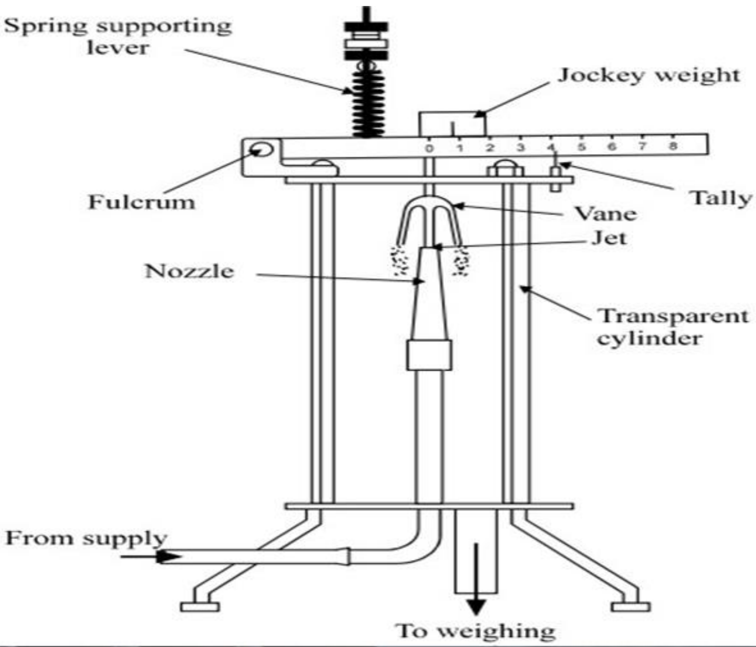
Impact of Jets

4.1 Introduction:

Water turbines are widely used throughout the world to generate power. In the type of water turbine referred to as a Pelton† wheel, one or more water jets are directed tangentially on to vanes or buckets that are fastened to the rim of the turbine disc. The impact of the water on the vanes generates a torque on the wheel, causing it to rotate and to develop power. Although the concept is essentially simple, such turbines can generate considerable output at high efficiency. Powers in excess of 100 MW, and hydraulic efficiencies greater than 95%, are not uncommon. It may be noted that the Pelton wheel is best suited to conditions where the available head of water is great, and the flow rate is comparatively small. For example, with a head of 100 m and a flow rate of 1 m3 /s, a Pelton wheel running at some 250 rev/min could be used to develop about 900 kW. The same water power would be available if the head were only 10 m and the flow were 10m3 /s, but a different type of turbine would then be needed.

To predict the output of a Pelton wheel, and to determine its optimum rotational speed, we need to understand how the deflection of the jet generates a force on the buckets, and how the force is related to the rate of momentum flow in the jet. In this experiment, we measure the force generated by a jet of water striking a flat plate or a hemispherical cup, and compare the results with the computed momentum flow rate in the jet.



1.1 Figure of impact jet

The jet of water is directed to hit the vanes of a particular shape a force is exerted on the vane by the jet.The amount of force depends on the diameter of the jet shape and the fluid flow rate it also depends on whether thevane is moving or stationary. In this experiment we are concerned about the stationary vane. The force on vane isgiven by the following formulas:

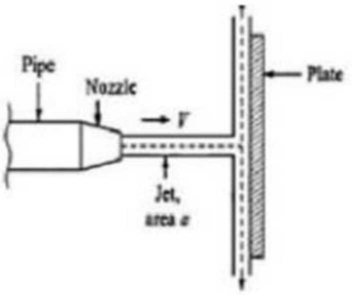
Flat Plate: $Ft = \rho \, a \, v^2$

Where a = area of jet in m^2

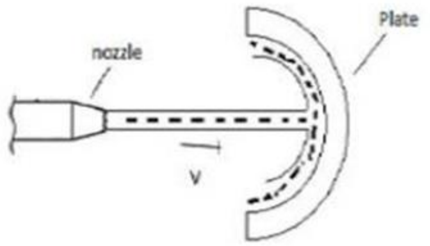
Hemispherical $F_t = 2 \rho a \, v^2$

ρ = density of water = 1000 kg/ m^3 v = velocity of jet in m/s

F_t = Force acting parallel to the direction of jet



Flat plate



Hemispherical plate

4.2 Impact of jet

The liquid comes out in the form of a jet from the outlet of a nozzle which is fitted to a pipe through which the liquid is flowing under pressure.A jet is a stream of fluid that is projected into a surrounding medium, usually from some kind of a nozzle, aperture or orifice.[1] Jets can travel long distances without dissipating.

