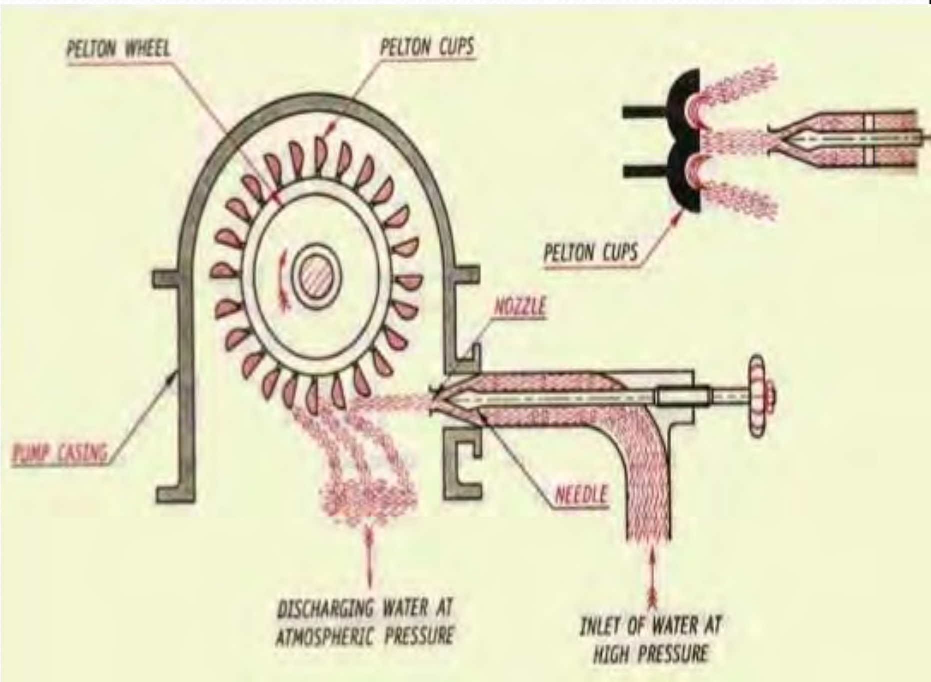
Hydraulic Machines

Raman Gahlaut
(Assistant Professor)
Mechanical Engineering Department
Shobhit Institute of Engineering & Technology
(Deemed to be University) MEERUT - 250110

Introduction

- Hydraulic turbines may be defined as prime movers that transform the kinetic energy of the falling water into mechanical energy of rotation and whose primary function is to drive a electric generator.
- A cubic meter of water can give about 9800 Joules of mechanical energy for every meter it descends and a flow of a cubic meter per second in a fall of 1 meter can provide 9800 W of power
- Hydro-power is essentially a controlled method of water descent usefully utilised to generate power.



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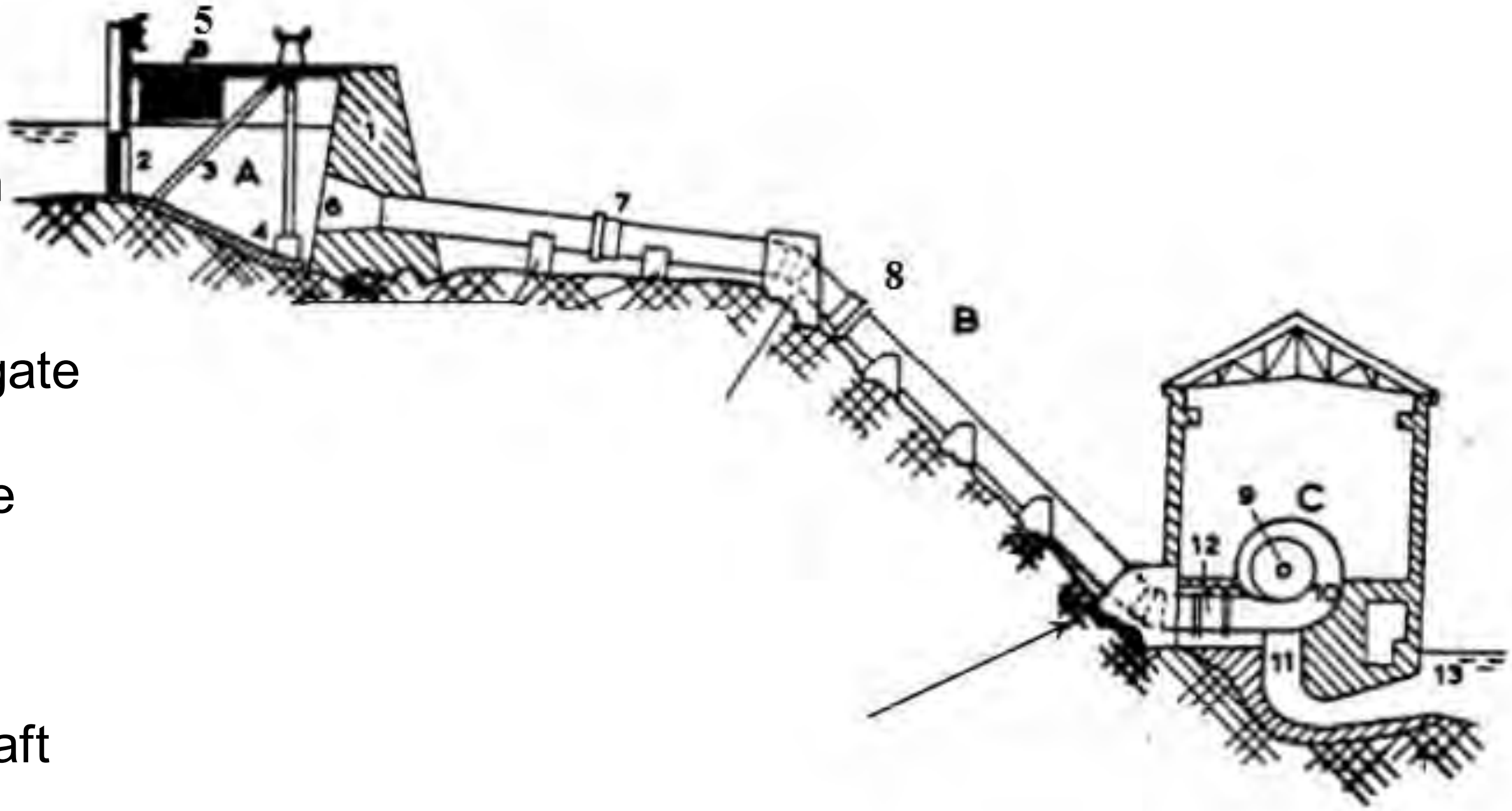
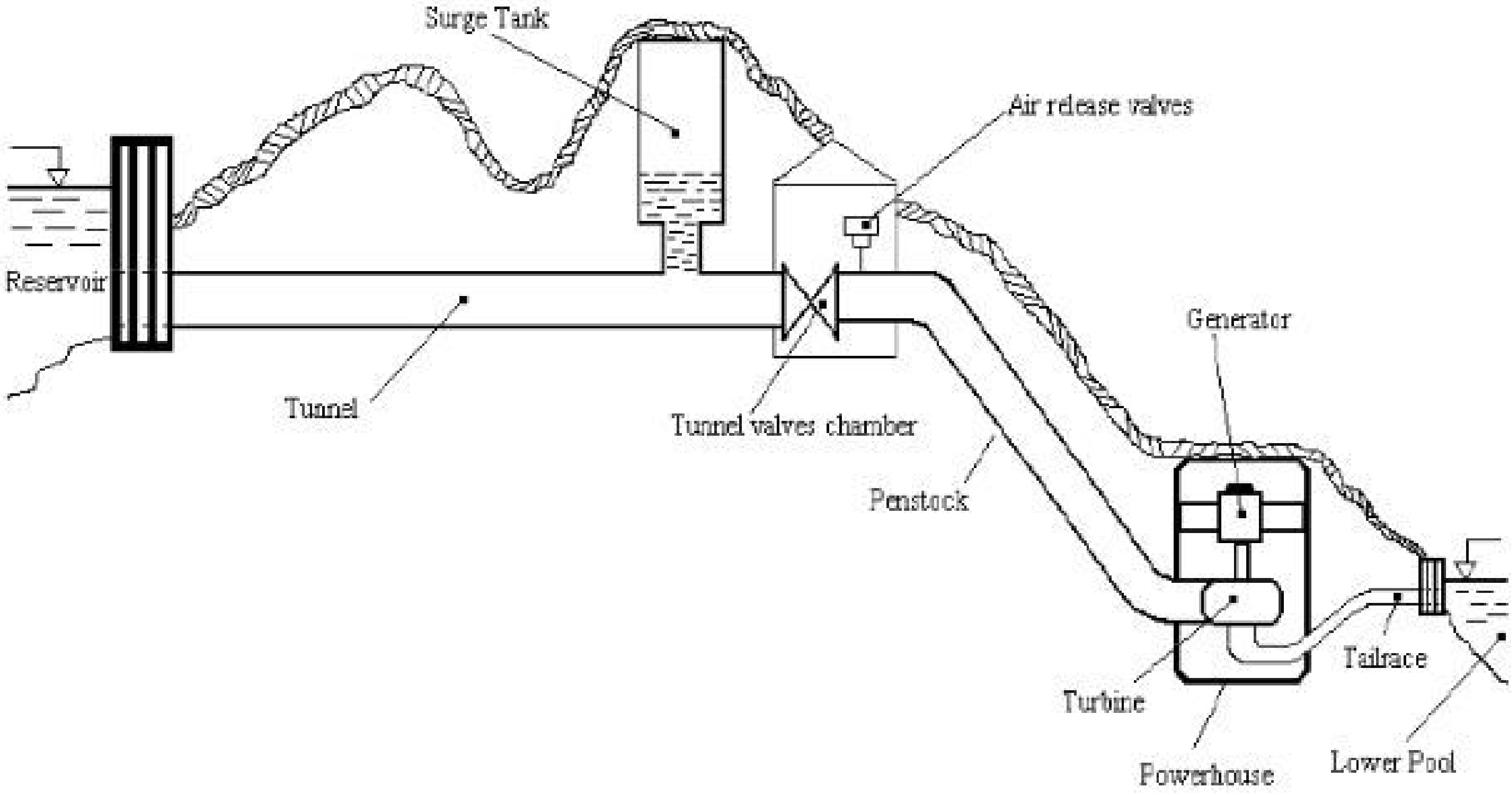
- Hydroelectric plants utilize the energy of water falling through a head that may vary from a few meters to ~1500 or even 2000 m. To manage this wide range of heads, many different kinds of turbines are employed, which differ in their working components.
- The main components of a hydroelectric system may be classified into two groups: groups:–
  1. The hydraulic system components that include the turbine, the associated conduits-like penstocks, tunnel and surge tank-and its control system, and
  2. The electric system components formed by the synchronous generator and its control system.

