32

Impulse Turbines

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32·1. Introduction

An impulse turbine, as the name indicates, is a turbine which runs by the impulse of water. In an impulse turbine, the water from a dam is made to flow through a pipeline, and then through guide mechanism and finally through the nozzle. In such a process, the entire available energy of the water is converted into kinetic energy, by passing it through nozzles; which are kept close to the runner. The water enters the running wheel in the form of a jet (or jets), which impinges on the buckets, fixed to the outer periphery of the wheel.

The jet of water impinges on the buckets with a high velocity, and after flowing over the vanes, leaves with a low velocity; thus imparting energy to the runner. The pressure of water, both at entering and leaving the vanes, is atmospheric. The commonest example of an impulsive turbine is Pelton wheel, which is discussed below.

32·2. Pelton Wheel

The *Pelton wheel is an impulsive turbine used for high heads of water. It has the following main components:

1. Nozzle,
2. Runner and buckets,
3. Casing, and
4. Breaking jet.

32·3. Nozzle

It is a circular guide mechanism, which guides the water to flow at a designed direction, and also to regulate the flow of water. This water, in the form of a jet, strikes the buckets. A conical needle or spear operates inside the nozzle in an axial direction. The main purpose, of this spear, is to control or regulate the quantity of water flowing through the nozzle as shown in Fig. 32·1.

A little consideration will show, that when the spear is pushed forward into the nozzle, it reduces the area of jet. As a result of this, the quantity of water flowing through the jet is also reduced. Similarly, if the spear is pushed back out of the nozzle, it allows a greater quantity of water to flow through the jet. The movement of the spear is regulated by hand or by automatic governing arrangement depending upon the requirement. Sometimes, it is very essential to close** the nozzle suddenly. This is done with the help of spear, which may cause the pipe to burst due to sudden increase of pressure. In order to avoid such a mishap, an additional nozzle (known as bypass nozzle) is provided through which the water can pass, without striking the buckets. Sometimes, a plate (known as

*Named after Pelton L.A. (1829 — 1908) who was an engineer of California. He made large scale experiments and developed a turbine used for high heads and low discharge.

deflector) is provided to the nozzle, which is used to deflect the water jet, and preventing it from striking the buckets.

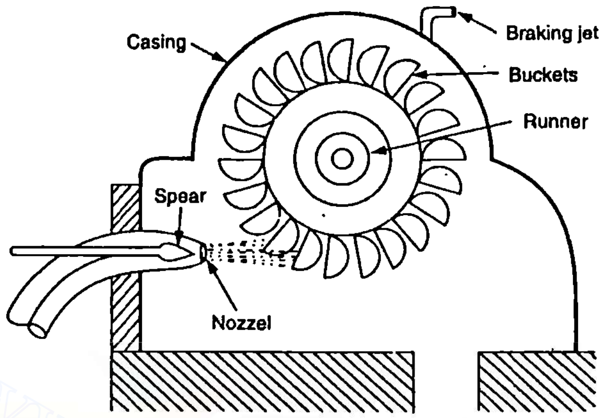
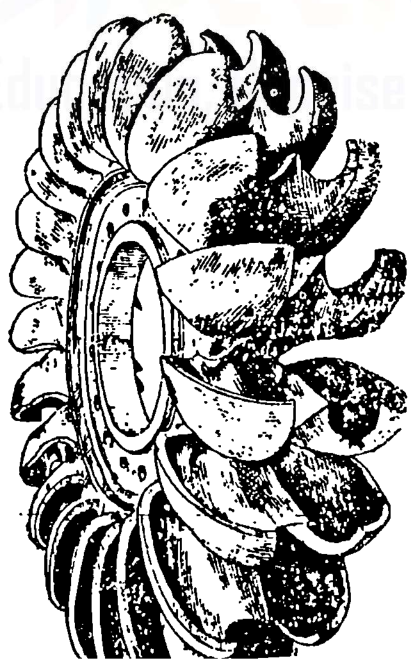


Fig. 32·1. Parts of a Pelton wheel

The nozzle is kept very close to the buckets, in order to minimise the losses due to windage.

32·4. Runner and Buckets

The runner of a Pelton wheel essentially consists of a circular disc fixed to a horizontal shaft. On the periphery of the runner, a number of buckets are fixed uniformly. A bucket resembles to a hemispherical cup or bowl with a dividing wall (known as splitter) in its centre in the radial direction of the runner as shown in Fig. 32·2.



The surface of the buckets is made very smooth. For low heads, the buckets are made of cast iron. But for high heads, the buckets are made of bronze, stainless steel or other alloys. When the water is chemically impure, the buckets are made of special alloys. The buckets are generally bolted to the runner disc. But, sometimes, the buckets and disc are cast as a single unit. Sometimes, all the buckets wear equally in a given time. But in actual practice, all the buckets do not wear equally. A few buckets get worn out and damaged early and need replacement. This can be done only if the buckets are bolted to the disc.

32·5. Casing

Strictly speaking, the casing of a Pelton wheel does not perform any hydraulic function. But it is necessary to safeguard the runner against accident, and also to prevent the splashing of water and lead the water to the tail race. The casing is, generally, made of cast or fabricated parts.

32·6. Braking Jet

Whenever the turbine has to be brought to rest, the nozzle is completely closed. It has been observed, that the runner goes an revolving for a considerable time, due to inertia, before it comes to rest. In order to bring the runner to rest in a short time, a small nozzle is provided in such a way, that it will direct a jet of water on the back of the buckets. It acts as a brake for reducing the speed of the runner.

32·7. Work Done by an Impulse Turbine

The jet of water, issuing from the nozzle, strikes the bucket at its splitter. The splitter then splits up the jet into two parts. One part of the jet glides over the inside surface of one portion of the vane and leaves it at its extreme edge. The other part of the jet glides over the inside surface of the other portion of the vane and leaves it at its other extreme edge as shown in Fig. 32·3.

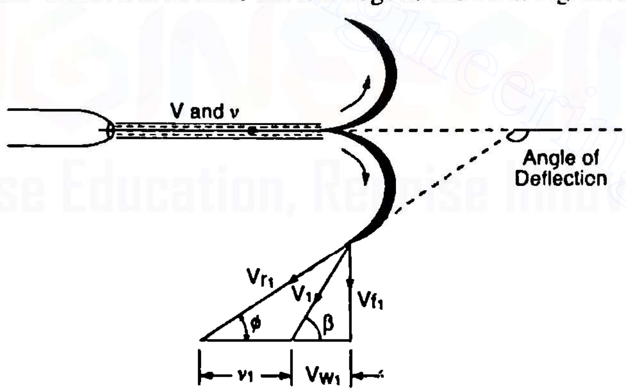


Fig. 32·3. Triangle of the velocities

A little consideration will show, that the mid-point of the bucket, where the jet strikes the splitter and gets divided, forms the inlet tip, and the two extreme edges, where the divided jet leaves the bucket, from the two outlet tips.

First of all, draw the velocity triangles at the splitter (which will be a straight line only) and *any one* of the outer tips of the hemispherical bucket as shown in Fig. 32·3. All the notations and theory of jet impinging on series of vanes is appliable in the case also.