Jet fluid has higher momentum compared to the surrounding fluid medium. In the case that the surrounding medium is assumed to be made up of the same fluid as the jet, and this fluid has a viscosity, the surrounding fluid is carried along with the jet in a process called entrainment.

4.3 Force Exerted by Fluid Jet on Stationary Flat Plate

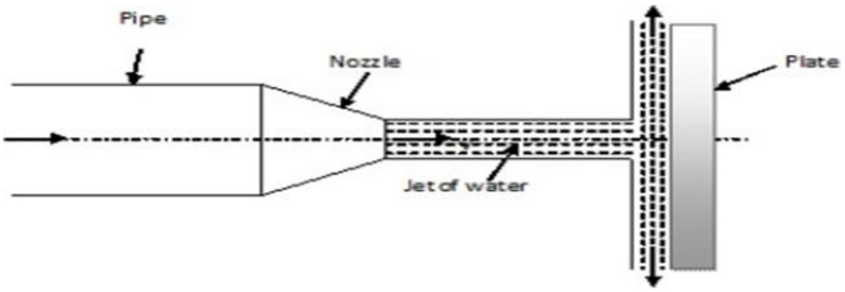
The following cases of the impact of jet, i.e. the force exerted by the jet on a plate will be considered

1. Force exerted by the jet on a stationary plate
a) Plate is vertical to the jet
b) Plate is inclined to the jet
c) Plate is curve

2. Force exerted by the jet on a moving plate
   a) Plate is vertical vertical to the jet
   b) Plate is inclined to the jet
   c) Plate is curved

4.4 Force exerted by the jet on a stationary vertical plate

Consider a jet o f water coming out from the nozzle strikes the vertical plate



V = velocity of jet, d = diameter of the jet, a = area of x – section of the jet

The force exerted by the jet on the plate in the direction of jet.

Fx = Rate of change of momentum in the direction of force

Rate of change of momentum in the direction of force = initial momentum – final momentum / time

= mass x initial velocity – mass x final velocity / time

= mass/time (initial velocity – final velocity)

= mass/ sec x (velocity of jet before striking mass/ sec x (velocity of jet before striking – final velocity of jet after striking)

4.5 Force of Jet Impinging On An Inclined Fixed Plate:

Consider a jet of water impinging normally on a fixed plate as shown in fig-2.

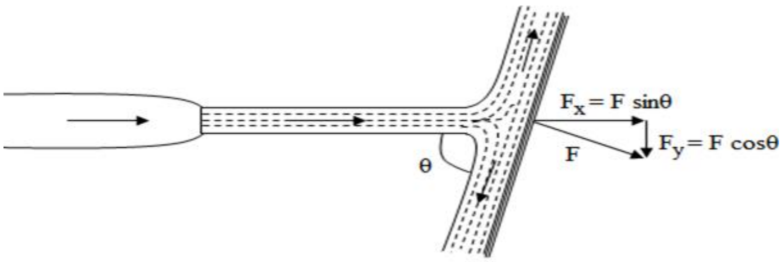


Fig-2 : Jet impinging on an inclined fixed plate

Let, • Θ = Angle at which the plate is inclined with the jet Force exerted by the jet on the plane = $\frac{waV^2}{g}$ KN

Force exerted by the jet in a direction normal to the plate, $F = \frac{waV^2 \sin\theta}{g}$ and the force exerted by the jet in the direction of flow,

$$F_x = F\sin\theta = \frac{waV^2 \sin\theta}{g} \times \sin\theta = \frac{waV^2 \sin^2\theta}{g}$$

Similarly.force exerted by the jet in a direction normal to flow,

$$F_y = F\cos\theta = \frac{waV^2 \sin\theta}{g} \times \cos\theta$$

$$\therefore F_y = \frac{waV^2 \sin 2\theta}{2g}$$

4.6 Force of Jet Impinging on a Moving Plate:

Consider a jet of water imping normally on a plate. As a result of the impact of the jet, let the plate move in the direction of the jet as shown in fig-3.