Layout of a Hydro-Electric Power Plant

1.Intake dam
2.Gate
3.Trash rack
4.Emptying gate
5Ice gate
6.Intake cone
7.Expansion stuffing box
8 Penstock
9.Turbine shaft
10. Turbine
11. Draft tube.
12.Closing valve
13. Tale race canal



Layout of a Hydro-Electric Power Plant



Schematic layout of a hydro-electric plant with surge tank

Necessity of Surge Tank

- The performance of hydraulic turbines is strongly influenced by the characteristics of water conduit that feeds the turbine. These characteristics include the effect of water inertia, water compressibility and pipe wall elasticity in the penstock.
- Hydroelectric turbines present non-minimal phase characteristics due to water inertia; this means that a change in the gate produces an initial change in mechanical power, which is opposite to the one requested.
- The water compressibility effect produces traveling waves of pressure and is usually called water hammer.
- The water hammer is characterized by a sudden high pressure rise caused by stopping the flow too rapidly. The wave propagation speed is around 1200 m/s.
- In those plants where distance between the forebay or reservoir and the turbine is quite large a surge tank is usually utilized is quite large, a surge tank is usually utilized.
- The function of this tank is to hydraulically isolate the turbine from deviations in the head produced by the wave effects in the conduits
- Some surge tanks include an orifice whose function is to dampen and absorb the energy of the hydraulic oscillations.

History of Hydraulic Turbines

- Water wheels – China and Egypt – thousands of years ago.
- Reaction runner – J A Segnar – 1950.
- Euler turbine theory – Leonard Euler – valid till today
- Turbine is a designation that was introduced in 1824 in a dissertation of the French engineer Burdin.
- Fourneyron designed a radial turbine and put to operation the first real turbine in 1827 – power 20-30kW and runner diameter of 500 mm
- Henschel and Jonval in 1840 independently developed turbine with axial water flow through it. They were the first ones to apply draft tube and in that way to utilize the water head between runner outlet and tail water level.
- Francis in 1849 developed the radial turbine, named Francis turbine.
- In 1870 professor Fink introduced an important improvement in Francis turbine by making the guide vanes turning on a pivot in order to regulate the flow discharge.
- In 1890 American engineer Pelton developed impulse turbine, named Pelton turbine
- In 1913 Kaplan designed a propeller turbine, named Kaplan turbine
- Subsequent developments were made on Francis, Pelton and Kaplan turbines.

Classification of Hydraulic Turbines

- Hydraulic turbines are generally classified as:

1. Impulse Turbine: Pelton, Turgo turbine
2. Reaction Turbine – Francis, Kaplan and Propeller turbine

- Based on flow direction, they are further classified as:

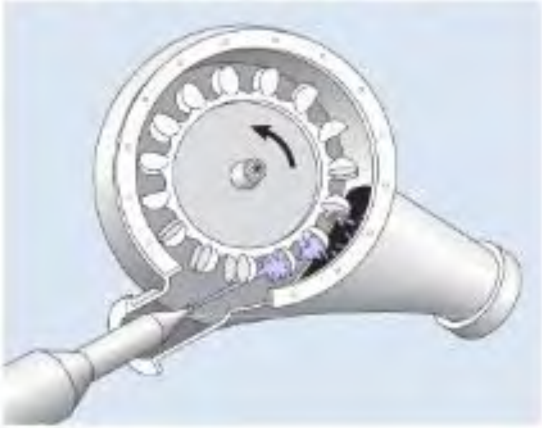
1. Tangential Flow
2. Radial Flow
3. Axial Flow
4. Mixed Flow

Impulse and Reaction Turbines

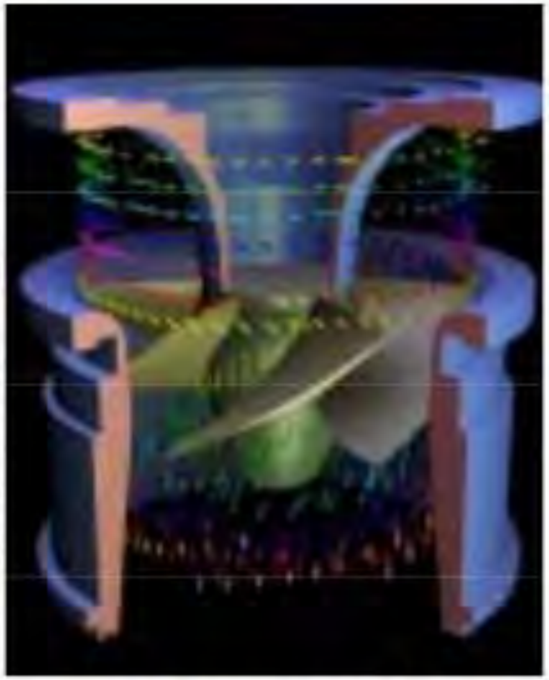
- The flow energy to the impulse turbines is completely converted to kinetic energy before transformation in the runner.
- The impulse forces being transferred by the direction changes of the flow velocity vectors when passing the buckets create the energy converted to mechanical energy on the turbine shaft.
- The flow enters the runner from jets spaced around the rim of the runners. The jet hits momentarily only a part of the circumference of the runner.
- In the reaction turbines two effects cause the energy transfer from the flow to the mechanical energy on the turbine shaft:
  - ➢ Firstly, it follows from a drop in pressure from inlet to outlet of the runner. This is denoted as the reaction part of the energy conversion.
  - ➢ Secondly the changes in the directions of the flow velocity vectors through the runner blade channels transfer impulse forces. This is denoted as the impulse part of the energy conversion.
  - The pressure drop from inlet to outlet off the runners is obtained because the runners are completely filled with water.

