*1. Introduction. 2. Efficiencies of Steam Turbine. 3. Condition for Maximum Efficiency of an Impulse Turbine. 4. Condition for Maximum Efficiency of a Reaction Turbine. 5. Compounding of Impulse Steam Turbines (Methods of Reducing Rotor Speeds). 6. Velocity Compounding of an Impulse Turbine. 7. Pressure Compounding of an Impulse Turbine. 8. Pressure-velocity Compounding of an Impulse Turbine. 9. Internal Losses in Turbines. 10. Governing of Steam Turbines. 11. Throttle Governing of Steam Turbines.*

## 24.1. Introduction

In the last two chapters, we have discussed impulse and reaction steam turbines. In these chapters, we have discussed power generated in these turbines. But in this chapter, we shall discuss their performance *i.e.* efficiencies and governing.

## 24.2. Efficiencies of Steam Turbine

The following efficiencies of impulse as well as reaction steam turbines are important from the subject point of view :

1. *Diagram or blading efficiency.* It is the ratio of the work done on the blades to the energy supplied to the blades.

Let $V$ = Absolute velocity of inlet steam in m/s, and

$m$ = Mass of steam supplied in kg/s.

∴ Energy supplied to the blade per second,

$$= \frac{mV^2}{2} \text{ J/s}$$

We know that work done on the blades per second

$$= m (V_w + V_{w1}) V_b \text{ J/s}$$

∴ Diagram* or blading efficiency,

$$\eta_b = \frac{m (V_w + V_{w1}) V_b}{mV^2/2} = \frac{2 (V_w + V_{w1}) V_b}{V^2}$$

The work done on the turbine blades may also be obtained from the kinetic energy of inlet and exit as discussed below :

Let $V_1$ = Absolute velocity of exit steam in m/s.

We know that kinetic energy at inlet per second

$$= \frac{mV^2}{2} \text{ J/s.}$$

* It is called diagram efficiency because the quantities involved are obtained from velocity diagram.




www.Jntufastupdates.com
Scanned by CamScanner

and kinetic energy at exit per second

$$= \frac{mV_1^2}{2} \text{ J/s}$$

∴ Work done on the blades per second,

= Loss of kinetic energy

$$= \frac{mV^2}{2} - \frac{mV_1^2}{2} = \frac{m}{2}(V^2 - V_1^2) \text{ J/s}$$

and power developed, $P = \frac{m(V^2 - V_1^2)}{2}$ watts ... (∵ 1 J/s = 1 watt)

∴ Blading efficiency, $\eta_b = \frac{\frac{m}{2}(V^2 - V_1^2)}{\frac{mV^2}{2}} = \frac{V^2 - V_1^2}{V^2}$

2. *Gross or stage efficiency.* It is the ratio of the work done on the blades per kg of steam to the total energy supplied per stage per kg of steam.

Let $h_1$ = Enthalpy or total heat of steam before expansion through the nozzle in kJ/kg of steam, and

$h_2$ = Enthalpy or total heat of steam after expansion through the nozzle in kJ/kg of steam.

∴ Enthalpy or heat drop in the nozzle ring of an impulse wheel,

$$h_d = h_1 - h_2 \text{ (in kJ/kg)}$$

and total energy supplied per stage = $1000\, h_d$ J/kg of steam

We know that work done on the blade per kg of steam

$$= 1 (V_w + V_{w1})\, V_b \text{ J/kg of steam}$$

∴ Gross or stage efficiency,

$$\eta_s = \frac{(V_w + V_{w1})\, V_b}{1000\, h_d} = \frac{(V_w + V_{w1})\, V_b}{1000\,(h_1 - h_2)}$$

3. *Nozzle efficiency.* It is the ratio of energy supplied to the blades per kg of steam to the total energy supplied per stage per kg of steam.