Let V = Absolute velocity of the entering water,

V_r = Relative velocity of water and bucket at inlet,

V_f = Velocity of flow at inlet,

D = Diameter of the wheel,
d = Diameter of the nozzle,
N = Revolutions of the wheel in r.p.m.
ϕ = Angle of the blade tip at outlet,
H = Total head of water, under which the wheel is working.

It will be interesting to know that inlet velocity triangle will be a straight line as shown in the figure. In this case, $\alpha = 0°$; $\theta = 0°$; $V_w = V$ and $V_r = V - v$.

As a matter of fact, the shape of the outlet velocity triangle depends upon the value of V_{w1}. If V_{w1} is in the same direction as that of the jet, its value is taken as positive. However, if V_{w1} is in the opposite (as shown in the figure) its value is taken as negative. The relation between these two velocity triangles, is

$$v_1 = v \quad \text{and} \quad V_{r1} = V_r = (V - v)$$

We know that force kN of water in the direction of motion of the jet

$$= \frac{1}{g}(V_w - V_{w1})$$

and work done

$$= \text{Force} \times \text{Distance} = \frac{1}{g}(V_w \cdot v - V_{w1} \cdot v_1)$$

$$= \frac{1}{g}(V_w - V_{w1}) \times v \qquad ...(\because v_1 = v)$$

$\therefore$ Hydraulic efficiency,

$$\eta_h = \frac{\text{Work done per kN of water}}{\text{Kinetic energy of the jet}} = \frac{\frac{1}{g}(V_w - V_{w1}) \times v}{\frac{V^2}{2g}}$$

$$= \frac{2(V_w - V_{w1}) \times v}{V^2}$$

Now consider a case, in which the value of V_{w1} is negative as shown in fig. Therefore work done per kN of water

$$= \frac{1}{g}[V_w - (-V_{w1})] \times v = \frac{1}{g}(V_w + V_{w1}) \times v$$

$$= \frac{V_w v}{g} + \frac{V_{w1} v}{g} = \frac{V_w v}{g} + \frac{V_{r1} \cos\phi - v)v}{g}$$

$$...(\because V_{w1} = V_{r1}\cos\phi - v)$$

$$= \frac{v}{g}\{V_w + [(V - v)\cos\phi - v]\}$$

$$...(\because V_{r1} = V_r = V - v)$$

$$= \frac{v}{g}(V + V\cos\phi - v) \qquad ...(\because V_w = V)$$

$$= \frac{v}{g}[V(1 + \cos\phi) - v(1 + \cos\phi)]$$

We know that the hydraulic efficiency,

$$\eta_\eta = \frac{\text{Work done per kN of water}}{\text{Energy supplied per kN of water}}$$

$$= \frac{\dfrac{v(V-v)(1+\cos\phi)}{g}}{\dfrac{V^2}{2g}} = \frac{2v(V-v)(1+\cos\phi)}{V^2}$$

For maximum efficiency, differentiate the numerator of the above equation, with respect to v and equate it to zero (as the maximum efficiency will be, when the numerator will be maximum).

$$\frac{d}{dv}[2v(V-v)(1+\cos\phi)] = 0$$

$$\frac{d}{dv}[(2Vv-2v^2)(1+\cos\phi)] = 0$$

$$2V-4v = 0 \text{ or } v = \frac{V}{2}$$

It means that the velocity of the wheel, for maximum hydraulic efficiency, should be half of the et velocity. Therefore maximum work done/kN of water

$$= \frac{v(V-v)(1+\cos\phi)}{g} = \frac{\dfrac{V}{2}\left(V-\dfrac{V}{2}\right)(1+\cos\phi)}{g}$$

...(Substituting $v = \frac{V}{2}$)

$$= \frac{V^2}{4g}(1+\cos\phi) \text{ kN}$$

$\therefore$ Maximum hydraulic efficiency,

$$\max \eta_h = \frac{\dfrac{V^2}{4g}(1+\cos\phi)}{\dfrac{V^2}{2g}} = \frac{(1+\cos\phi)}{.2}$$

Notes : 1. It may be noted that the efficiency is maximum when $\cos\phi = 1$ *i.e.*, $\phi = 180°$. But in actual practice, the jet is deflected through an angle of 160° to 165° only. Because, if the jet is made to deflect through an angle of 180°, the water discharged from one bucket, will have an impact on the bucket, in front of it.

2. In actual practice, maximum efficiency takes place when the velocity of wheel is 0·46 times the velocity of the jet (*i.e.*, $v = 0{\cdot}46V$)

3. The power generated by the turbine may be found out as usual by multiplying the discharge in m^3/s with the work done per kN of water.

32·8. Power Produced by an Impulse Turbine

We have seen in the previous articles, that some work is done per kN of water, when the jet strikes the buckets of an impulse turbine. If we know the quantity of water in kN, flowing through the jets per second, and the amount of work done per second, then the power produced by the turbine may be found out with the help of velocity triangles as usual. The power produced may also be found out from the relation,

$$P = wQH \text{ kW}$$

where w = specific weight of water (9·81 kN/m^3),

Q = Discharge of the turbine in m^3/s, and

H = Head of water in metres.

32·9. Efficiencies of an Impulse Turbine

In general, the term efficiency may be defined as the ratio of work done to the energy supplied. An impulse turbine has the following three types of efficiencies:

1. Hydraulic efficiency,
2. Mechanical efficiency, and
3. Overall efficiency.

32·10. Hydraulic Efficiency

It is the ratio of work done, on the wheel, to the energy of the jet. We have sen in Art. 30·7 that the hydraulic efficiency of a turbine,

$$\eta_h = \frac{2v(V-v)(1 + \cos\phi)}{V^2}$$

and maximum hydraulic efficiency,

$$\max \eta_h = \frac{(1 + \cos\phi)}{2}$$

32·11. Mechanical Efficiency

It has been observed that all the energy supplied to the wheel does not come out as useful work. But a part of it is dissipated in overcoming friction of bearings and other moving parts. Thus the mechanical efficiency is the ratio of actual work available at the turbine to the energy imparted to the wheel.

32·12. Overall Efficiency

It is a measure of the performance of a turbine, and is the ratio of actual power produced by the turbine to the energy actually supplied by the turbine. *i.e.*,

$$\eta_0 = \frac{P}{wQH}$$

Example 32·1. *A Pelton wheel develops 2000 kW under a head of 100 metres, and with an overall efficiency of 85%. Find the diameter of the nozzle, if the coefficient of velocity for the nozzle is 0·98.*

Solution. Given : P = 2000 kW; H = 100 m; η_0 = 85% = 0·85 and C_v = 0·98.

Let d = Diameter of the nozzle, and

Q = Discharge of the turbine.