Some Hydraulic Turbines

Pelton turbine



Francis Turbine



Kaplan turbine

Introduction of Pelton Turbine

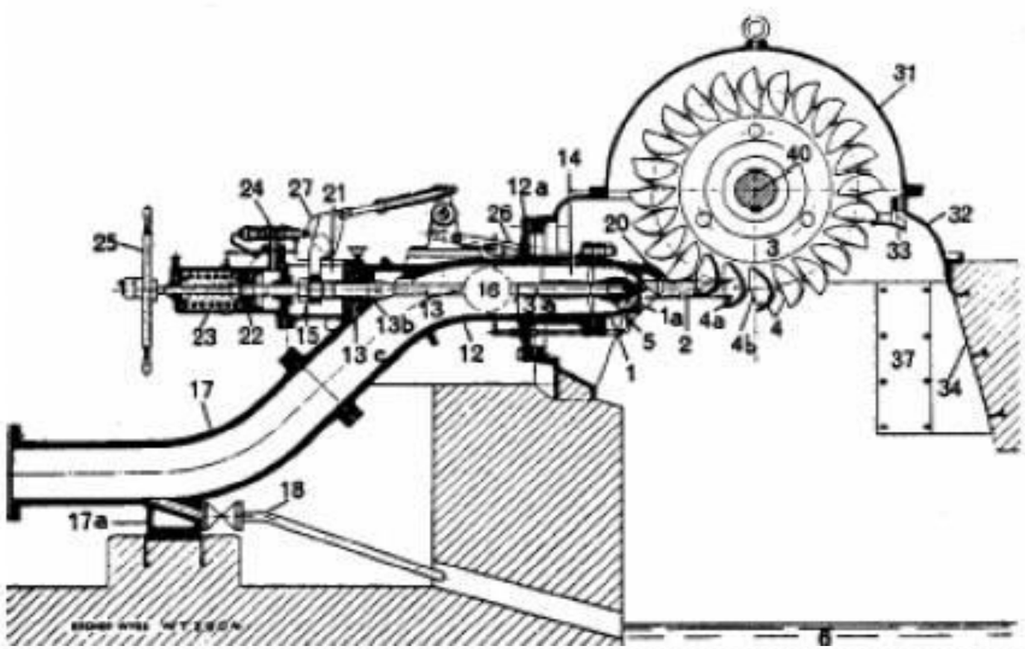
- Invented by Pelton in 1890.
- The Pelton turbine is a tangential flow impulse turbine.
- The Pelton wheel is most efficient in high head applications.
- Power plants with net heads ranging from 200 to 1,500 m.
- The largest units can be up to 200 Megawatts.
- Pelton turbines are best suited for high head and low flow sites.
- Depending on water flow and design, Pelton wheels can operate with heads as small as 15 meters and as high as 1800 meters.
- As the height of fall increases, less volume of water can generate same power.

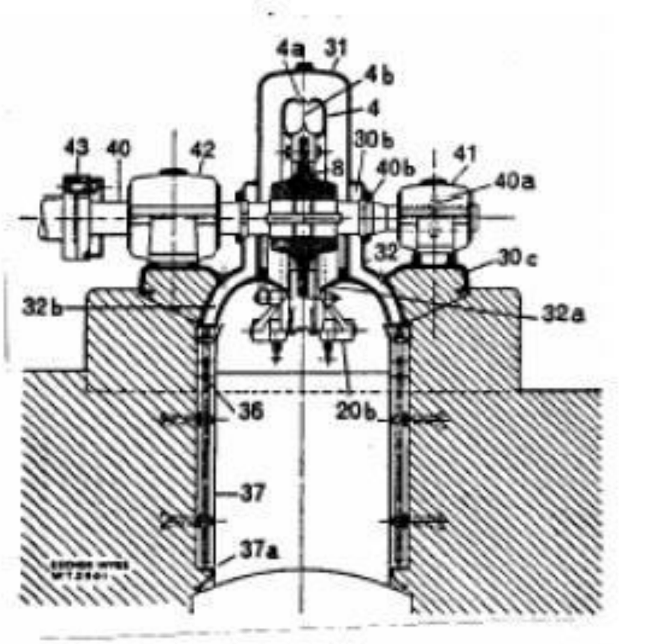
Pelton Turbine

Pelton Turbine is a Tangential flow impulse turbine in which the pressure energy of water is converted into kinetic energy to form high speed water jet and this jet strikes the wheel tangentially to make it rotate. It is also called as Pelton Wheel.

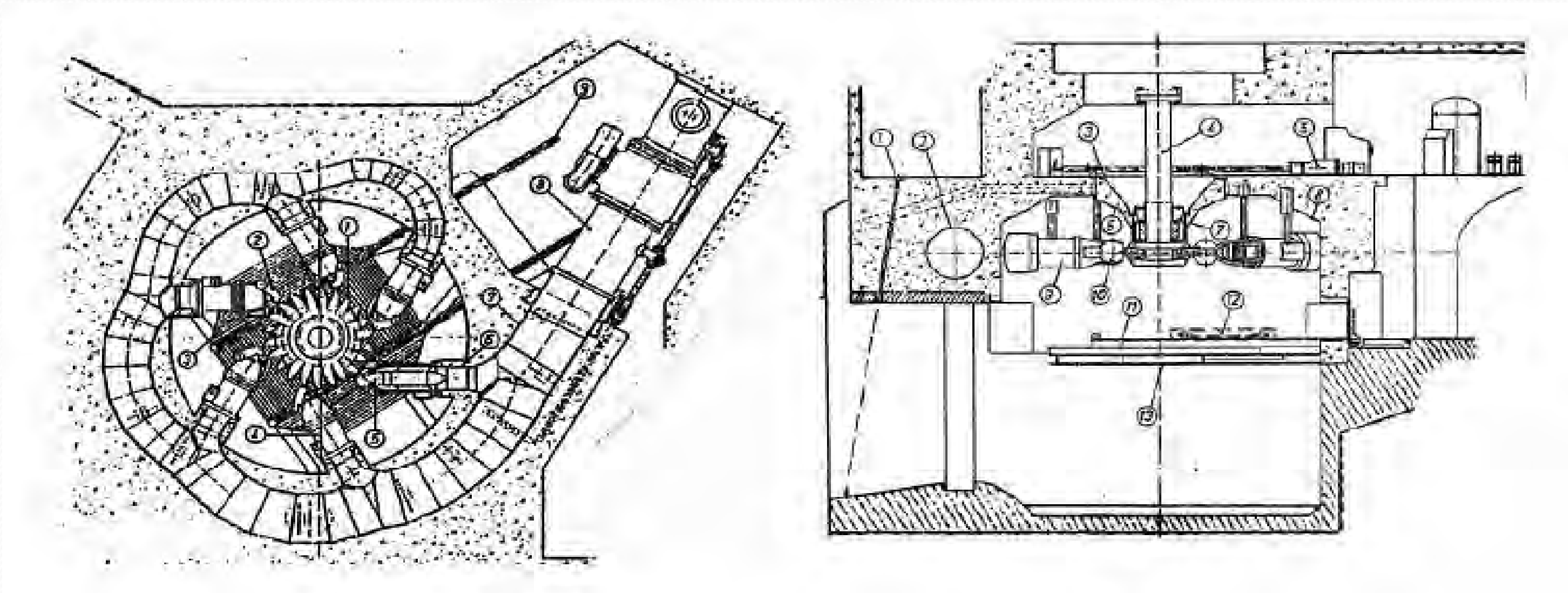
Horizontal Arrangement of a Pelton Turbine

Horizontal arrangement is found only in medium and small sized turbines with usually one or two jets. In some designs, up to four jets have been used. The flow passes through the inlet bend to the nozzle outlet, where it flows out as a compact jet through atmospheric air on to wheel buckets. From the outlet the buckets the water falls through the pit down into the tail water canal.



