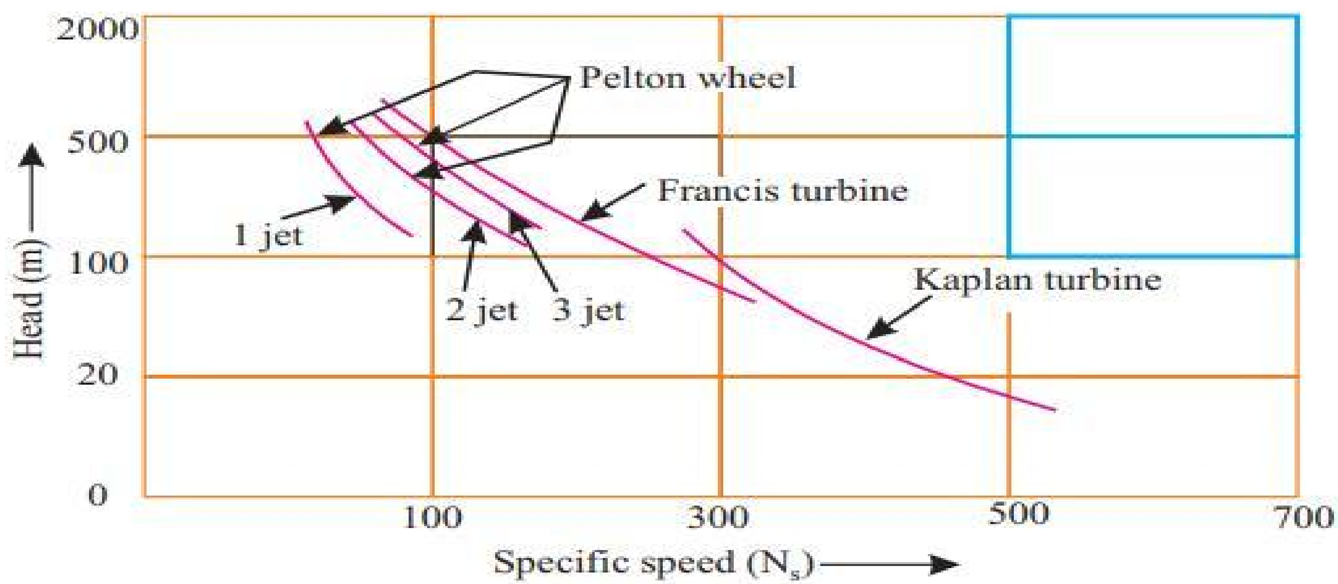
The *curve for the best performance is obtained by joining the peak points of the various efficiency curves.*

The constant efficiency curves are helpful for determining the zone of constant efficiency and for predicting the performance of the turbine at various efficiencies.

Question 1 *Give the range of specific speed values of the Kaplan, Francis turbines and Pelton wheels. What factors decide whether Kaplan, Francis or a Pelton wheel type turbine would be used in a hydroelectric project.* **[UPSC]**

Solution. • The **specific speed** *of a turbine is defined* as *the speed of a turbine which is identical in shape, geometrical dimensions, blade angles, gate opening, etc. which would develop unit power when working under a unit head.*

- Based on specific speed, the turbines for the project are selected as shown in the Fig.
- In general, the selection of a turbine for hydroelectric project is based on the following considerations :



Selection of turbine

1. For *high heads*, *Pelton wheels* are invariably selected.
2. For *intermediate heads*, *Francis turbines* are selected.
3. For *low head* and *high discharge*, Kaplan turbines are selected.

Numerical Problem

Question 2 *In a hydroelectric station, water is available at the rate of 175 m^3/s under a head of 18 m. The turbines run at a speed of 150 r.p.m. with overall efficiency of 82%. Find the number of turbines required if they have the maximum specific speed of 460.* **[GATE]**

Solution. *Given* : $Q = 175\ m^3/s$; $H = 18$ m; $N = 150$ r.p.m.; $\eta_0 = 82\%$; $N_s = 460$.