We know that the velocity of jet,

$$V = C_v\sqrt{2gH} = 0·98 \times \sqrt{2 \times 9·81 \times 100} = 43·4 \text{ m/s}$$

and overall efficiency (η_0),

$$0·85 = \frac{P}{wQH} = \frac{2000}{9·81 \times Q \times 100} = \frac{2·04}{Q}$$

$$\therefore \quad Q = 2·04/0·85 = 2·4 \text{ m}^3\text{/s}$$

Now the total discharge of the wheel should be equal to the discharge through the jet. *i.e.*,

or
$$2{\cdot}4 = 43{\cdot}4 \times \frac{\pi}{4} \times (d)^2 = 34{\cdot}1\, d^2$$

$$d^2 = 2{\cdot}4/34{\cdot}1 = 0{\cdot}0704 \text{ or } d = 0{\cdot}265 \text{ m} = 265 \text{ mm} \quad \textbf{Ans.}$$

Example 32·2. *A Pelton wheel, having semi-circular buckets and working under a head of 140 metres, is running at 600 r.p.m. The discharge through the nozzle is 500 litres/s and diameter of the wheel is 600 mm. Find:*

(a) Power available at the nozzle, and

(b) Hydraulic efficiency of the wheel, if coefficient of velocity is 0·98.

Solution. Given : $\phi = 180° - 180° = 0°$ (Because of semi-circular buckets); $H = 140$m; $N = 600$ r.p.m.; $Q = 500$ litres/s $= 0{\cdot}5$ m^3/s; $D = 600$ mm $= 0{\cdot}6$ m and $C_v = 0{\cdot}98$.

(a) Power available at the nozzle

We know that power available at the nozzle.
$$P = wQH = 9{\cdot}81 \times 0{\cdot}5 \times 140 = 686{\cdot}7 \text{ kW} \quad \textbf{Ans.}$$

(b) Hydraulic efficiency of the wheel

We also know that velocity of the jet,
$$V = C_v \sqrt{2gH} = 0{\cdot}98 \times \sqrt{2 \times 9{\cdot}81 \times 140} = 51{\cdot}36 \text{ m/s}$$

and tangential velocity of the wheel,
$$v = \frac{\pi DN}{60} = \frac{\pi \times 0{\cdot}6 \times 600}{60} = 18{\cdot}85 \text{ m/s}$$

∴ Hydraulic efficiency of the wheel,
$$\eta_\eta = \frac{2v(V - v)(1 + \cos\phi)}{V^2}$$
$$= \frac{2 \times 18{\cdot}85\,(51{\cdot}36 - 18{\cdot}85)\,(1 + \cos 0°)}{(51{\cdot}36)^2}$$
$$= 0{\cdot}465\,(1 + 1) = 0{\cdot}929 = 92{\cdot}9\% \quad \textbf{Ans.}$$

Example 32·3. *A Pelton wheel, working under a head of 500 metres, produces 13 000 kW at 430 r.p.m. If the efficiency of the wheel is 85%, determine (a) discharge of the turbine, (b) diameter of the wheel, and (c) diameter of the nozzle. Assume suitable data.*

Solution. Given : $H = 500$ m; $P = 13\,000$ kW; $N = 430$ r.p.m. and $\eta_0 = 85\% = 0{\cdot}85$

(a) Discharge of the turbine

Let Q = Discharge of the turbine.

We know that overall efficiency of the Pelton wheel (η_0),
$$0{\cdot}85 = \frac{P}{wQH} = \frac{13\,000}{9{\cdot}81 \times Q \times 500} = \frac{2{\cdot}65}{Q}$$

∴ $Q = 2{\cdot}65/0{\cdot}85 = 3{\cdot}12$ m^3/s **Ans.**

(b) Diameter of the wheel

Let us assume coefficient of velocity (c_v) = 0·98 and tangential velocity of wheel, (v) = 0·46 V (where V is the velocity of the jet).

We know that the velocity of jet,
$$V = C_v \sqrt{2gH} = 0{\cdot}98 \sqrt{2 \times 9{\cdot}81 \times 500} = 97{\cdot}1 \text{ m/s}$$
$$v = 0{\cdot}46\,V = 0{\cdot}46 \times 97{\cdot}1 = 44{\cdot}7 \text{ m/s}$$

We also know that the tangential velocity of the wheel (v)
$$\ldots = \frac{\pi DN}{} = \frac{\pi D \times 430}{} = 22{\cdot}5D$$

Diameter of the nozzle

Let d = Diameter of the nozzle.

The discharge through the nozzle must be equal to the discharge of the turbine. *i.e.,*

$$Q = V \times \frac{\pi}{4} \times (d)^2$$

or
$$3{\cdot}12 = 97{\cdot}1 \times \frac{\pi}{4} \times (d)^2 = 76{\cdot}3\,(d)^2$$

$$\therefore \quad d^2 = 3{\cdot}12/76{\cdot}3 = 0{\cdot}041 \text{ or } d = 0{\cdot}2 \text{ m} = 200 \text{ mm} \quad \textbf{Ans.}$$

Example 32·4. *In a hydroelectric scheme, the distance between high level reservoir at the top of mountains and turbine is 1·6 km and difference of their levels is 500 m. The water is brought in 4 penstocks each of diameter of 0·9 m connected to a nozzle of 200 mm diameter at the end. Find:*

(a) Power of each jet, and

(b) total power available at the reservoir, taking the value of Darcy's coefficient of friction as 0·008.

Solution. Given : l = 1.6 km = 1600 m; H = 500 m; No. of penstocks (n) = 4; Dia. of each penstock (D) 0·9 = m; Dia. of nozzle (d) = 200 mm = 0·2 m and f = 0·008.

(a) Power of each jet

We know that area of each nozzle,

$$a = \frac{\pi}{4} \times (d)^2 = \frac{\pi}{4} \times (0{\cdot}2)^2 = 0{\cdot}0314 \text{ m}^2$$

and velocity of the jet,
$$V = C_v\sqrt{2gH} = 0{\cdot}98 \times \sqrt{2 \times 9{\cdot}81 \times 500} = 97{\cdot}1 \text{ m/s}$$

...(Assuming C_v = 0·98)

$\therefore$ Discharge through each jet,

$$Q = a \,.\, V = 0{\cdot}0314 \times 97{\cdot}1 = 3{\cdot}05 \text{ m}^3\text{/s}$$

and power of each jet = $wQH = 9{\cdot}81 \times 3{\cdot}05 \times 500 = 14\,960$ kW **Ans.**

(b) Total power available at the reservoir

We also know that area of the penstock,

$$A = \frac{\pi}{4} \times (D)^2 = \frac{\pi}{4} \times (0{\cdot}9)^2 = 0{\cdot}636 \text{ m}^2$$

and velocity of water in the penstock,

$$v = \frac{Q}{A} = \frac{3{\cdot}05}{0{\cdot}636} = 4{\cdot}8 \text{ m/s}$$

$\therefore$ Head lost due to friction in each penstock,

$$H_f = \frac{4flv^2}{2gd} = \frac{4 \times 0{\cdot}008 \times 1600 \times (4{\cdot}8)^2}{2 \times 9{\cdot}81 \times 0{\cdot}9} = 66{\cdot}8 \text{ m}$$

and total power available at the reservoir (in 4 penstocks)

$$P = 4 \times wQ\,(H + H_f) = 4 \times 9{\cdot}81 \times 3{\cdot}05\,(500 + 66{\cdot}8) \text{ kW}$$
$$= 67\,836 \text{ kW} \quad \textbf{Ans.}$$

Example 32·5. *The Pykara Power House, in South India, is equipped with impulse turbines of pelton type. Each turbine delivers a maximum power of 14 250 kW, when working under a head of 900 metres and running at 600 r.p.m.*

Find the diameter of the jet and the mean diameter of the wheel. Take ...