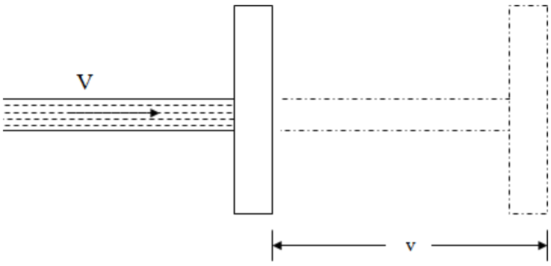


Fig-3 : Jet impinging on a moving plate

Let, v= Velocity of the plate, as a result of the impact of jet A little conversation will show that the relative velocity of the jet with respect to the plate equal to **(V-v)** m/s. For analysis purposes, it will be assumed that the plate is fixed and the jet is moving with a velocity of **(V-v)** m/s. Therefore force exerted by the jet,

$$F = Mass\ of\ water\ flowing\ per\ second \times Change\ of\ velocity$$

$$\Rightarrow F = \frac{wa(V-v)}{g} \times [(V-v)-0]$$

$$\Rightarrow F = \frac{wa(V-v)^2}{g} KN$$

4.7 Force of Jet Impinging on a Moving Curved Vane:

Consider a jet of water entering and leaving a moving curved vane as shown in fig-4.

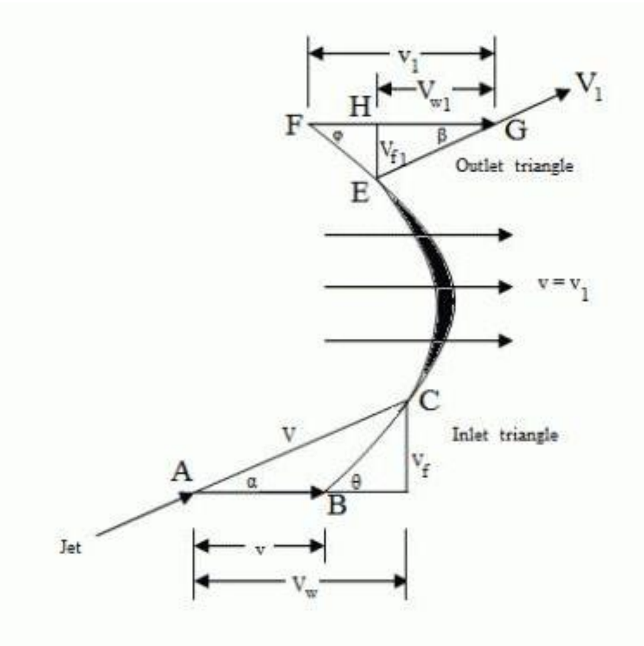


Fig-4 : Jet impinging on a moving curved vane

Let,

• V = Velocity of the jet (AC), while entering the vane,

• v_1 = Velocity of the jet (EG), while leaving the vane,

• v_1, v_2 = Velocity of the vane (AB, FG)

- α = Angle with the direction of motion of the vane, at which the jet enters the vane,
- β = Angle with the direction of motion of the vane, at which the jet leaves the vane,
- Vr = Relative velocity of the jet and the vane (BC) at entrance (it is the vertical difference between V and v)
- Vr1 = Relative velocity of the jet and the vane (EF) at exit (it is the vertical difference between v1 and v2)
- Ɵ = Angle, which Vr makes with the direction of motion of the vane at inlet (known as vane angle at inlet),
- β = Angle, which Vr1 makes with the direction of motion of the vane at outlet (known as vane angle at outlet),
- Vw = Horizontal component of V (AD, equal to). It is a component parallel to the direction of motion of the vane (known as velocity of whirl at inlet),
- Vw1 = Horizontal component of V1 (HG, equal to). It is a component parallel to the direction of motion of the vane (known as velocity of whirl at outlet),
- Vf = Vertical component of V (DC, equal to). It is a component at right angles to the direction of motion of the vane (known as velocity of flow at inlet),
- Vf1 = Vertical component of V1 (EH, equal to). It is a component at right angles to the direction of motion of the vane (known as velocity of flow at outlet),
- a = Cross sectional area of the jet. As the jet of water enters and leaves the vanes tangentially, therefore shape of the vanes will be such that Vr and Vr1 will be a long with tangents to the vanes at inlet and outlet. The relations between the inlet and outlet triangles (until and unless given) are: (i) V=v1 , and