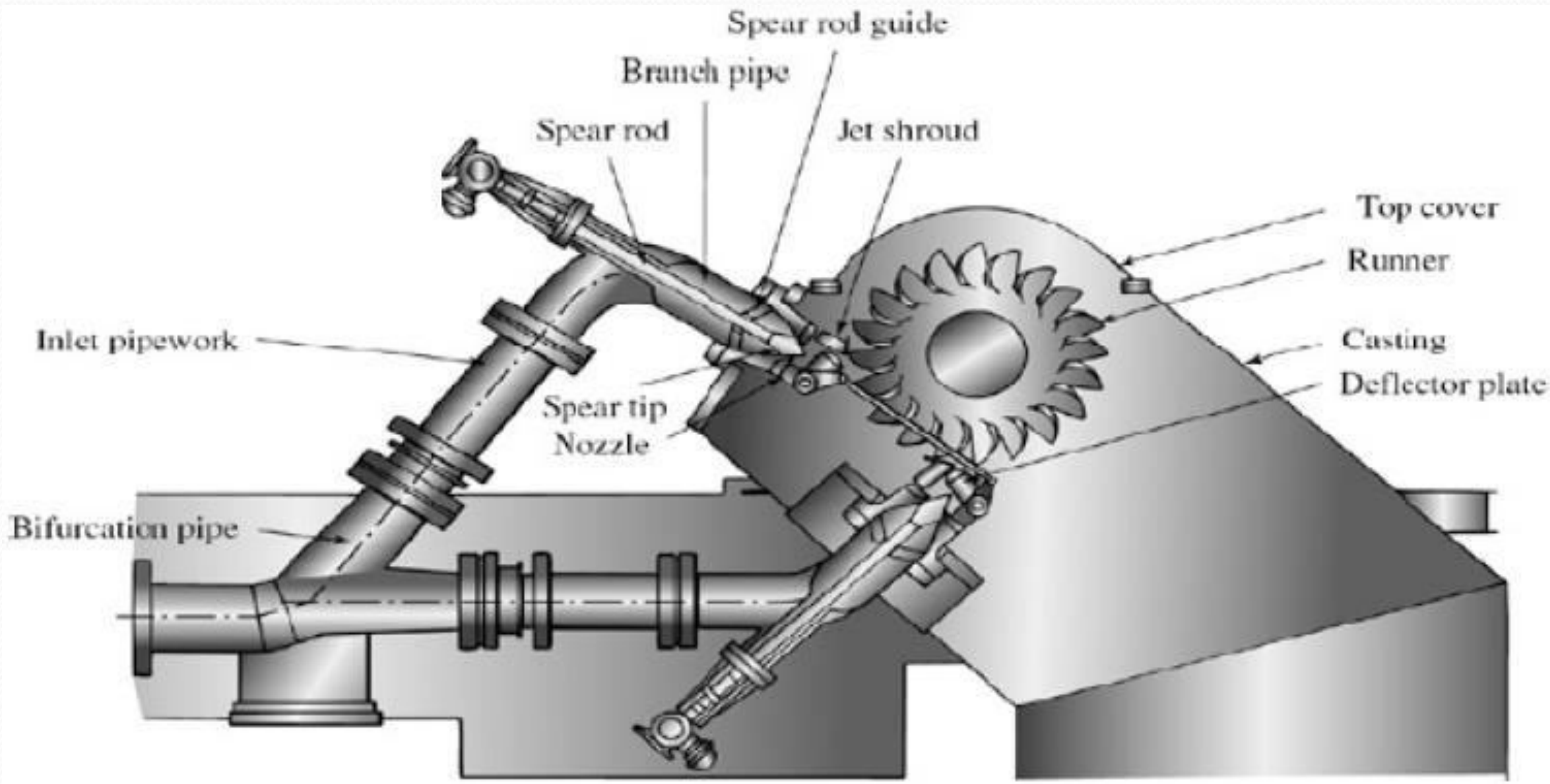


Vertical Arrangement of a Pelton Turbine



Large Pelton turbines with many jets are normally arranged with vertical shaft. The jets are symmetrically distributed around the runner to balance the jet forces. The figure shows the vertical and horizontal sections of the arrangement of a six jet vertical Pelton turbine.

Parts of a Pelton Turbine



Parts of a Pelton Turbine

- The Pelton runners may be designed either by casting of the disc and buckets in one piece, i.e. monocast, or the disc and each of the buckets are casted in separate pieces.
- The shape of the buckets is decisive for the efficiency of the turbines. Limitations however are that bucket shape always will be a compromise between a hydraulically ideal and a structural optimum design.
- The runner disc is fastened to the shaft by bolts and nuts.
- The turbine shaft of vertical Pelton turbines is made of forged steel with an integral flange at both ends. A hole is drilled centrally through the whole length of the shaft. An oil reservoir is a rotating member bolted to the shaft flange.
- Journal and thrust bearings are provided with circulating oil to carry the heat dissipated by the shaft and bearings.
- The distributor pipe is designed to provide an acceleration of the water flow through the bifurcation towards each of the main injectors. This design is advantageous, because it by contributes in keeping a uniform velocity profile of the flow.
- The injector is operated hydraulically by servo motors.

Working of Pelton Turbine

- The water is transferred from the high head source through a long conduit called Penstock.
- Nozzle arrangement at the end of penstock helps the water to accelerate and it flows out as a high speed jet with high velocity and discharge at atmospheric pressure.
- The jet will hit the splitter of the buckets which will distribute the jet into two halves of bucket and the wheel starts revolving.
- The kinetic energy of the jet is reduced when it hits the bucket and also due to spherical shape of buckets the directed jet will change its direction and takes U-turn and falls into tail race.
- In general, the inlet angle of jet is in between 1^o to 3^o, after hitting the buckets the deflected jet angle is in between 165^o to 170^o.
- The water collected in tail race should not submerge the Pelton wheel in any case.
- To generate more power, two Pelton wheels can be arranged to a single shaft or two water jets can be directed at a time to a single Pelton wheel.

Material of Pelton Turbine

- Case : fabricated carbon steel to BS EN 10025:1993 S275JR
- Runner: : cast Stainless BS3100 Grade 425 C11
- Shaft seal: : cast gunmetal labyrinth type seal
- Bearings: : rolling element or sleeve type
- Spear / : stainless steel internal components housed in a carbon
- Needle valve :steel fabricated or cast branch pipe
- Deflector : stainless steel plate

The material of the runner and buckets are chosen according to the head, stresses, content of sand in the water and other strain factors. For the large turbines the main strain factors are cavitation, sand erosion and cycle fatigue.

Design aspects of Pelton Turbine

Following are the aspects to be considered while designing the Pelton wheel turbine.

1. Velocity of jet
2. Velocity of wheel
3. Angle of deflection of jet
4. Mean diameter of the wheel
5. Jet ratio
6. Bucket dimensions
7. Number of jets
8. Number of buckets

Cont…

1. Velocity of Jet:

The velocity of the jet at inlet is given by

$$V_1 = C_v \sqrt{2gH}$$

Where Cv = co-efficient of velocity =0.98 or 0.99.

H= Net head on turbine

2. Velocity of Wheel:

The velocity of wheel (u) is given by

$$u = \phi \sqrt{2gH}$$

Where, = speed ratio ϕ = 0.43 to 0.48

3. Angle of Deflection of Jet:

The angle of deflection of jet after striking the buckets is taken as 165^o if no deflection angle is given

Cont…

4. **Mean Diameter of The Wheel:**

The mean diameter or the pitch diameter D of the pelton turbine is given by

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

5. **Jet Ratio:**

It is defined as the ratio of the pitch diameter (D) of the pelton turbine to the diameter of the jet (d). It is denoted by m and is given as

$$\mathbf{m = D/d}$$

Jet ratio(m) is lies between 11 to 16 for maximum hydraulic efficiency. however, In most of the cases it is taken as 12.

6. **Bucket Dimensions:**

Buckets dimensions are designed in such a way that its breadth should be 3 to 4 times of diameter of jet, length should be 2 to 3 times of diameter of jet and thickness should be 0.8 to 1.2 times the diameter of jet.

Cont…

7. Number of Jets:

It is obtained by dividing the total rate of flow through the turbine by the rate of flow of water through a single jet.

In general, Number of jets are limited to two in case of vertical runner and six in case of horizontal runner.