Solution. Given : P = 14 250 kW; H = 900 m; N = 600 r.p.m. and $\eta_0 = 89.2\% = 0.892$

Diameter of the jet

Let d = Diameter of the jet, and

Q = Discharge of the turbine.

We know that overall efficiency of the turbine (η_0),

$$0.892 = \frac{P}{wQH} = \frac{14\,250}{9.81 \times Q \times 900} = \frac{1.61}{Q}$$

or $Q = 1.61/0.892 = 1.8 \text{ m}^3/\text{s}$

and velocity of the jet, $V = C_v \times \sqrt{2gH} = 0.98 \times \sqrt{2 \times 9.81 \times 900} = 130.2$ m/s

...(Assuming $C_v = 0.98$)

Now the discharge through the turbine must be equal to discharge through the jet. *i.e.*,

$$Q = V \times \frac{\pi}{4} \times (d)^2$$

or $1.8 = 130.2 \times \frac{\pi}{4} \times (d)^2 = 102.3\, d^2$

$\therefore$ $d^2 = 1.8/102.3 = 0.018$ or $d = 0.134$ m $= 134$ mm **Ans.**

Mean diameter of the wheel

Let D = Mean diameter of the wheel.

We know that peripheral velocity of the wheel,

$$v = 0.46 \times V = 0.46 \times 130.2 = 59.9 \text{ m/s}$$

We also know that peripheral velocity of the wheel (v),

$$59.9 = \frac{\pi DN}{60} = \frac{\pi D \times 600}{60} = 31.42D$$

$\therefore$ $D = 59.9/31.42 = 1.91$ m **Ans.**

Example 32·6. *A Pelton wheel is required to generate 3750 kW under an effective head of 400 metres. Find the total flow in litres/second and size of the jet. Assume generator efficiency 95%, overall efficiency 80%, coefficient of velocity 0·97, speed ratio 0·46. If the jet ratio is 10, find the mean diameter of runner.*

Solution. Given : P = 3750 kW; H = 400 m; $\eta_\gamma = 95\% = 0.95\%$ $\eta_0 = 80\% = 0.8$;

$C_v = 0.97$; and speed ratio $\frac{v}{\sqrt{2gH}} = 0.46$

Total flow of water in litres/second

Let Q = Total flow of water in litres/s

We know that power available,

$$P = \frac{\text{Power generated}}{\text{Generator efficiency}} = \frac{3750}{0.95} = 3947 \text{ kW}$$

and overall efficiency (η_0),

$$0.8 = \frac{P}{wQH} = \frac{3947}{9.81 \times Q \times 400} = \frac{1}{Q}$$

Size of jet

Let $\quad d =$ Diameter of the jet.

We know that velocity of the jet,

$$V = C_v \sqrt{2gH} = 0{\cdot}97 \times \sqrt{2 \times 9{\cdot}81 \times 400} = 85{\cdot}9 \text{ m/s}$$

Now the total discharge of the wheel should be equal to the discharge through the jet. *i.e.,*

$$Q = V \times \frac{\pi}{4} \times (d)^2$$

or

$$1{\cdot}25 = 85{\cdot}9 \times \frac{\pi}{4} \times (d)^2 = 67{\cdot}5\, d^2$$

$\therefore$

$$d^2 = 1{\cdot}25/67{\cdot}5 = 0{\cdot}0185 \text{ or } d = 0{\cdot}136 \text{ m} = 136 \text{ mm} \quad \textbf{Ans.}$$

Example 32·7. *A Pelton wheel has a mean bucket speed of 15 m/s with a jet of water impinging with a velocity of 40 m/s and discharging 450 litres/s. If the buckets deflect the jet through an angle of 165°, find the power generated by the wheel.*

Solution. Given : $v = 15$ m/s; $V = 40$ m/s; $Q = 450$ litres/s $= 0{\cdot}45$ m^3/s and $\phi = 180° - 165° = 15°$ (Because the jet is deflected through 165°).

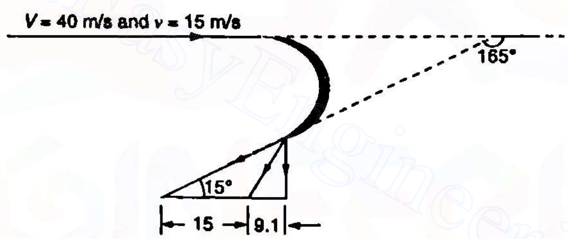


Fig. 32·4

From the inlet trianglet, we find that velocity of whirl at inlet

$$V_w = 40 \text{ m/s} \quad \ldots(\because V = V_w)$$

and relative velocity, $\quad V_r = V - v = 40 - 15 = 25$ m/s

From the outlet triangle, we also find that

$$V_{r1} = V_r = 25 \text{ m/s}$$

and velocity of buckets, $\quad v_1 = v = 15$ m/s

$\therefore$ Velocity of whirl at outlet,

$$V_{w1} = v_1 - V_{r1} \cos\phi = 15 - (25 \cos 15°) = 15 - (25 \times 0{\cdot}9659) \text{ m/s}$$

$$= 15 - 24{\cdot}1 = -9{\cdot}1 \text{ m/s}$$

...(Minus sign indicates that the direction of V_{w1} is opposite to that of V or v)

We know that work done per kN of water,

$$= \frac{v}{g}(V_w - V_{w1}) = \frac{15}{9{\cdot}81}[40 - (-9{\cdot}1)] = \frac{15}{9{\cdot}81} \times 49{\cdot}1 \text{ kN-m/s}$$

and total work done $= 9{\cdot}81 \times 0{\cdot}45 \times 75{\cdot}1 = 331{\cdot}5$ kN-m/s

$\therefore$ Power generated by the wheel,

$$P = 331{\cdot}5 \text{ kJ/s} = 331{\cdot}5 \text{ kW} \quad \textbf{Ans.}$$

Example 32·8. *A Pelton wheel has a tangential velocity of buckets of 15 m/s. The water is being supplied under a head of 150 metres at the rate of 200 litres/s. The buckets deflect the jet through an angle of 160°. If the coefficient of velocity for the nozzle is 0·98, find the power produced by the wheel and its hydraulic efficiency.*

Solution. Given : $v = 30$ m/s; $H = 150$ m; $Q = 200$ litres/s $= 0{\cdot}2$ m^3/s; $\phi = 180° - 160° = 20°$ (Because the jet is deflected through 160°) and $C_v = 0.98$.