  (ii) Vr=Vr1 We know that the force of jet, in the direction of motion of the vane,

$$F_x = Mass\ of\ water\ flowing\ per\ second \times Change\ of\ velocity\ of\ whirl$$

$$\Rightarrow F_x = \frac{waV}{g}(V_w - V_{w1})$$

4. HYDRAULIC TURBINES

A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. The work produced by a turbine can be used for generating electrical power when combined with a generator.

4.1 CLASSIFICATION OF TURBINES

Hydraulic turbines may be classified according to several considerations as discussed below.

1. According to the action of the water flowing through the turbine runners the turbine may be classified as impulse turbines and reaction turbines.

In an *impulseturbine,* **all the available energy of water is converted into kinetic energy or velocity head** by passing it through a **contracting nozzle** provided at the end of the penstock. The water coming out of the nozzle is formed into a free jet which impinges on a series of buckets of the runner thus causing it to revolve. The runner revolves freely in air.

The water is in contact with only a part of the runner at a time, and throughout its action on the runner and in its subsequent flow to the tail race, the water is at atmospheric pressure. A casing is however provided on the runner to prevent splashing and to guide the water discharged from the buckets to the tail race. Some of the impulse turbines are Pelton wheel, Turgo-impulse wheel, Girard turbine, Banki turbine, Jonval turbine etc. Out of these turbines only **Pelton wheel** is predominantly used at present, which has been described later.

In a *reactionturbine,* at the entrance to the runner, **only a part of the available energy of water is converted into kinetic energy and a substantial part remains in the form of pressure energy.** As water flows through the runner the change from pressure to kinetic energy takes place gradually. As such the pressure at the inlet to the turbine is much higher than the pressure at the outlet and it varies throughout the passage of water through the turbine. For this gradual change of pressure to be possible the runner in this case must be completely enclosed in an air-tight casing and the passage in entirely full of water throughout the operation of the turbine.

The difference of pressure (or pressure drop) between the inlet and the outlet of the runner is called *reactionpressure*, and hence these turbines are known as reaction turbines. Some of the reaction turbines are Fourneyron, Thomson, Francis, Propeller, Kaplan, etc. Out of these the **Francis** and the **Kaplan** turbines are predominantly used at present which have been described later.

2. The turbines may also be classified according to the main direction of flow of water in the runner as

(i) tangential flow turbine,

(ii) radial flow turbine,

(iii) axial flow turbine, and

(iv) mixed flow turbine.

In a *tangentialflow* turbine the water flows along the tangent to the path of rotation of the runner. **Peltonwheel** is a tangential flow turbine.

In a *radialflow* turbine the water flows along the radial direction and remains wholly and mainly in the plane normal to the axis of rotation, as it passes through the runner. A radial flow turbine may be either inward radial flow type or outward radial flow type. In an *inwardradial* flow turbine the water enters at the outer circumference and flows radially inwards towards the centre of the runner. **Old Francis turbine**, Thomson turbine, Girard radial flow turbine etc., are some of the examples of inward radial flow turbine. In an *outwardradial* flow turbine water enters at the centre and flows radially outwards towards the outer periphery of the runner. Fourneyron turbine is an example of outward radial flow turbine.

In an *axialflow* turbine the flow of water through the runner is wholly and mainly along the direction parallel to the axis of rotation of the runner. Jonval turbine, Girard axial flow turbine, Propeller turbine, **Kaplan turbine** etc., are some of the examples of axial flow turbines.