8. Number of Buckets:

The number of buckets (z) on a runner is given by

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

Where, D = Pitch diameter

d = Diameter of Jet

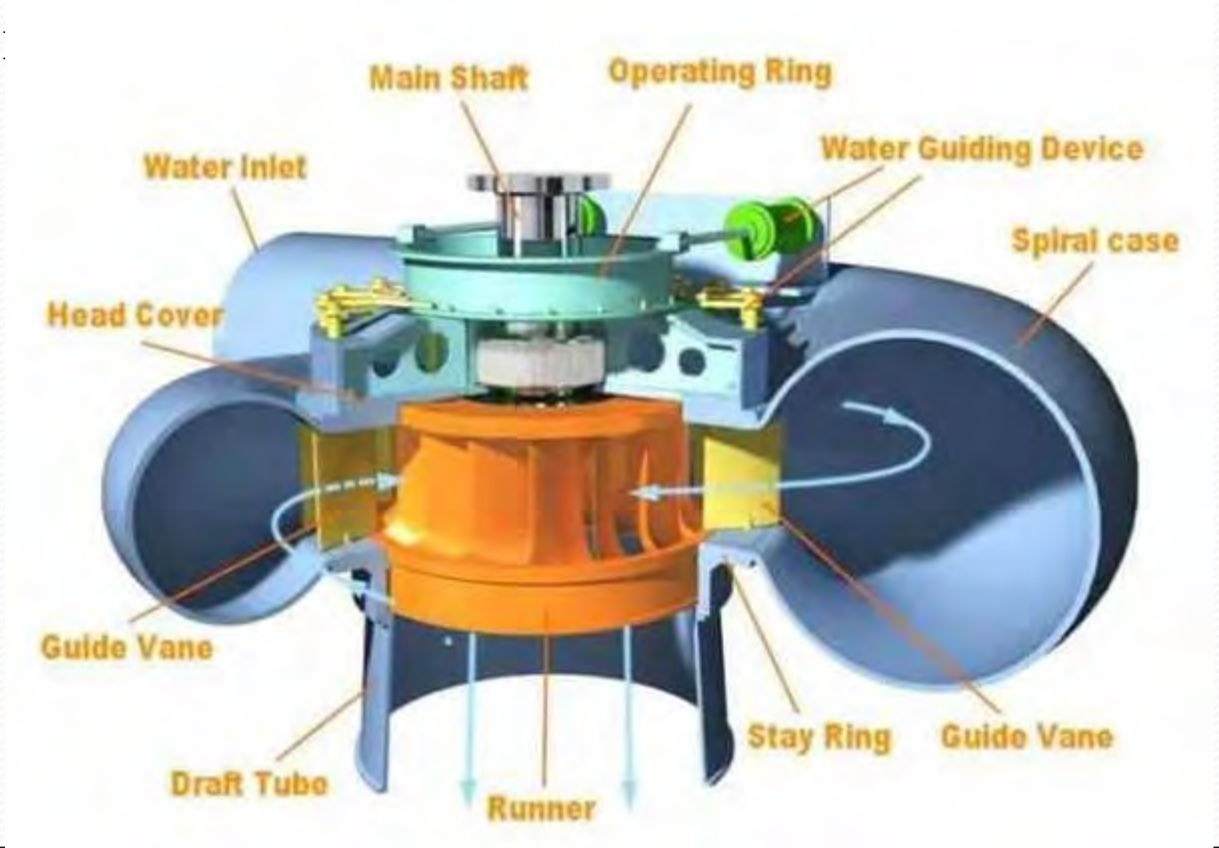
m = jet ratio

Introduction of Francis Turbine

- Francis Turbine is a combination of both impulse and reaction turbine, where the blades rotate using both reaction and impulse force of water flowing through them producing electricity more efficiently. Francis turbine is used for the production of electricity in hydro power stations.
- Majorly there are 2 turbines flow patterns on which they work, namely radial and axial flow concepts. An American civil engineer by name, James B. Francis in Lowell, Massachusetts comes up with an idea of combining both impulse and reaction turbine where water enters the turbine radically and exits axially

Francis Turbine

The main reason of higher efficiency of Francis turbine lies in the design of blades, these blades rotate using both reaction and impulse force of water flowing through them. Due the use of this type of turbines the main problem faced due to the water head availability is eliminated as the turbine uses both the kinetic and potential e



Main Components of Francis Turbine

1. **Spiral casing:**

   Spiral casing is the inlet medium of water to the turbine. The water flowing from the reservoir or dam is made to pass through this pipe with high pressure. The blades of the turbines are circularly placed, which mean the water striking the turbines blades should flow in the circular axis for efficient striking. So the spiral casing is used, but due to circular movement of the water, it looses its pressure.

   To maintain the same pressure the diameter of the casing is gradually reduced, so as to maintain the pressure uniform, thus uniform momentum or velocity striking the runner blades

2. **Stay Vanes:**

   Stay vanes and guide vanes guides the water to the runner blades. Stay vanes remain stationary at their position and reduces the swirling of water due to radial flow, as it enters the runner blades. Thus making turbine more efficient

Cont…

3. **Guide Vanes:**

   Guide vanes are not stationary, they change their angle as per the requirement to control the angle of striking of water to turbine blades to increase the efficiency. They also regulate the flow rate of water into the runner blades thus controlling the power output of a turbine according to the load on the turbine.

4. **Runner Blades:**

   The performance and efficiency of the turbine is dependent on the design of the runner blades. In a Francis turbine, runner blades are divided into 2 parts. The lower half is made in the shape of small bucket so that it uses the impulse action of water to rotate the turbine.

   The upper part of the blades use the reaction force of water flowing through it. These two forces together makes the runner to rotate

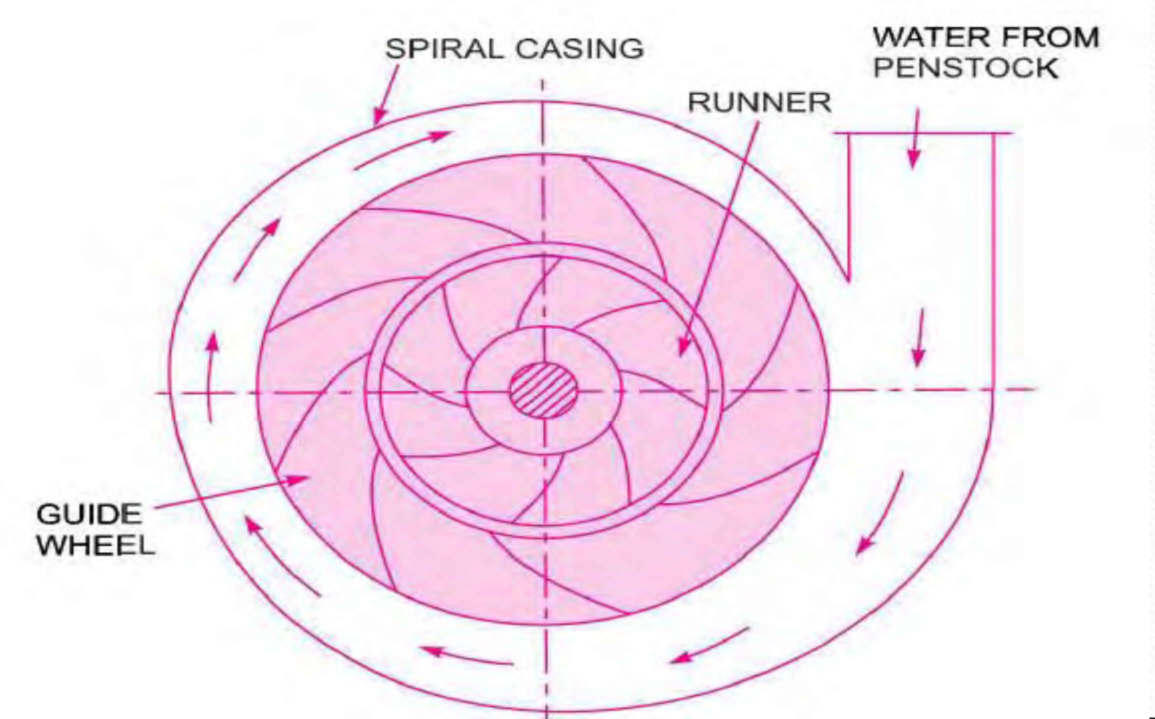
5. **Draft Tube:**

   The pressure at the exit of the runner of 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 turbine to the tail race.

   This tube of increasing area is called Draft Tube. One end of the tube is connected to the outlet of runner while the other end is sub-merged below the level of water in the tail-race.

Working Principle

Francis turbine blades are designed in such a way that one portion of the blade design creates the pressure difference between the opposite faces of the blade when water flows through it, and the remaining portion's blade design use the impulse force of water hitting it and this combined action of pressure difference and impulse force generates enough power to get turbine moving at a required speed. Thus there would be a decrease in both kinetic energy and potential energy of water at exit, then what it has when it enters the turbine.

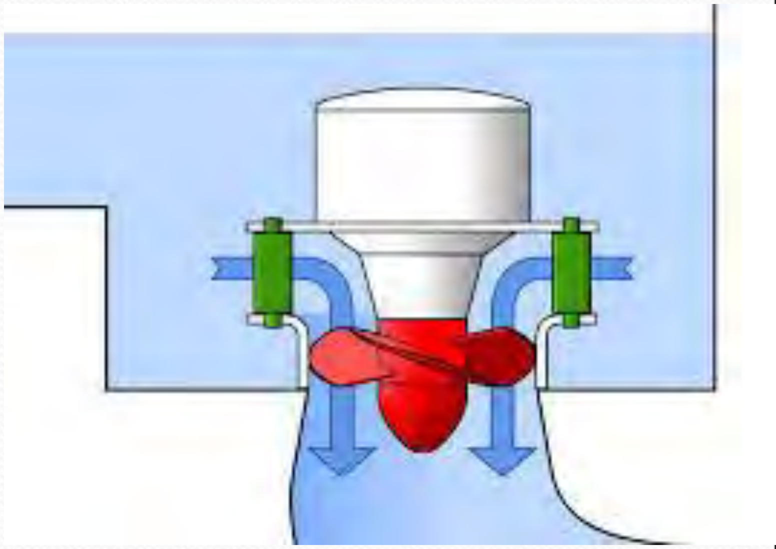


Applications of Francis Turbine

1. Francis turbine is the most widely used turbine in hydro-power plants to generate electricity.
2. Mixed flow turbine is also used in irrigation water pumping sets to pump water from ground for irrigation.
3. It is efficient over a wide range of water head and flow rate.
4. It is most efficient hydro-turbine we have till date