Power produced by the wheel

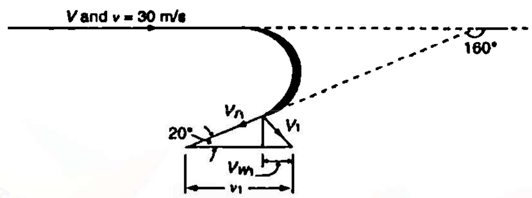


Fig. 32·5

We know that velocity of the jet,

$$V = C_v \times \sqrt{2gH} = 0{\cdot}98 \times = \sqrt{2 \times 9{\cdot}81 \times 150} \text{ m/s}$$

$$= 53{\cdot}2 \text{ m/s}$$

Fr m the inlet triangle, we find that velocity of whirl at inlet

$$V_w = 53{\cdot}2 \text{ m/s}$$

and relative velocity, $V_r = V - v = 53{\cdot}2 - 30 = 23{\cdot}2$ m/s

From the outlet triangle, we also find that the relative velocity.

$$V_{r1} = V_r = 23{\cdot}2 \text{ m/s}$$

and velocity of buckets, $v_1 = v = 30$ m/s

$\therefore$ Velocity of whirl at outlet,

$$V_{w1} = v_1 - V_{r1} \cos\phi = 30 - (23{\cdot}2 \cos 20°) \text{ m/s}$$

$$= 30 - (23{\cdot}2 \times 0{\cdot}9397) = 30 - 21{\cdot}8 = 8{\cdot}2 \text{ m/s}$$

Since the value of $V_{r1} \cos\phi$ ($28{\cdot}2 \cos 20° = 28{\cdot}2 \times 0{\cdot}9397 = 21{\cdot}8$) in less than v_1 (25), therefore shape of the outlet triangle will be as shown in Fig. 32·5. Moreover, the velocity of whirl (V_{w1}) will be positive, as it is in the same direction as that of V_{w1}.

We know that work done per kN of water,

$$= \frac{v}{g}(V_w - V_{w1}) = \frac{30}{9{\cdot}81}(53{\cdot}2 - 8{\cdot}2) = 137{\cdot}6 \text{ kN-m/s}$$

and total work done by the water $= 9{\cdot}81 \times 0{\cdot}2 \times 137{\cdot}6 = 270$ kN . m/s $= 270$ kJ/s

$\therefore$ Power produced by the wheel,

$$P = 270 \text{ kJ/s} = 270 \text{ kW} \quad \textbf{Ans.}$$

Hydraulic efficiency of the wheel

We also know that hydraulic efficiency of the wheel,

$$2(V_w - V_{w1}) \times v \qquad 2(53{\cdot}2 - 8{\cdot}2) \times 30$$

EXERCISE 32·1

1. An impulse turbine working under a head of 100 m is required to develop 250 kW. If the overall efficiency of the turbine is 85%, find the discharge of the turbine. **(Ans.** 0·3 m^3/s)
2. A Pelton wheel has mean bucket speed of 15 m/s with a jet of water flowing under a head of 120 m. If the jet is deflected through an angle of 160° and the coefficient of velocity is 0·97, find the hydraulic efficiency of the turbine. **(Ans.** 84·2%)
3. The overall efficiency of a Pelton wheel is 86% when the power developed is 500 kW under a head of 80 m. If the coefficient of velocity for the nozzle is 0·97, find the diameter of the nozzle. **(Ans.** 157 mm)
4. A Pelton wheel of 1 meter diameter is working under a head of 150 metres. Find the speed of the runner, if the coefficient of velocity and velocity ratio is 0·98 and 0·47 respectively. **(Ans.** 480 r.p.m.)
5. A Pelton wheel is producing 1350 kW under a head of 80 metres at 300 r.p.m. Find the diameter of the wheel, if the speed ratio is 0·45. Take C_v = 0·98. **(Ans.** 1·11 m)
6. A Pelton wheel is working under a head of 85 m and the rate of flow of water through the jet is 800 litres/s. If the bucket speed is 14 m/s and the jet is deflected through 165°, find the power produced by the wheel and its efficiency. Take coefficient of velocity as 0·985. **(Ans.** 576·8 kW; 86·5%)

32·13. Number of Jets of a Pelton Wheel

A Pelton turbine, generally, has a single jet only. But whenever a single jet cannot develop the required power, we may have to employ more than one jets. In Fig. 32·6 show an arrangement of four jets for a Pelton wheel.

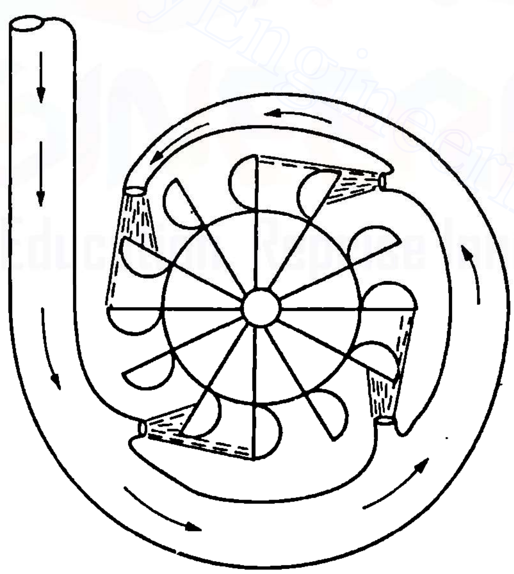


Fig. 32·6. Number of jets

In general, the maximum number of jets provided to a Pelton wheel are six. While designing the jets, care should always be taken to provide the jets at equidistant on the outer periphery of the wheel.

Sometimes, instead of providing a number of jets to a wheel (as shown in Fig. 32·6) two or three wheels are mounted on a common shaft. Such a system is known as overhung wheels

Example 32·9. *A double overhung Pelton wheel unit is directly coupled to 1000 kW generator. Find the power developed by each wheel, if the generator efficiency is 84%.*

Solution. Given : Total output of the unit (P) = 1000 kW and η = 84% = 0·84.

We know that power generated by the Pelton wheel runner

$$= \frac{P}{\eta} = \frac{1000}{0 \cdot 84} = 1190 \text{ kW}$$

Since the Pelton wheel is double overhung (*i.e.* two wheels are mounted on the runner), therefore power developed by each wheel

$$= 1190/2 = 595 \text{ kW} \quad \textbf{Ans.}$$

Example 32·10. *A Pelton wheel is supplied water under a head of 200 m through a 100 mm diameter pipes. If the quantity of water supplied to the wheel is 1.25 m³/s. Find the number of jets. Assume C_v = 0·97.*

Solution. Given : H = 200 m; d = 100 mm = 0.1 m; Q = 1·25 m³/s and C_v = 0·97.

Let n = Number of jets

We know that cross-sectional area of one pipe,

$$a = \frac{\pi}{4} \times (d)^2 = \frac{\pi}{4} \times (0 \cdot 1)^2 = 7 \cdot 854 \times 10^{-3} \text{ m}^2$$

and velocity of the jets,

$$V = C_v\sqrt{2gH} = 0 \cdot 97 \times \sqrt{2 \times 9 \cdot 81 \times 200} = 60 \cdot 8 \text{ m/s}$$

Now the total discharge of the wheel must be equal to the discharge through the jets. *i.e.*,

$$1 \cdot 25 = n \times V \times a = n \times 60 \cdot 8 \times (7 \cdot 854 \times 10^{-3}) = 0 \cdot 478\ n$$

$$\therefore \quad n = 1 \cdot 25/0 \cdot 478 = 2 \cdot 6 \text{ say } 3 \quad \textbf{Ans.}$$

Example 32·11. *A Pelton wheel has to develop 5000 kW under a net head of 300 m, while running at a speed of 500 r.p.m. If the coefficient of velocity for the jet = 0·97, speed ratio = 0·46 and the ratio of the jet diameter is 1/10 of wheel diameter, calculate (a) quantity of water supplied to the wheel, (b) diameter of pitch circle, (c) diameter of jets, and (d) number of jets.*

Assume overall efficiency of the wheel as 80%.