We know that energy supplied to the blades per kg of steam

$$= V^2/2 \text{ (in joules)}$$

∴ Nozzle efficiency, $\eta_n = \frac{V^2/2}{1000\, h_d} = \frac{V^2}{2000\, h_d}$

Note : We know that stage efficiency,

$$\eta_s = \frac{(V_w + V_{w1})\, V_b}{1000\, h_d} = \frac{2(V_w + V_{w1})\, V_b}{V^2} \times \frac{V^2}{2000\, h_d}$$

$$= \eta_b \times \eta_n$$

*i.e.* Stage efficiency = Blading efficiency × Nozzle efficiency

**Example 24.1.** *The velocity of steam at inlet to a simple impulse turbine is 1000 m/s and the nozzle angle is 20°. The mean blade speed is 400 m/s and the blades are symmetrical. The mass flow*


www.Jntufastupdates.com

Scanned by CamScanner

*rate of steam is 0.75 kg/s. The friction effects on the blades are negligible. Estimate : (a) the blade angles ; (b) the tangential force on the blades; (c) the axial thrust; (d) the diagram power; and (e) the diagram efficiency.*

**Solution.** Given : $V = 1000$ m/s ; $\alpha = 20^\circ$ ; $V_b = 400$ m/s ; $\theta = \phi$ for symmetrical blades, $m = 0.75$ kg/s

(a) *Blade angles*

Now draw the combined velocity triangle, as shown in Fig. 24.1, as discussed below :

1. First of all, draw a horizontal line and cut off $AB$ equal to 400 m/s, to some suitable scale, to represent the blade speed ($V_b$).

2. Now draw inlet velocity triangle $ABC$ on the base $AB$ with $\alpha = 20^\circ$ and $BC = V = 1000$ m/s. By measurement, we find that blade angle at inlet,

$$\theta = 33^\circ \text{ Ans.}$$

3. Similarly, draw outlet velocity triangle $ABD$ on the same base $AB$ with $\phi = \theta = 33^\circ$ and $V_{r1} = V_r$.

4. From $C$ and $D$, draw perpendiculars to meet the line $AB$ produced at $E$ and $F$.

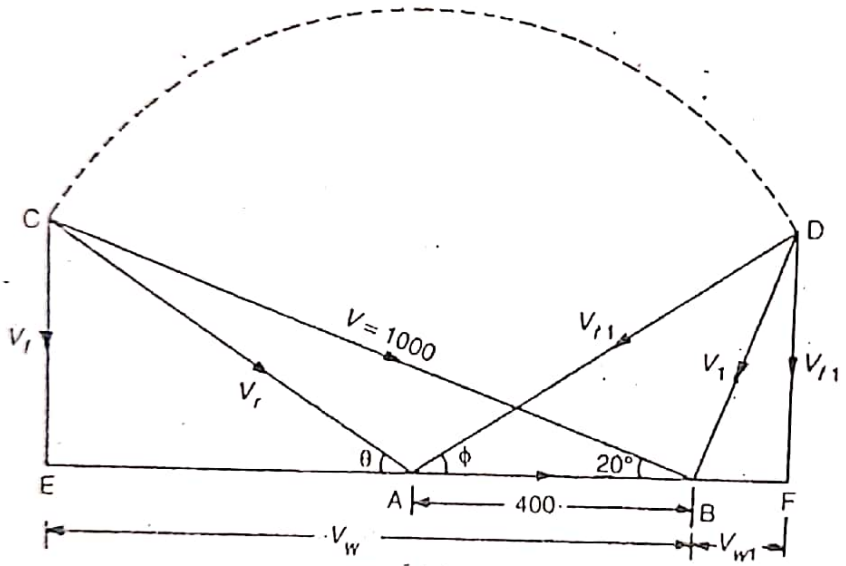



Fig. 24.1

(b) *Tangential force on the blades*

By measurement from the velocity diagram, we find that change in the velocity of whirl,

$$V_w + V_{w1} = EF = 1120 \text{ m/s}$$

We know that tangential force on the blades,

$$F_X = m (V_w + V_{w1}) = 0.75 \times 1120 = 840 \text{ N Ans.}$$

(c) *Axial thrust*

We know that axial thrust,

$$F_Y = m (V_f - V_{f1}) = 0 \text{ Ans.}$$

Note : Since the blades are symmetrical and friction effects on the blades are neglected, therefore $V_f = V_{f1}$.

(d) *Diagram power*

We know that diagram power,

$$P = m (V_w + V_{w1}) V_b = 0.75 \times 1120 \times 400 = 336\,000 \text{ W}$$
$$= 336 \text{ kW Ans.}$$


www.Jntufastupdates.com

Scanned by CamScanner

(e) *Diagram efficiency*

We know that diagram efficiency,

$$\eta_h = \frac{2 (V_w + V_{w1}) V_b}{V^2} = \frac{2 \times 1120 \times 400}{(1000)^2} = 0.896 \text{ or } 89.6\% \text{ Ans.}$$