In *mixedflow* turbine, water enters the runner at the outer periphery in the radial direction and leaves it at the centre in the direction parallel to the axis of rotation of the runner. **ModemFrancisturbine** is an example of the mixed flow type turbine.

3. On the basis of the head and quantity of water required, the turbines may be classified as

(i) high head turbine,

(ii) medium head turbine, and

(iii) low head turbine.

Highhead turbines are those which are capable of working under very high heads ranging from several hundred metres to few thousand metres. These turbines thus require relatively less quantity of water. In general **impulseturbines** are high head turbines. In particular **Peltonwheel** has so far been used under a highest head of about 1770 m (5800 ft.).

Mediumhead turbines are those which are capable of working under medium heads ranging from about 60 m to 250 m. These turbines require relatively large quantity of water. **Modern Francis turbines** may be classified as medium head turbines.

Lowhead turbines are those which are capable of working under the heads less than 60 m. These turbines thus require a large quantity of water. **Kaplan** and other propeller turbines may be classified as low head turbines.

4. The turbines may also be classified according to their specific speed. The *specificspeed* of a turbine is **the speed of a geometrically similar turbine that would develop one kilowatt power when working under a head of one metre**. However, in metric units the *specificspeed* of a turbine is defined as the speed of a geometrically similar turbine that would develop one metric horse power when working under a head of one metre.

On the basis of the specific speed the various turbines may be considered in the following three groups in which the values given in the brackets represent the range of specific speed in metric units.

(i) Specific speed varying from 8.5 to 30 (10 to 35) — Pelton wheel with single jet and upto 43 (50) for Pelton wheel with double jet.

(ii) Specific speed varying from 50 to 340 (60 to 400) —Francis turbine.

(iii) Specific speed varying from 255 to 860 (300 to 1000) — Kaplan and other propeller turbines.

5. The turbines may also be classified according to the disposition of their shafts. The turbines may be disposed with either vertical or horizontal shafts and hence these may be classified as turbines with *verticaldispositionofshaft* and turbines with *horizontal disposition of shaft*. Out of the two types the turbines with **verticaldisposition** of shaft are commonly adopted.

4.2 PELTON WHEEL

The only hydraulic turbine of the impulse type in common use, is named after an American engineer Laster A Pelton, who contributed much to its development around the year 1880. Therefore this machine is known as Pelton turbine or Pelton wheel. It is an efficient machine particularly suited to high heads. The rotor consists of a large circular disc or wheel on which a number (seldom less than 15) of spoon shaped buckets are spaced uniformly round is periphery as shown in Figure 4.1.

The wheel is driven by jets of water being discharged at atmospheric pressure from pressure nozzles. The nozzles are mounted so that each directs a jet along a tangent to the circle through the centres of the buckets. Down the centre of each bucket, there is a splitter ridge which divides the jet into two equal streams which flow round the smooth inner surface of the bucket and leaves the bucket with a relative velocity almost opposite in direction to the original jet.