Solution. Given : P = 8000 kW; H = 300 m; N = 500 r.p.m.; C_v = 0·97; v = 0·46V; $d = \frac{D}{10}$ (where D is the diameter of the wheel) and η = 80% = 0·8.

(a) Quantity of water supplied to the wheel

Let Q = Quantity of water supplied to the wheel.

We know that overall efficiency of the wheel (η_0),

$$0 \cdot 8 = \frac{P}{wQH} = \frac{8000}{9 \cdot 81 \times Q \times 300} = \frac{2 \cdot 72}{Q}$$

$$\therefore \quad Q = 2 \cdot 72/0 \cdot 8 = 3 \cdot 4 \text{ m}^3/\text{s} \quad \textbf{Ans.}$$

(b) Diameter of pitch circle

Let D = Diameter of pitch circle.

We know that the velocity of jet,

$$V = C_v\sqrt{2gH} = 0 \cdot 97\sqrt{2 \times 9 \cdot 81 \times 300} = 74 \cdot 4 \text{ m/s}$$

and peripheral velocity, $v = 0 \cdot 46\ V = 0 \cdot 46 \times 74 \cdot 4 = 34 \cdot 2$ m/s

We also know that peripheral velocity (v),

$$34{\cdot}2 = \frac{\pi DN}{60} = \frac{\pi \times D \times 500}{60} = 26{\cdot}2\,D$$

$$\therefore \qquad D = 34{\cdot}2/26{\cdot}2 = 1{\cdot}3 \text{ m} \quad \textbf{Ans.}$$

(c) Diameter of the jets

We know that diameter of the jets,

$$d = \frac{D}{10} = \frac{1{\cdot}3}{10} = 0{\cdot}13 \text{ m} = 130 \text{ mm} \quad \textbf{Ans.}$$

(d) Number of jets

Let n = Number of jets.

Now total discharge of the wheel, must be equal to the discharge through the jets. *i.e.,*

$$3{\cdot}4 = n \times V \times \frac{\pi}{4} \times (d)^2 = n \times 74{\cdot}4 \times \frac{\pi}{4} \times (0{\cdot}13)^2 = 0{\cdot}99\,n$$

$$n = 3{\cdot}4/0{\cdot}99 = 3{\cdot}4 \text{ say } 4 \quad \textbf{Ans.}$$

EXERCISE 32·2

1. A double overhung impulse turbine is coupled to a 2400 kW generator. What is the power developed by each wheel, if the generator efficiency is 80%. **(Ans. 1500 kW)**
2. A Pelton wheel operating under a head of 150 m develops 2500 kW. Find the number of jets required for the wheel, if its overall efficiency is 85%. Take coefficient of velocity for the jet as 0·98 and diameter of the pipes as 120 mm. **(Ans. 4)**
3. A Pelton wheel, working under a head of 250 metres, develops 6000 kW while running at 600 r.p.m. with an overall efficiency of 90%. The ratio of jet diameter to the wheel diameter is 1/8. The coefficient of velocity for the nozzle is 0·98 and the ratio of tangential velocity of the wheel to the velocity of the wheel is 0·46. Find (*i*) rate of flow, (*ii*) diameter of the wheel, and number of jets. **(Ans. 2·45 m^3/s; 1 m; 3)**

32·14. Design of Pelton Wheels

A Pelton wheel is, generally, designed for a given head of water, power to be developed and speed of the runner. In modern design offices, a Pelton wheel is designed to find out the following data:

1. Diameter of wheel,
2. Diameter of the jet,
3. Size (*i.e.,* width and depth) of the buckets
4. No. of buckets.

While designing a Pelton wheel, if sufficient data is not available, then the following assumptions are made, which are meant for the best results:

1. Overall efficiency between 80% and 87% (preferably 85%)
2. Coefficient of velocity 0·99 (preferably 0·985)
3. Ratio of peripheral velocity to the jet velocity as 0·46.

Note. As a matter of fact, diameter of wheel and diameter of jets is obtained from the discharge condition. We have already discussed these points in our previous examples. In the following pages, we shall discuss the size of the buckets and no. of buckets.

32·15 Size of Buckets of a Pelton Wheel

In general, the buckets of a Pelton wheel have the following dimensions :

Width of the bucket $= 5 \times d$

and depth of the bucket $= 1{\cdot}2 \times d$

where d = Diameter of the jet.

32·16. Number of Buckets on the Periphery of a Pelton Wheel

The number of buckets, on the periphery of a Pelton wheel, is decided mainly on the following two principles, *viz.*

1. The number of buckets should be as few as possible, so that there may be as little loss, due to friction, as possible.
2. The jet of water must be fully utilised, so that no water from the jet should go waste.

Now consider a jet of water impinging on the buckets of a Pelton wheel with O as centre.

Let R = Radius of the mean bucket circle,

d = Diameter of the jet, and

α = Angle, subtended by the two adjacent buckets at the centre of the wheel.

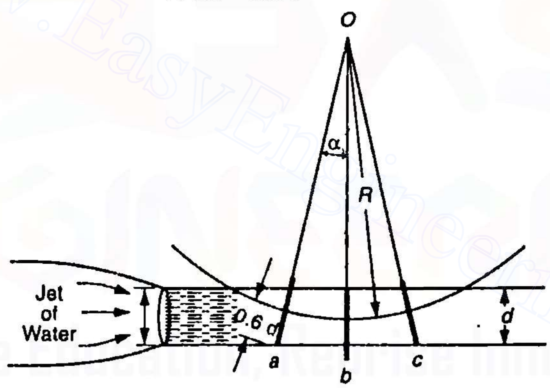


Fig 32·7. No. of buckets on the periphery

At one instant let a, b and c be the position of three adjacent buckets as shown in Fig. 32·7. Before this instant, the jet was having some impact on the bucket b also. But at this instant, the jet will be intercepted by the bucket a, which will have its impact. (This happens when the outer edge of the bucket a just touches the lower portion of the jet). It may be noted, that such a stage comes, when half of the depth of the bucket (*i.e.*, 0·6 d), projecting from the mean circumference, will just touch the lower portion of the jet. At this instant, the bucket a will move as a result of the jet impact.

When have seen in Art. 32·7 that the velocity of jet is twice the velocity of buckets. Therefore the time taken by the bucket b in travelling up to c is equal to the time taken by the last particle of water (which is just on the right side of bucket a) in travelling up to c. It is thus obvious, that the bucket b will continue to have impact till it reaches at c.