Number of turbines required :

Specific speed of the turbine, $= \dfrac{N\sqrt{P}}{H^{5/4}}$ ...[Eqn.

$$460 = \frac{150\sqrt{P}}{(18)^{5/4}}$$ (where, P is in kW and H is in metres.)

or, Power available at turbine shaft, $P = \left[\dfrac{460 \times (18)^{5/4}}{150}\right]^2 = 12927.5$ kW

Power available from turbines $= wQH \times \eta_0 = 9.81 \times 175 \times 18 \times 0.82 = 25339.23$ kW

Numerical Problem

$$\textit{No. of turbines required} = \frac{25339.23}{12927.5} = 1.96 \ \text{ say } \mathbf{2} \ \textbf{(Ans.)}$$

Model relationship

(i) Head co-efficient, C_H :

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

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

$\therefore$
$$ND = \sqrt{H}, \text{ or, } \frac{H}{N^2D^2} = \text{constant}$$

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

Model relationship

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

Discharge through the turbine, $Q = \text{Area} \times \text{velocity} = A \times V_f$

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

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

Substituting the value of Q in eqn. (2.43), we obtain:

$$Q \propto D_2 \times ND \propto ND^3$$

or, $$\frac{Q}{ND^3} = \text{constant}$$

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

Model relationship

(*iii*) Power co-efficient C_P :

The shaft power available from a turbine,

$$P = \eta_0 \times wQH \propto QH$$

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

or, $$\frac{P}{N^3D^5} = \text{constant}$$

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

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

Model to Prototype ratio of Powers

The equation of powers may also be obtained in terms of heads by eliminating speeds of rotation and Np.

$$\frac{H}{N^2 D^2} = \text{constant}$$

$$\frac{H_m}{N_m^2 D_m^2} = \frac{H_p}{N_p^2 D_p^2}$$

$$\frac{N_m^2}{N_p^2} = \frac{H_m D_p^2}{H_p D_m^2}$$

$$\boxed{\frac{N_m^3}{N_p^3} = \frac{H_m^{3/2} D_p^3}{H_p^{3/2} D_m^3}}$$

$$\frac{P}{N^3 D^5} = \text{constant}$$

Model to Prototype ratio of Powers

$$\frac{N_m^3}{N_p^3} = \frac{H_m^{3/2} D_p^3}{H_p^{3/2} D_m^3}$$

$$\frac{P}{N^3 D^5} = \text{constant}$$

$$\frac{P_m}{N_m^3 D_m^5} = \frac{P_p}{N_p^3 D_p^5} \Rightarrow \frac{N_m^3}{N_p^3} = \frac{P_m D_p^5}{P_p D_m^5}$$

$$\frac{N_m^3}{N_p^3} = \frac{P_m D_p^5}{P_p D_m^5} \Rightarrow \frac{H_m^{3/2} D_p^3}{H_p^{3/2} D_m^3}$$

Model to Prototype ratio of Powers

$$\frac{N_m^3}{N_p^3} = \frac{P_m D_p^5}{P_p D_m^5} \Rightarrow \frac{H_m^{3/2} D_p^3}{H_p^{3/2} D_m^3}$$

$$\frac{P_m D_p^2}{P_p D_m^2} \Rightarrow \frac{H_m^{3/2}}{H_p^{3/2}}$$

$$\therefore \quad \frac{P_m}{H_m^{3/2} D_m^2} \Rightarrow \frac{P_p}{H_p^{3/2} D_p^2}$$

Example *A hydro-turbine is required to give 25 MW at 50 m head and 90 r.p.m. runner speed. The laboratory facilities available permit testing of 20 kW model at 5 m head. What should be the model runner speed and model to prototype scale ratio?*

Solution. *Given* : $P_p = 25$ MW; $H_p = 50$ m; $N_p = 90$ r.p.m.; $P_m = 20$ kW; $H_m = 5$ m

$$\mathbf{N_m ; \frac{D_p}{D_m} (= L_r):}$$

$$\text{Prototype specific speed, } (N_s)_p = \frac{N_p \sqrt{P_p}}{(H_p)^{5/4}} \qquad \text{(where, } P \text{ is in kW)}$$

$$= \frac{90 \times \sqrt{25 \times 10^3}}{(50)^{5/4}} = 107$$

For model, $$107 = \frac{N_m \sqrt{P_m}}{(H_m)^{5/4}} \qquad [\because (N_s)_p = (N_s)_m]$$

or, $$N_m = \frac{107 \times (H_m)^{5/4}}{\sqrt{P_m}} = \frac{107 \times (5)^{5/4}}{\sqrt{20}} = \mathbf{178.89\ r.p.m.}\ \textbf{(Ans.)}$$