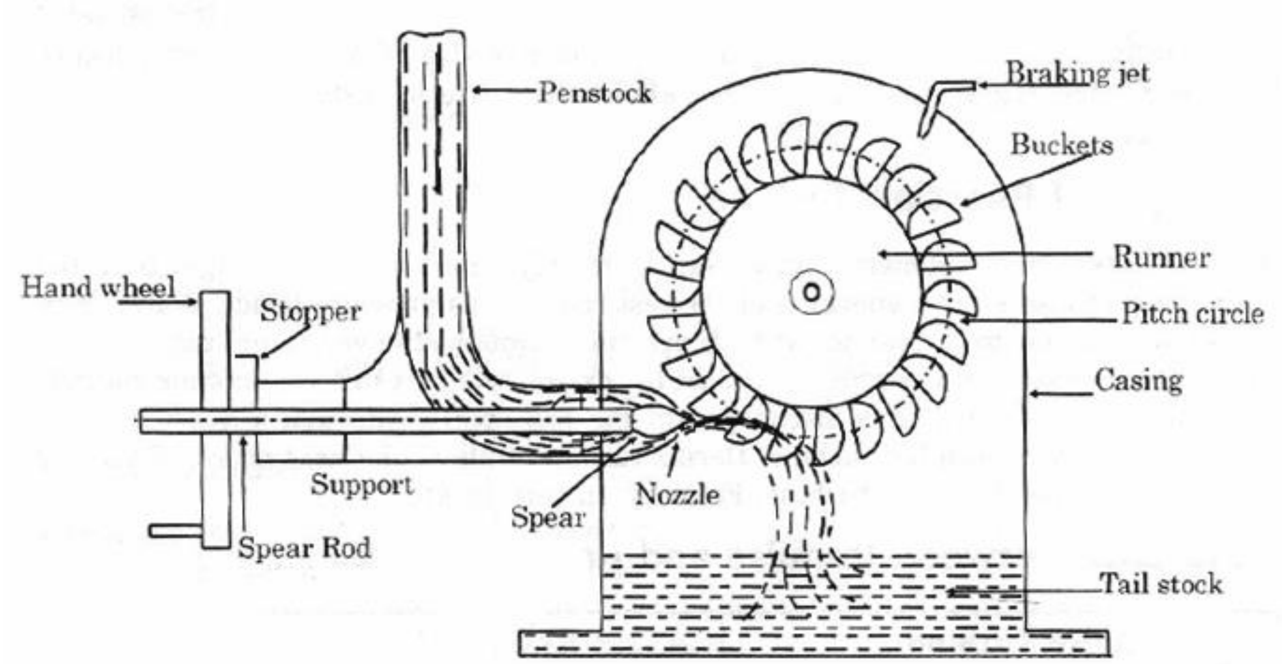


Fig. 4.1 Pelton wheel

For maximum change in momentum of the fluid and hence for the maximum driving force on the wheel, the deflection of the water jet should be 180˚. In practice, however, the deflection is limited to about 165˚ so that the water leaving a bucket may not hit the back of the following bucket. Therefore, the camber angle of the buckets is made as 165˚ ($\Theta = 165˚$).

4.2.1 Analysis of force on the bucket and power generation

Fig. 4.2 a shows a section through a bucket which is being acted on by a jet. The plane of section is parallel to the axis of the wheel and contains the axis of the jet. The absolute velocity of the jet V_1 with which it strikes the bucket is given by

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

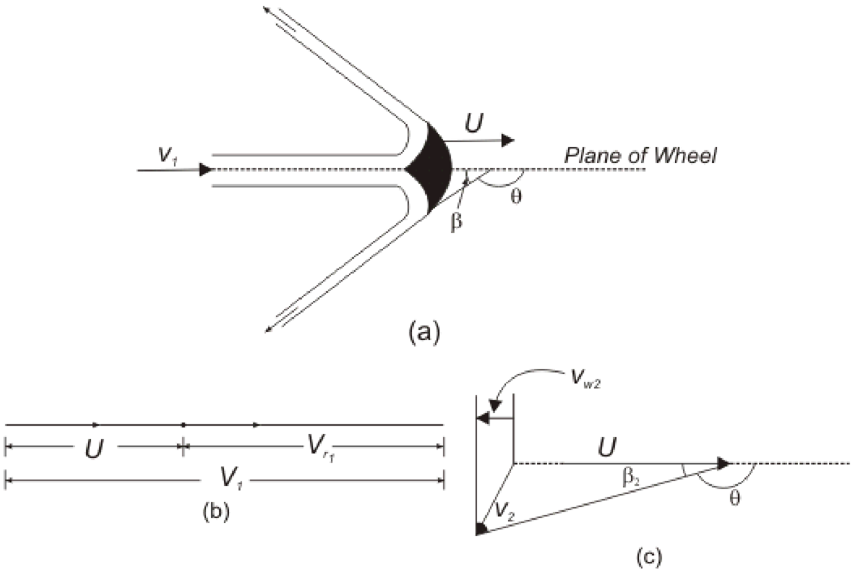


Fig. 4.2 (a) Flow along the bucket of a pelton wheel (b) Inlet velocity triangle (c) Outlet velocity triangle