From the geometry of the figure, we find that

$$\cos \alpha = \frac{R + 0{\cdot}5d}{R + 0{\cdot}6d}$$

and then the number of buckets may be found out by the relation:

Note: It is a theoretical relation, derived for the number of buckets required for a Pelton wheel. But in actual practice, we provide the number of buckets to a Pelton wheel as half of the buckets obtained from the above equation. This unsatisfactory result has given birth to many empirical formulate. One of such formulae, which is widely used is;

$$\text{Number of buckets} = \left(\frac{D}{2d} + 15\right)$$

where D = Mean bucket diameter, and

d = Diameter of the jet.

Example 32·12. *Design a Pelton wheel for a head of 350 m at a speed of 300 r.p.m. Take overall efficiency of the wheel as 85% and ratio of jet to the wheel diameter as 1/10.*

Solution. Given : $H = 350$ m; $N = 300$ r.p.m.; $\eta_0 = 85\% = 0{\cdot}85$ and $\frac{d}{D} = \frac{1}{10}$ or $d = \frac{D}{10}$

...(where D is the diameter of the wheel).

1. Diameter of the wheel

Let D = Diameter of wheel.

We know that velocity of the jet,

$$V = C_v \times \sqrt{2gH} = 0{\cdot}98 \times \sqrt{2 \times 9{\cdot}81 \times 350} = 81{\cdot}2 \text{ m/s}$$

...(Assuming $C_v = 0{\cdot}98$)

and peripheral velocity of the wheel,

$$v = 0{\cdot}46\, V = 0{\cdot}46 \times 81{\cdot}2 = 37{\cdot}4 \text{ m/s}$$

We also know that peripheral velocity (v)

$$37{\cdot}4 = \frac{\pi DN}{60} = \frac{\pi \times D \times 300}{60} = 15{\cdot}7\, D$$

$$\therefore \quad D = 37{\cdot}4/15{\cdot}7 = 2{\cdot}4 \text{ m} \quad \textbf{Ans.}$$

2. Diameter of the jet

We know that diameter of the jet,

$$d = \frac{\text{Dia. of wheel}}{10} = \frac{2{\cdot}4}{10} = 0{\cdot}24 \text{ m} = 240 \text{ mm} \quad \textbf{Ans.}$$

3. Width of the buckets

We know that width of the buckets

$$= 5 \times d = 5 \times 0{\cdot}24 = 1{\cdot}2 \text{ m} \quad \textbf{Ans.}$$

4. Depth of the buckets

We know that depth of the buckets

$$= 1{\cdot}2 \times d = 1{\cdot}2 \times 0{\cdot}24 = 0{\cdot}48 \text{ m} \quad \textbf{Ans.}$$

5. No. of buckets

We also know that the number of buckets

$$= \frac{D}{2d} + 15 = \frac{2{\cdot}4}{2 \times 0{\cdot}24} + 15 = 20 \quad \textbf{Ans.}$$

Example 32·13. *Design a Pelton wheel for the following data:*

Head of water = *150 metres*

Power to be developed = *600 kW*

Solution. Given : $H = 150$ m; $P = 600$ kW and $N = 360$ r.p.m.

1. Diameter of the wheel

Let D = Diameter of the wheel.

We know that velocity of the jet,

$$V = C_v \times \sqrt{2gH} = 0{\cdot}985 \times \sqrt{2 \times 9{\cdot}81 \times 150} = 53{\cdot}5 \text{ m/s}$$

...(Assuming $C_v = 0{\cdot}985$)

and peripheral velocity, $v = 0{\cdot}46\, V = 0{\cdot}46 \times 53{\cdot}4 = 24{\cdot}6$ m/s

...(Assuming $v = 0{\cdot}46V$)

We also know that peripheral velocity (v),

$$24{\cdot}6 = \frac{\pi DN}{60} = \frac{\pi \times D \times 360}{60} = 18{\cdot}85\ D$$

$$D = 24{\cdot}6/18{\cdot}85 = 1{\cdot}3 \text{ m} \quad \textbf{Ans.}$$

2. Diameter of the jet

Let d = Diameter of the jet.

We know that overall efficiency of the jet,

$$0{\cdot}85 = \frac{P}{wQH} = \frac{600}{9{\cdot}81 \times Q \times 150} = \frac{0{\cdot}408}{Q}$$

...(Assuming $\eta_0 = 85\%$)

$$\therefore \quad Q = 0{\cdot}408/0{\cdot}85 = 0{\cdot}48 \text{ m}^3\text{/s}$$

Now the discharge through the wheel, must be equal to the discharge through the jet. *i.e.*,

$$Q = V \times \frac{\pi}{4} \times d^2$$

or

$$0{\cdot}48 \times 53{\cdot}4 \times \frac{\pi}{4} \times (d)^2 = 41{\cdot}9\, d^2$$

$$\therefore \quad d^2 = 0{\cdot}48/41{\cdot}9 = 0{\cdot}011 \quad \text{or} \quad d = 0{\cdot}105 \text{ m} = 105 \text{ mm} \quad \textbf{Ans.}$$

3. Width of the buckets

We know that width of the buckets

$$= 5 \times d = 5 \times 0{\cdot}105 = 525 \text{ mm} \quad \textbf{Ans.}$$

4. Depth of the buckets

We know that depth of the buckets

$$= 1{\cdot}2 \times d = 1{\cdot}2 \times 105 = 210 \text{ mm} \quad \textbf{Ans.}$$

5. No. of the buckets

We also know that the no. of buckets

$$= \frac{D}{2d} + 15 = \frac{1{\cdot}3}{2 \times 0{\cdot}105} + 15 = 21 \quad \textbf{Ans.}$$

32·17. Governing of an Impulse Turbine (Pelton Wheel)

In actual practice, load on the generator (which is coupled to an impulse turbine) is always fluctuating from time to time. This fluctuating load, on the generator, has some effect on the turbine also, because the generator is directly coupled to the turbine. A little consideration will show, that ... of load on the turbine, is sure to change its speed and rate of flow. It has been observed the turbine. Though there are many methods of governing an impulse turbine, yet the servomotor method or relay cylinder method is commonly used these days which is discussed below:

The servomotor method is a mechanism consisting of the following parts as shown in Fig. 32·8.

1. Centrifugal governor,
2. Control valve,
3. Servomotor,
4. Gear pump,
5. Oil pump,
6. Spear or needle, and
7. A set of pipes, connecting oil sump with control valve, and control valve with relay cylinder.

The centrifugal governor is driven from the main shaft of the turbine, either by belt or gear arrangement. The control valve controls the direction of flow of the liquid (which is pumped by gear pump from the oil sump) either in pipe *AA* or *BB*. The servomotor or relayvalve has a piston (whose motion, towards left or right, depends upon the pressure of the liquid flowing through the pipes *AA* or *BB*) is connected to a spear or needle, which reciprocates inside the nozzle as shown in Fig. 32·8.