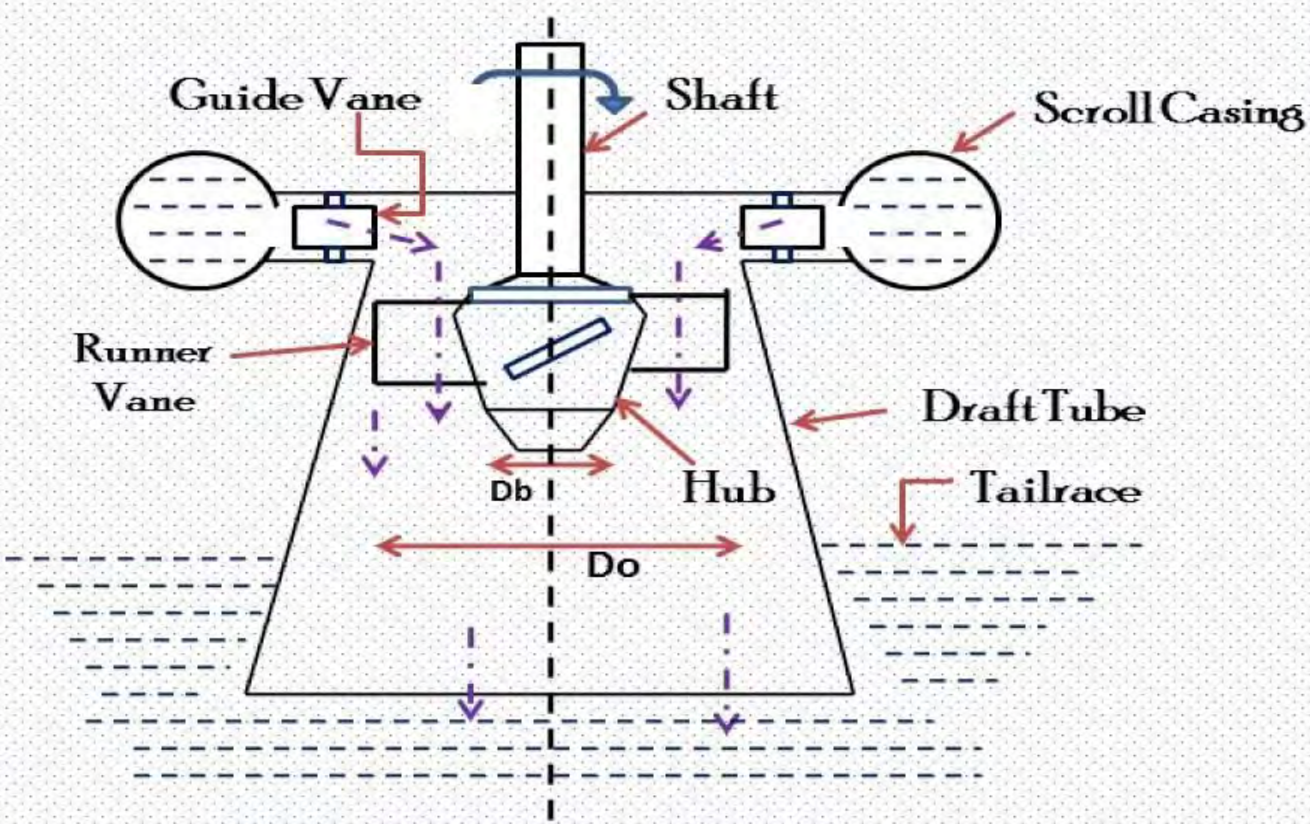
Kaplan Turbine

- Kaplan Turbine works on the principle of axial flow reaction. In axial flow turbines, the water flows through the runner along the direction parallel to the axis of rotation of the runner. The water at the inlet of the turbine possesses both kinetic energy as well as pressure energy for effective rotation the blades in a hydro-power station.



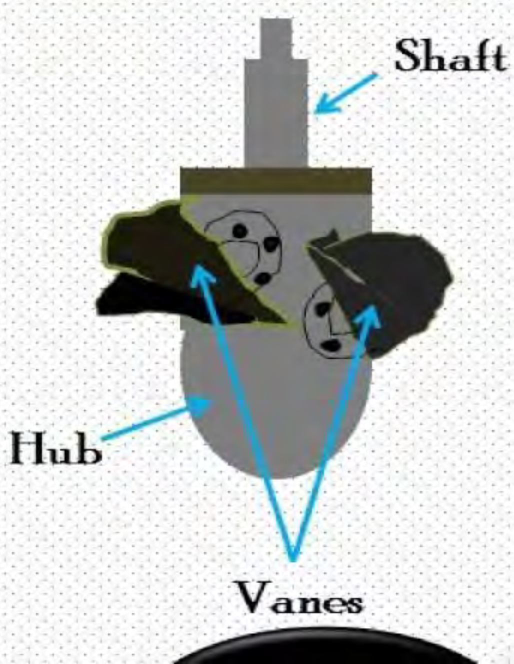
Kaplan Turbine

In 1913, an Austrian professor Viktor Kaplan who developed this tu combined automatically adjusted propeller blades with automatically adjusted wicket gates to achieve efficiency over a wide range of flow and water level. It is also called as propeller turbine and evolved from the Francis Turbine. It is capable of working at low head and high flow rates very efficiently which is impossible with Francis turbine



D_b – Diameter of Hub
D_o – Outer Diameter of Runner
V_{f1} – Velocity of flow at Inlet

$Q = \pi/4 * (D_o^2 - D_b^2) * V_{f1}$



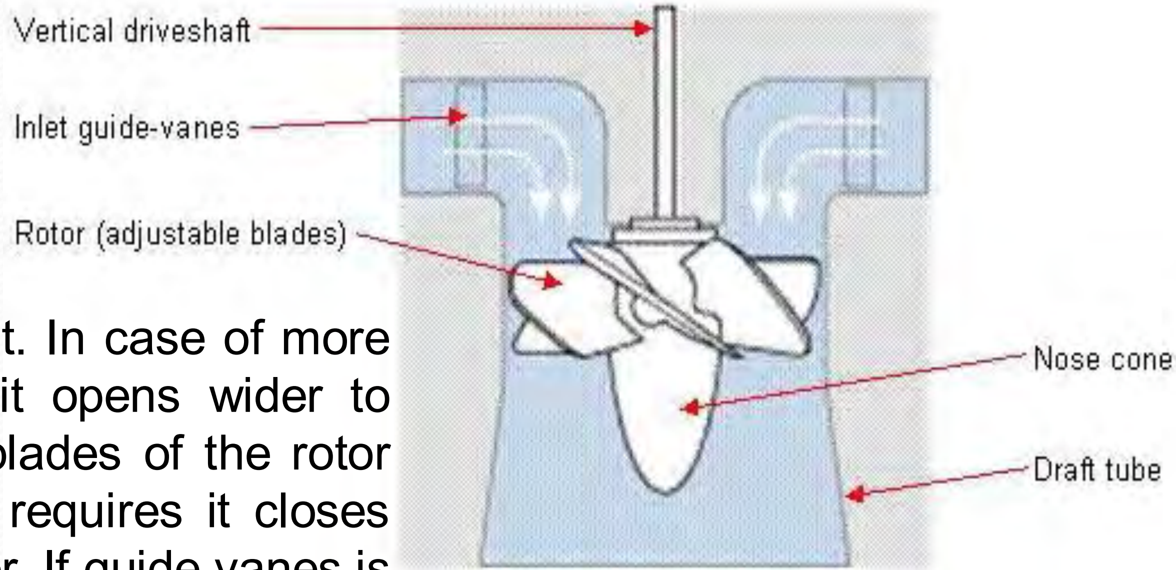
Main Components of Kaplan Turbine

1. **Scroll Casing:**

   It is a spiral type of casing that has decreasing cross section area. The water from the penstocks enters the scroll casing and then moves to the guide vanes where the water turns through 90° and flows axially through the runner. It protects the runner, runner blades guide vanes and other internal parts of the turbine from an external damage.

2. **Guide Vane Mechanism:**

   It is the only controlling part of the whole turbine, which opens and closes depending upon the demand of power requirement. In case of more power output requirements, it opens wider to allow more water to hit the blades of the rotor and when low power output requires it closes itself to cease the flow of water. If guide vanes is absent than the turbine can not work efficiently and its efficiency decreases.