where, C_v is the coefficient of velocity which takes care of the friction in the nozzle. *H* is the head at the entrance to the nozzle which is equal to the total or gross head of water stored at high altitudes minus the head lost due to friction in the long pipeline leading to the nozzle. Let the velocity of the bucket (due to the rotation of the wheel) at its centre where the jet strikes be *U*. Since the jet velocity V_1 is tangential, i.e. V_1 and *U* are collinear, the diagram of velocity vector at inlet (Fig. 4.2 b) becomes simply a straight line and the relative velocity is given by

$$V_{r1} = V_1 - U$$

It is assumed that the flow of fluid is uniform and it glides the blade all along including the entrance and exit sections to avoid the unnecessary losses due to shock. Therefore the direction of relative velocity at entrance and exit should match the inlet and outlet angles of the buckets respectively. The velocity triangle at the outlet is shown in Fig. 4.2(c). The bucket velocity *U* remains the same both at the inlet and outlet. With the direction of *U* being taken as positive, we can write. The tangential component of inlet velocity (Fig. 4.2 (b)),

$$V_{w1} = V_1 = Vr_1 + U$$

and the tangential component of outlet velocity (Fig. 4.2 (c))

$$V_{w_2} = -(V_{r_2} \cos \beta_2 - U)$$

where V_{r1} and V_{r2} are the velocities of the jet relative to the bucket at its inlet and outlet and β_2 is the outlet angle of the bucket.

The energy delivered by the fluid per unit mass to the rotor can be written as,

$$E/m = [V_{w_1} - V_{w_2}]\,U$$
$$= [V_{r_1} + V_{r_2}\ \cos\ \beta_2]\,U$$

The relative velocity V_{r2} becomes slightly less than V_{r1} mainly because of the friction in the bucket. Some additional loss is also inevitable as the fluid strikes the splitter ridge, because the ridge cannot have zero thickness. These losses are however kept to a minimum by making the inner surface of the bucket polished and reducing the thickness of the splitter ridge. The relative velocity at outlet V_{r2} is usually expressed as $V_{r2} = KV_{r1}$ where, K is a factor with a value less than 1. However in an ideal case (in absence of friction between the fluid and blade surface) K=1.

If Q is the volume flow rate of the jet, then the power transmitted by the fluid to the wheel, then wheel efficiency of a pelton turbine can be written as,

$$\eta_w = \frac{2\rho Q[1+K\ \cos\ \beta_2](V_1 - U)U}{\rho Q V_1^2}$$
$$= 2\,[1+K\ \cos\ \beta_2]\left[1-\frac{U}{V_1}\right]\frac{U}{V_1}$$

4.3 FRANCIS TURBINE

The water from the penstock enters a ***scroll casing*** (also called *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 an approximately **constant velocity** for the water so distributed. In order to keep the velocity of water constant throughout its path around the runner, the **cross-sectional area of the casing is gradually decreased**.

The casing is made of cast steel, **plate steel**, concrete or concrete and steel depending upon the pressure to which it is subjected. Out of these a **plate steel scroll casing** is commonly provided for turbines operating under 30m or higher heads. From the scroll casing the water passes through a *speed ring* or *stay ring.* The speed ring consists of an upper and a lower ring held together by series of fixed vanes called *stay vanes*. The number of stay vanes is usually taken as **half** the number of guide vanes.

The speed ring has two functions to perform.

- It directs the water from the scroll casing to the guide vanes or wicket gates.
- Further it resists the load imposed upon it by the internal pressure of water and the weight of the turbine and the electrical generator and transmits the same to the foundation.

The speed ring may be either of cast iron or cast steel or fabricated steel. From the speed ring the water passes through a series of guide vanes or wicket gates provided all around the periphery of the turbine runner. The function of guide vanes is to regulate the quantity of water supplied to the runner and to direct water on to the runner at an angle appropriate to the design.