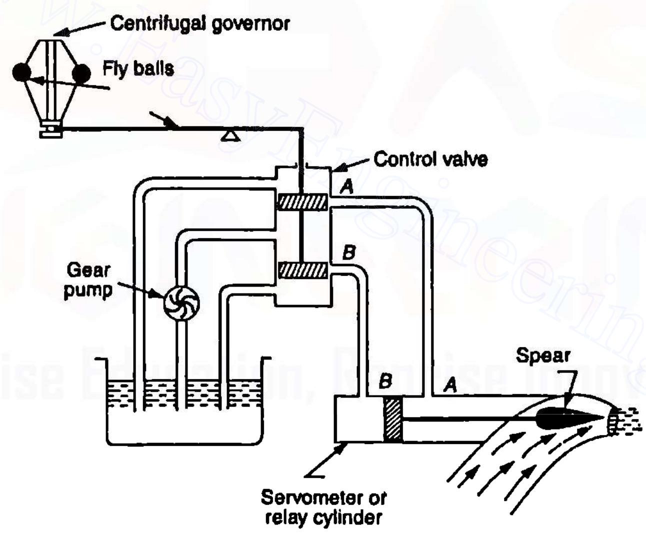


Fig. 32·8. Governing of impulse turbine

When the turbine is running at its normal speed, the positions of piston (in a servomotor or relay cylinder), control valve and fly balls of centrifugal governor will be in their normal positions as shown in the figure. The oil pumped by the gear pump, into the control valve, will come back to the oil sump as the mouths of both the pipes. *AA* and *BB* are closed by the two wings of the control valve..

Now, let the load on the turbine increase, which will decrease the speed of the turbine. This decrease in the speed of the turbine runner will also decrease the speed of centrifugal governor. As a result of this, the fly balls will come down, thus decreasing their amplitude (due to decrease in centrifugal force). This coming down of the fly balls, will also bring down the sleeve, as the sleeve is connected to the central vertical bar of the centrifugal governor. This downward movement of the sleeve will raise the control valve rod (as the sleeve is connected to the control valve rod through a lever pivoted on a fulcrum). Now, a slight upwards movement of from the control valve to the right side of the piston in the servomotor through the pipe *AA*. This oil, under pressure, will move the piston and spear towards the left, which will open more area of the nozzle controlling the flow to the turbine. This increase in the area of flow will increase the rate of flow. As a result of this, there will be an increase in the speed of the turbine. When the speed of the runner will come up to the normal speed, fly balls will move up and the sleeve as well as the control valve rod will occupy its normal position.

It may be noted that when the load on the turbine decreases, its speed will increase. As a result of this the fly balls will go up (due to increase in centrifugal force) and sleeve will also go up. This will push the control valve downwards. This downward movement of the control valve rod will open the mouth of the pipe *BB* (still keeping the mouth of the pipe *AA* closed). Now the oil (under pressure) will rush from the control valve to the left side of the piston in servomotor through the pipe *BB*. This oil, under pressure, will move the piston and spear towards the right, which will decrease the area of the nozzle and ultimately decrease the rate of flow. This decrease in the rate of flow will decrease the speed of the turbine till the speed, once again, comes down to the normal.

32·18. Other Impulse Turbines

The Pelton wheel is considered to be the most popular impulse turbine, for high heads, and is widely used successfully all over the world. Many scientists and engineers, working in hydraulic research stations all over the world are busy in developing improved type of turbines. Some of them have also been able to design new impulse turbines. Though these turbines are not of practical importance, yet they have some academic importance. Following impulse turbines are important from the subject point of view:

1. *Girard turbine.* In a Girard turbine, the direction of flow of water is parallel to the axis of wheel. The guide vanes allow the water to impact through two diametrically opposite quadrants. The Girard turbine is suitable for the generation of large power, under low heads. In case of low heads, the turbine wheel is kept horizontal and for larger heads, the wheel is kept vertical.
2. *Turgo turbine.* In a Turgo turbine, the flow of water is parallel to the axis of wheel (in the same way as that of Girard turbine). It has one or two nozzles similar to the Pelton wheel. The only difference between a Pelton wheel are turgo turbine is that in a Pelton wheel, the jet strikes the buckets in the centre. But in a turgo turbine, the jet strikes at one end, and leaves at the other. The flow of water is regulated in the same way as that of Pelton wheel. For the same jet diameter and discharge, the diameter of a Turgo turbine is much less than that of a Pelton wheel. But its peripheral speed is higher than that of a Pelton wheel.
3. *Banki turbine.* In a Banki turbine, the jet of water after striking the buckets is made to pass through the runner. The water passing through the runner, gives some impulse to the runner. As a result of this, the velocity of water is utilised two times, which improves its efficiency.

Through the theory of utilising the velocity of water two times did not succeed in actual practice, yet this idea is utilised in steam turbines.

EXERCISE 32·3

1. A Pelton wheel working under a head of 100 metres produces 500 kW at 250 r.p.m. The overall efficiency of the wheel and coefficient of velocity for the nozzle are 80% and 0·98 respectively. If the wheel diameter is 1 metre, find

   (1) diameter of the jet (2) width of the buckets

   (3) depth of the buckets (4) number of buckets (**Ans.** 137 mm; 685 mm; 164 mm; 19)

2. A Pelton wheel is to be designed to produce 400 kW under a head of 60 m when running at 200 r.p.m. The overall efficiency of the wheel is 85% and coefficient of velocity for the jet is 0.98 Take velocity of the buckets = 0·45 times the velocity of the jet.

(**Ans.** d = 180 mm; D = 1·4 m; Width of buckets = 900 mm; Depth of buckets = 216 mm; No. of buckets = 14)

QUESTIONS

1. What is meant by an impulse turbine?
2. Describe, withe the help of simple sketches, the working of an impulse turbine.
3. Derive an equation for the hydraulic efficiency of a Pelton wheel.
4. Show from, first principles, that the theoretical value for peripheral coefficient of a Pelton wheel is 0·5.
5. On what factors does the number of jets depend in the case of Pelton wheels?
6. What is the ratio of width of the buckets and depth of the buckets to the jet diameter?
7. By means of a neat sketch, giving complete operation, explain how the turbines are governed for constant speed.

OBJECTIVE TYPE QUESTIONS

1. A Pelton wheel is an

   (*a*) axial flow impulse turbine (*b*) inward flow impulse turbine

   (*c*) outward flow impulse turbine (*d*) all of these

2. An impulse turbine is used for

   (*a*) low head of water (*b*) medium head of water

   (*c*) high head of water (*d*) any one of these

3. The maximum hydraulic efficiency of an impulse turbine is equal to

   (*a*) $\frac{1 + \cos\phi}{2}$ (*b*) $\frac{1 - \cos\phi}{2}$ (*c*) $\frac{1 + \sin\phi}{2}$ (*d*) $\frac{1 - \sin\phi}{2}$

   where ϕ is the angle of blade tip at outlet.

4. A double overhung Pelton wheel has

   (*a*) two jets (*b*) two runners (*c*) four jets (*d*) four runners.

5. The number of buckets on the periphery of a Pelton wheel is given by

   (*a*) $\frac{D}{2d} + 5$ (*b*) $\frac{D}{2d} + 10$ (*c*) $\frac{D}{2d} + 15$ (*d*) $\frac{D}{2d} + 20$

Answers

1. (*a*), 2. (*c*), 3. (*a*), 4. (*b*), 5. (*c*)