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4. **Runner Blades :**

 The heart of the component in kaplan turbine are its runner blades, as it the rotating part which helps in production of electricity.Its shaft is connected to the shaft of the generator. The runner of the this turbine has a large boss on which its blades are attached and the the blades of the runner is adjustable to an optimum angle of attack for maximum power output. The blades of the Kaplan turbine has twist along its length.

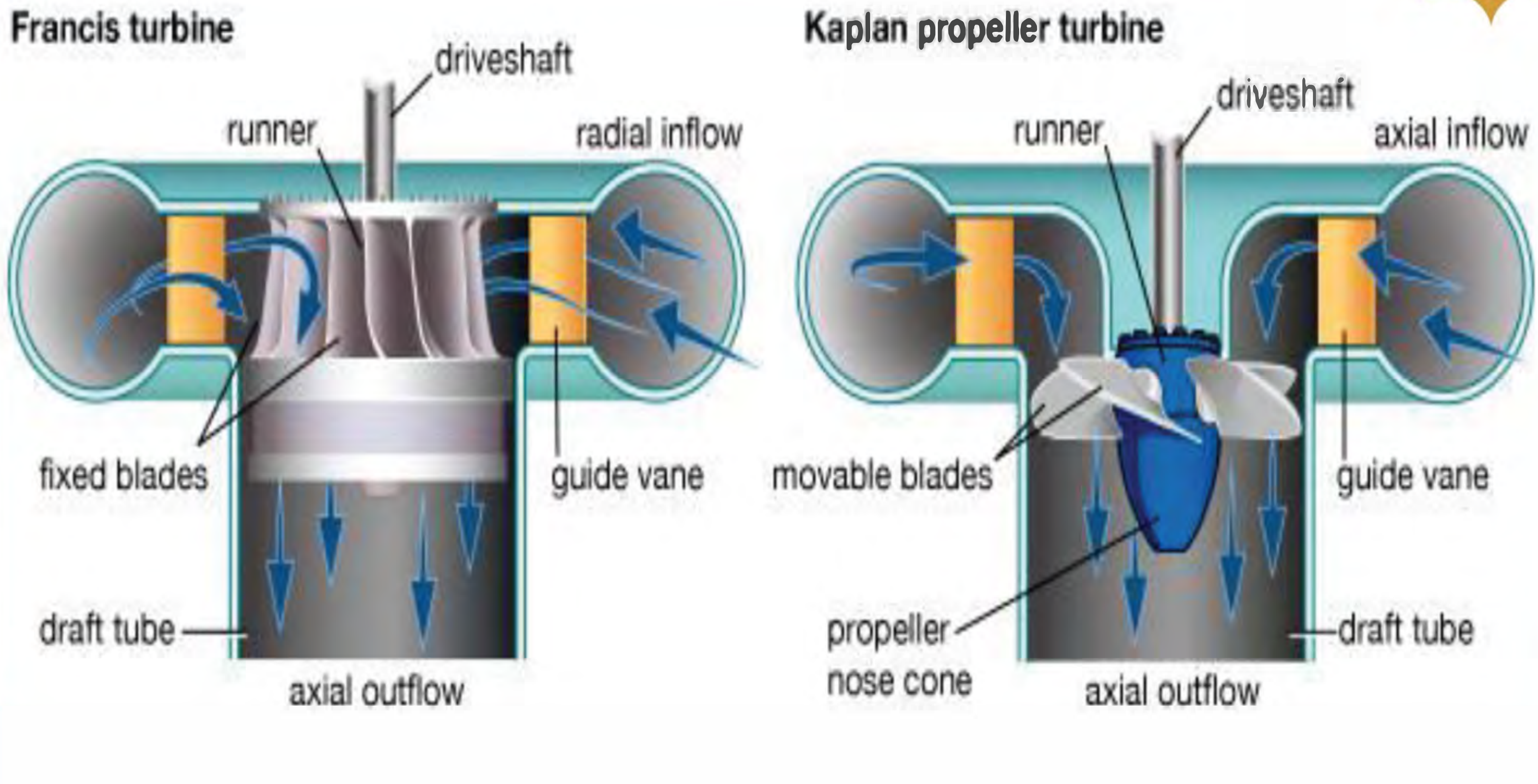
Working of Kaplan turbine

- The water coming from the pen-stock is made to enter the scroll casing. The scroll casing is made in the required shape that the flow pressure is not lost. The guide vanes direct the water to the runner blades. The vanes are adjustable and can adjust itself according to the requirement of flow rate. The water takes a 90 degree turn, so the direction of the water is axial to that of runner blades.
- The runner blades start to rotate as the water strikes due to reaction force of the water. The runner blades has twist along its length in order to have always optimum angle of attack for all cross section of blades to achieve greater efficiency.
- From the runner blades, the water enters into the draft tube where its pressure energy and kinetic energy decreases. Kinetic energy is gets converted into pressure energy results in increased pressure of the water.
- The rotation of the turbine is used to rotate the shaft of generator for electricity production.

Advantages

- Kaplan turbines are widely used throughout the world for electrical power production.
- It can work more efficiently at low water head and high flow rates as compared with other types of turbines.
- It is smaller in size and easy to construct.
- The efficiency of Kaplan turbine is very high as compares with other hydraulic turbine.

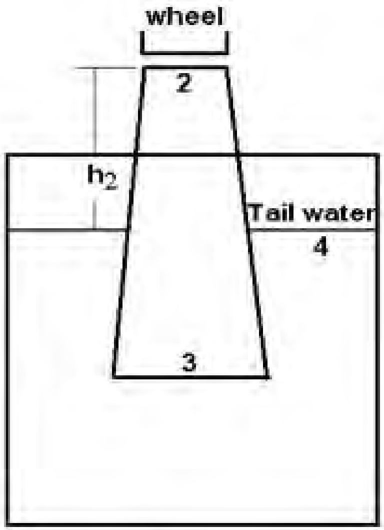
Disadvantages: The only disadvantage of kaplan turbine is cavitation, which occurs due to pressure drop in draft tube. Use of draft tube and proper material generally stainless steel for the runner blades may reduce the cavitation problem to a greater extent.


Francis turbine
driveshaft
runner
radial inflow
fixed blades
guide vane
draft tube
axial outflow
Kaplan propeller turbine
driveshaft
runner
axial inflow
movable blades
guide vane
propeller
nose cone
draft tube
axial outflow

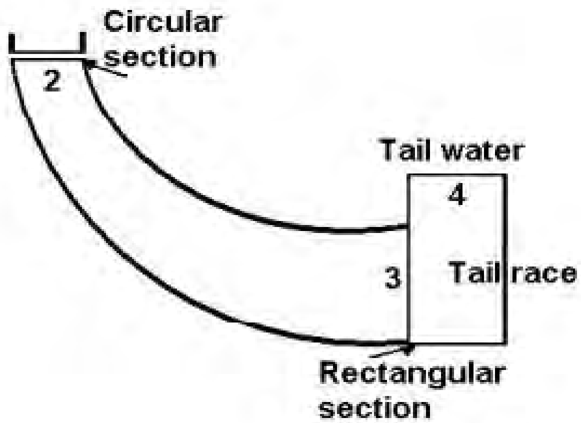
Draft Tube

- In a reaction turbine, water leaves the runner with remaining kinetic energy. To recover as much of this energy as possible, the runner outlet is connected to a diffuser, called draft tube. The draft tube converts the dynamic pressure (kinetic energy) into static pressure dynamic pressure (kinetic energy) into static pressure.
- Draft tube permits a suction head to be established at the runner exit, thus making it possible for placing the wheel and connecting machinery at a level above that of water in the tail race under high water flow conditions of river, without loss of head.
- To operate properly, reaction turbines must have a submerged discharge.
- The water after passing through the runner enters the draft tube, which directs the water to the point of discharge.
- The aim of the draft tube is also to convert the main part of the kinetic energy at the runner outlet to pressure energy at the draft tube outlet.
- This is achieved by increasing the cross section area of the draft tube in the flow direction.
- In an intermediate part of the bend, however, the draft tube cross sections are decreased in the flow direction to prevent separation and loss of efficiency.