The guide vanes are airfoil shaped and they may be made of cast steel, stainless steel or plate steel. Each guide vane is provided with two stems, the upper stem passes through the head cover and the lower stem seats in a bottom ring.st steel, stainless steel or plate steel. By a system of levers and links, all the guide vanes may be turned about their stems, so as to alter the width of the passage between the adjacent guide vanes, thereby allowing a variable quantity of water to strike the runner. The guide vanes are operated either by means of a wheel (for very small units) or automatically by a <u>**governor**</u>. **The main purpose of the various components so far described is to lead the water to the runner with a minimum loss of energy.**

The runner of a Francis turbine consists of a **series of a curved vanes** (about 16 to 24 in number) evenly arranged around the circumference in the annular space between two plates. The vanes are so shaped that **water enters the runner radially** at the outer periphery and **leaves it axially** at the inner periphery. The change in the direction of flow of water, from radial to axial, as it passes through the runner, produces a **circumferential force** on the runner which makes the runner to rotate and thus contributes to the useful output of the runner.

The runners are usually made up of cast iron, cast steel, mild steel or stainless steel. Often instead of making the complete runner of stainless steel, only those portions of the runner blades, which may be subjected to cavitation erosion, are made of **stainless steel**. This reduces the cost of the runner and at the same time ensures the operation of the runner with a minimum amount of maintenance. The runner is keyed to a shaft which is usually of forged steel. The torque produced by the runner is transmitted to the generator through the shaft which is usually connected to the generator shaft by a bolted flange connection. The water after passing through the runner flows to the tail race through a draft tube.

4.3.1 WORK DONE AND EFFICIENCIES OF FRANCIS TURBINE

If W is the weight of water percentage second which strikes the runner then work done percentage second on the runner may be expressed as

$$\text{Work done} = \frac{W}{g}[V_{w1}u_1 - V_{w2}u_2]$$

$$\text{Hydraulic efficiency, } \square_{hh} = \frac{[V_{w1}u_1 - V_{w2}u_2]}{gH}$$

$\square_{hh}$ ranges from 85 to 95%

If P is the power available at the runner shaft then the mechanical efficiency is given by

$$\square_{hm} = \frac{P}{\frac{W}{g}[V_{w1}u_1 - V_{w2}u_2]}$$

$$\square_{h0} = \square_{hh} \times \square_{hm} = \frac{P}{WH}$$

The overall efficiency of a Francis turbine ranges from 80 to 90%.

4.3.2 Degree of reaction

Degree of reaction ρ, is defined as the ratio of pressure drop in the runner to the hydraulic work done on the runner.

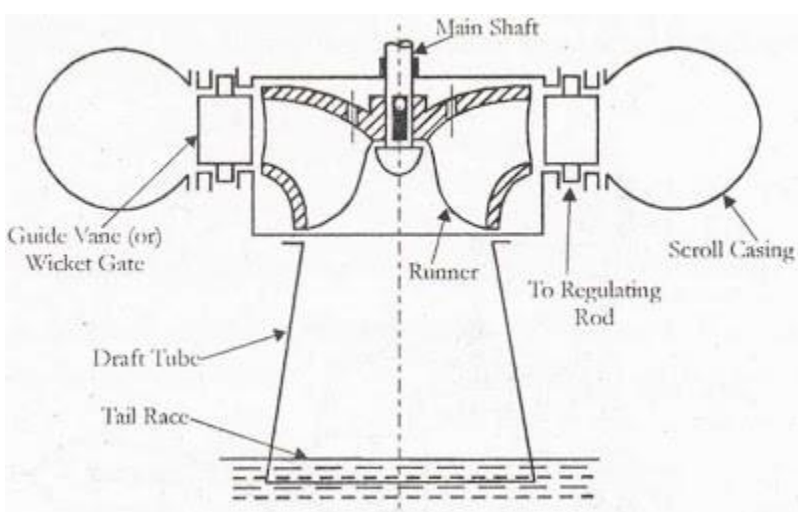


Fig. 4.3 Francis Turbine

where p_1 and p_2 are the pressures at the inlet and outlet of the runner

$$\varrho = \frac{\left(\frac{p_1}{\gamma} - \frac{p_2}{\gamma}\right)}{\left[\frac{[V_{w1}u_1 - V_{w2}u_2]}{g}\right]}$$