For similar turbines $\frac{P}{H^{3/2}D^2}$ should be equal.

$$\therefore \quad \frac{P_p}{H_p^{3/2} D_p^2} = \frac{P_m}{H_m^{3/2} D_m^2}$$

or, $$\frac{D_p}{D_m} (= L_r) = \sqrt{\frac{P_p}{P_m} \times \left(\frac{H_m}{H_p}\right)^{3/2}} = \sqrt{\frac{25 \times 10^3}{20} \times \left(\frac{5}{50}\right)^{3/2}} = \mathbf{6.287}\ \textbf{(Ans.)}$$

Example *A water turbine delivering 10 MW power is to be tested with the help of a geometrically similar 1 : 8 model, which runs at the same speed as the prototype.*

(*i*) *Find the power developed by the model assuming the efficiencies of the model and the prototype are equal.*

(*ii*) *Find the ratio of the heads and the ratio of mass flow rates between the prototype and the model.*

Solution. *Given* : $P_p = 10$ MW; $N_p = N_m$; $\frac{L_m}{L_p} = \frac{D_m}{D_p} = \frac{1}{8}$; $\eta_p = \eta_m$.

(*i*) **Power developed by the model, P_m :**

We know that, $P \propto N^3 \times D^5$

(where, N is the speed and D is the diameter.)

$$\therefore \qquad P_p \propto N_p^3\ D_p^5, \text{ and, } \ P_m \propto N_m^3\ D_m^5$$

or, $$\frac{P_p}{P_m} = \left(\frac{N_p}{N_m}\right)^3 \times \left(\frac{D_p}{D_m}\right)^5 = (1)^3 \times \left(\frac{8}{1}\right)^5 = 8^5 \qquad (\because N_p = N_m)$$

$\therefore$ $$P_m = \frac{P_p}{(8)^5} = \frac{10 \times 10^6}{(8)^5} = \mathbf{305.2\ W}\ \textbf{(Ans.)}$$

(*ii*) Ratio of heads $\left(\frac{H_p}{H_m}\right)$ and ratio of mass flow rates $\left(\frac{m_p}{m_m}\right)$:

We know that, $$H \propto N^2D^2$$

$\therefore$ $$\frac{H_p}{H_m} = \left(\frac{N_p}{N_m}\right)^2 \times \left(\frac{D_p}{D_m}\right)^2 = (1)^2 \times (8)^2 = \mathbf{64}$$

Also, discharge, $$Q \propto ND^3$$

$\therefore$ Ratio of mass flow rates, $$\frac{Q_p}{Q_m} = \frac{m_p}{m_m} = \left(\frac{N_p}{N_m}\right)\left(\frac{D_p}{D_m}\right)^3 = 1 \times (8)^3 = \mathbf{512}$$

Example *A hydraulic turbine is to develop 1015 kW when running at 120 r.p.m. under a net head of 12 m. Work out the maximum flow rate and specific speed for the turbine if the overall efficiency at the best operating point is 92 per cent. In order to predict its performance, a 1 : 10 scale model is tested under a head of 7.2 m. What would be the speed, power output and water consumption of the model if it runs under the conditions similar to the prototype ?*

SELECTION OF HYDRAULIC TURBINES

The following points should be considered while selecting right type of hydraulic turbines for hydroelectric power plant :

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

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

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

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

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

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

SELECTION OF HYDRAULIC TURBINES

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

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

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

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

(*iv*) *Low heads* (*below 60 m*). Between 30 and 60 m heads both Francis and Kaplan turbines may be used. The latter is more expensive but yields a higher efficiency at partloads and overloads.

It is therefore preferable for *variable loads*. *Kaplan turbine is generally employed for heads under 30 m. Propeller turbines are however, commonly used for heads up to 15 m. They are adopted only when there is practically no load variations*.