Types of Draft Tube



(a)



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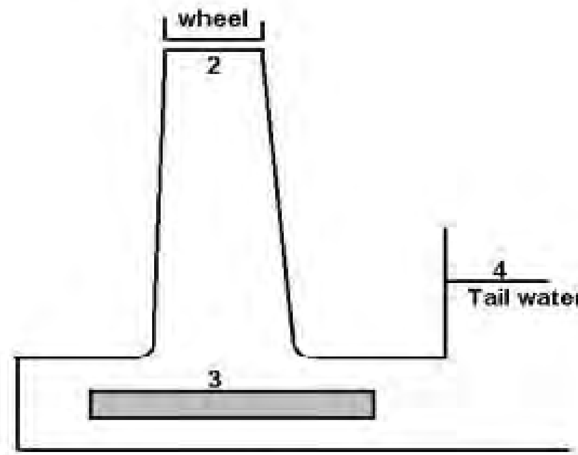

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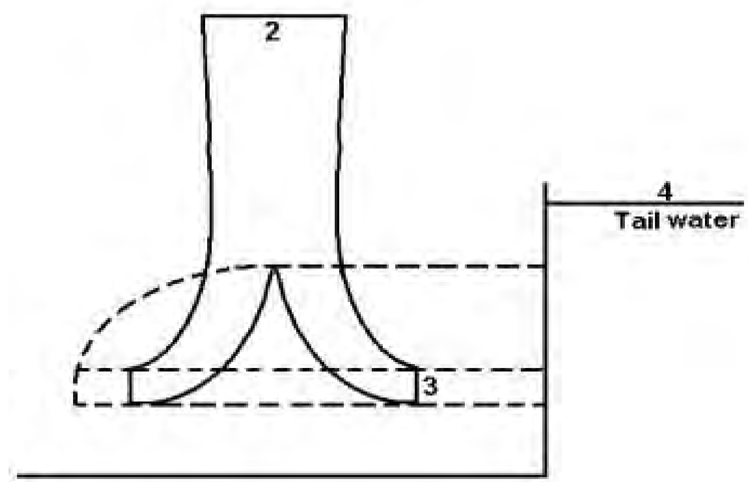


(a) Conical type

(b) Elbow type

(c) Hydraucone type

(d) Moody spreading type

Cavitation in Turbines

- Cavitation is a term used to describe a process, which includes nucleation, growth and implosion of vapour or gas filled cavities. These cavities are formed into a liquid when the static pressure of the liquid for one reason or another is reduced below its vapour pressure at the prevailing temperature. When cavities are carried to high-pressure region, they implode violently.
- Cavitation is an undesirable effect that results in pitting, mechanical vibration and loss of efficiency. and loss of efficiency.
- If the nozzle and buckets are not properly shaped in impulse turbines, flow separation from the boundaries may occur at some operating conditions that may cause regions of low pressure and result in cavitation.
- The turbine parts exposed to cavitation are the runners, draft tube cones for the Francis and Kaplan turbines and the needles, nozzles and the runner buckets of the Pelton turbines.
- Measures for combating erosion an d damage under cavitation conditions include improvements in hydraulic design and production of components with erosion resistant materials and arrangement of the turbines for operations within good range of acceptable cavitation conditions.

Cavitation in Turbines

Traveling bubble cavitation in Francis turbine

Leading edge cavitation damage in Francis turbine

Inlet edge cavitation in Francis turbine

Efficiencies of Hydraulic Turbines

Efficiencies:

Various efficiencies of hydraulic turbines are:

- Hydraulic efficiency
- Volumetric efficiency
- Mechanical Efficiency
- Overall Efficiency

Efficiency in general is defined as the ratio of power delivered to the shaft (brake Power) to the power taken from water.

Hydraulic efficiency : It is the ratio of the power developed by the runner to the water power available at the inlet of turbine.

Total available power of a plant is given by

$$P_{available} = \rho Q g H_n$$

Power transfer from the fluid to the turbine runner is given by

$$P_{shaft} = \rho Q (U_1 V_{u1} - U_2 V_{u2})$$

Efficiencies of Hydraulic Turbines

The ratio of these two powers is given by

$$\eta_{hydraulic} = \frac{Power_{shaft}}{Power_{available}}$$

$$\eta_{hydraulic} = \frac{\rho Q(U_1 V_{u1} - U_2 V_{u2})}{\rho Q g H_n}$$

$$\eta_{hydraulic} = \frac{(U_1 V_{u1} - U_2 V_{u2})}{g H_n}$$

The rearrangement of this equation gives the main turbine equation

$$\eta_{hydraulic} H_n = \frac{(U_1 V_{u1} - U_2 V_{u2})}{g}$$

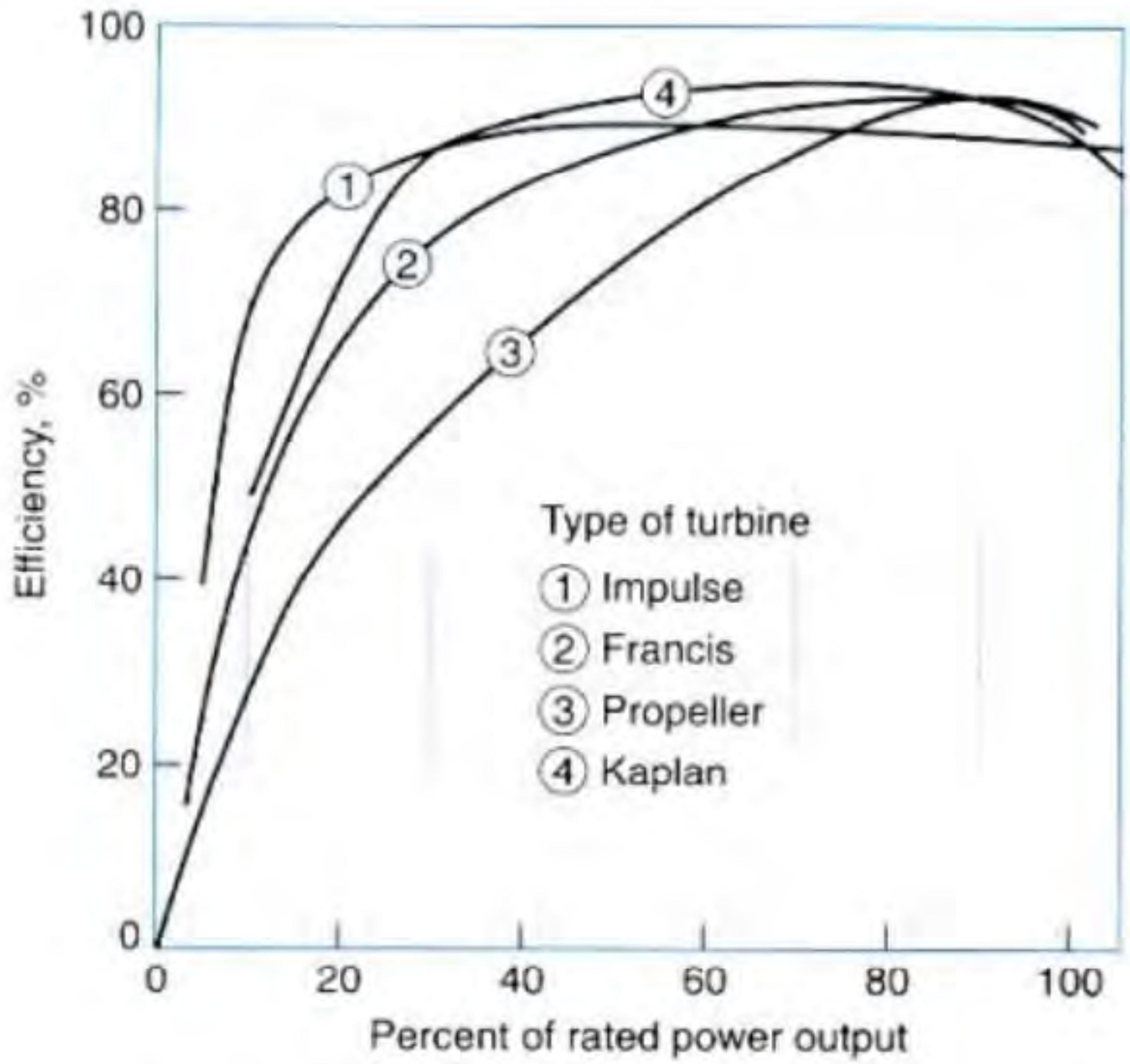
Specific Speed

- 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.
- This is the speed at which the runner of a particular diameter will develop l kW (1 hp) power under l m (1 ft) head.

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

- The specific speed is an important factor governing the selection of the type of runner best suited for a given operating range. The impulse (Pelton) turbines have very low specific speeds relative to Kaplan turbines. The specific speed of a Francis turbine lies between the impulse and Kaplan turbine.

Efficiency vs Load for Turbines



Selection of Turbines

Turbine	Head	Specific Speed (SI)
Pelton Wheel	>300 m	8.5-30 (Single Jet) 30-51 (2 or More)
Francis Turbine	50-450 m	51-255
Kaplan Turbine	Up to 60 m	255-860