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

Criteria for Selection of Turbines

S. No.	Type of turbine	Head H(m)	Specific speed (N_s)	Speed ratio (K_u)	Maximum hydraulic efficiency (%)	Remarks
1.	*Pelton*: 1 jet 2 jets 4 jets	up to 2000 up to 1500 up to 500	12 to 30 17 to 50 24 to 70	0.43 to 0.48	89	Employed for very high head.
2.	*Francis*: High-head Medium head Low head	up to 300 50 to 150 30 to 60	80 to 150 150 to 250 250 to 400	0.6 0.9 to	93	Full load efficiency high; partload efficiency lower than Pelton wheel.
3.	*Propeller and Kaplan*	4 to 60	300 to 1000	1.4 to 2	93	High part load efficiency; high discharge with low head.
4.	*Bulb or tubular turbines*	3 to 10	1000 to 1200	6 to 8	91	Employed for very low head– *tidal power plants.*

Overall efficiency (η_0) of all turbines ≃ 85 per cent.

Difference between Thermal Power Plant and Hydroelectric Power Plant

Basis of Difference	Thermal Power Plant	Hydroelectric Power Plant
Definition	A power generating station which converts the heat energy of burning of fossil fuels such as coal into electrical energy is known as thermal power plant.	A power generating station which converts the potential energy of water stored at a height into electrical energy is known as hydroelectric power plant.
Fuel or source of energy	Thermal power plant uses fossil fuels (mainly coal) to produce heat for the operation.	Hydroelectric power plant uses water as the source of energy.
Turbine	Steam turbines are used to drive the alternator in a thermal power station.	Water turbines are used to drive the alternators in a hydro power plant.

Difference between Thermal Power Plant and Hydroelectric Power Plant

Basis of Difference	Thermal Power Plant	Hydroelectric Power Plant
Types of turbines	Two types of steam turbines viz. ‘impulse turbine’ and ‘reaction turbine’ are used in thermal power stations.	In hydro power plant, three types of water turbines, i.e. Pelton wheel turbine, Francis turbine and Kaplan turbine, are used.
Production of steam	Steam is produced in a thermal power plant.	In hydroelectric power, there is no need of conversion of water into steam.
Type of source of energy	Thermal power plant uses non-renewable sources of energy such as fossil fuels (coal, etc.) for generating electricity.	Hydroelectric power plant uses renewable source of energy (water) for electricity generation.

Difference between Thermal Power Plant and Hydroelectric Power Plant

Basis of Difference	Thermal Power Plant	Hydroelectric Power Plant
Plant site	Thermal power plants are setup at a place where ample supply of water and coal is available and the transportation facilities are adequate.	Hydroelectric power plants are setup where large reservoirs of water can be obtained by constructing a dam such as in hill areas.
Initial cost	The initial cost of a thermal power plant is relatively low.	Due to construction of dam and excavation work, the initial cost of hydroelectric power station is comparatively high.

Difference between Thermal Power Plant and Hydroelectric Power Plant

Operating cost	The operating cost of thermal power plant is high because of the need of large amount of coal.	Since no fuel is required, therefore the operating cost of hydroelectric power plant is low.
Maintenance cost	The maintenance cost of thermal power plant is high.	Hydroelectric power plant involves very low maintenance cost

Difference between Thermal Power Plant and Hydroelectric Power Plant

Basis of Difference	Thermal Power Plant	Hydroelectric Power Plant
Starting time	Thermal power station needs long time for starting	Hydroelectric power plants can be started instantly.
Standby losses	Thermal power plant has high standby losses because the boiler remains in operation even when turbine is not working.	There is no standby losses in case of hydro power plant.
Efficiency	Thermal power plants are less efficient. The overall efficiency of a typical thermal power plant is about 25%.	The efficiency of hydro power plant is very. For a typical hydro power plant, the overall efficiency is about 85%.

Difference between Thermal Power Plant and Hydroelectric Power Plant

Basis of Difference	Thermal Power Plant	Hydroelectric Power Plant
Transmission cost	The cost of transmission is low because these are located comparatively near the load centers.	As hydro power plants located quite away from the load centers, therefore, the transmission cost is high.
Life span	The life span of thermal power plants is smaller.	Hydro power plants have longer life span.

Difference between Thermal Power Plant and Hydroelectric Power Plant

Basis of Difference	Thermal Power Plant	Hydroelectric Power Plant
Size of plant	The size of the thermal power plant is smaller.	Hydro plants require large area for reservoir. Hence their size is large.
Cleanliness	In thermal power plant, ash, smoke, etc. produce, hence these are less clean.	The hydroelectric power plants are the most clean power generation stations.
Impact on environment	Thermal power plants pollute the environment due to smoke.	Hydro plants also have some impacts on the environment such as the blocking of water affect fishes and other organisms in the water body.