**Example 24.2.** *The following particulars refer to a single row impulse turbine :*

*Mean diameter of blade ring = 2.5 m ; Speed = 3000 r.p.m. ; Nozzle angle = 20° ; Ratio o blade velocity to steam velocity = 0.4 ; Blade friction factor = 0.8 ; Blade angle at exit = 3° less tha that at inlet ; Steam flow = 36 000 kg/h.*

*Draw velocity diagram for moving blade and estimate (a) Power developed ; (b) Blad efficiency ; and (c) Steam consumption is kg/kW h.*

**Solution.** Given : $d_m = 2.5$ m ; $N = 3000$ r.p.m. ; $\alpha = 20°$ ; $V_b / V = 0.4$ ; $K = V_{r1} / V_r = 0.8$ ; $\phi = \theta - 3°$ ; $m = 36\,000$ kg/h = 10 kg/s

We know that blade velocity,

$$V_b = \frac{\pi d_m N}{60} = \frac{\pi \times 2.5 \times 3000}{60} = 393 \text{ m/s}$$

∴ Steam velocity, $V = V_b / 0.4 = 393 / 0.4 = 982.5$ m/s

Now draw the combined velocity triangle, as shown in Fig. 24.2, as discussed below :

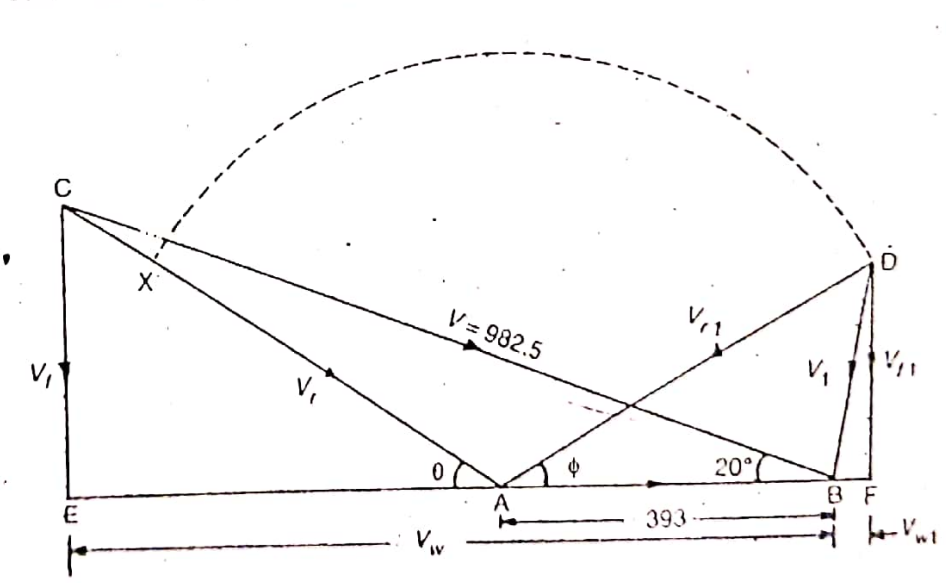



Fig. 24.2

1. First of all, draw a horizontal line and cut off $AB$ equal to 393 m/s, to some suitable scale, to represent the blade velocity ($V_b$).

2. Now draw inlet velocity triangle $ABC$ on the base $AB$ with $\alpha = 20°$ and $BC = V = 982.5$ m/s. By measurement, we find that blade angle at inlet ($\theta$) = 32.5°, and relative velocity of steam at inlet ($V_r$) = 626.7 m/s.

3. Similarly, draw outlet velocity triangle $ABD$ on the same base $AB$ with $\phi = \theta - 3° = 32.5 - 3 = 29.5°$ and $V_{r1} = AX = 0.8\ V_r = 0.8 \times 626.7 = 501.4$ m/s.

4. From $C$ and $D$, draw perpendiculars to meet the line $AB$ produced at $E$ and $F$.

By measurement from velocity triangle, we find that change in the velocity of whirl,

$$V_w + V_{w1} = EF = 967 \text{ m/s}$$


www.Jntufastupdates.com

Scanned by CamScanner

(a) *Power developed*

We know that power developed,

$$P = m (V_w + V_{w1}) V_b = 10 \times 967 \times 393 = 3800 \times 10^3 \text{ W}$$
$$= 3800 \text{ kW Ans.}$$

(b) *Blade efficiency*

We know that blade efficiency,

$$\eta_b = \frac{2 (V_w + V_{w1}) V_b}{V^2} = \frac{2 \times 967 \times 393}{(982.5)^2} = 0.787 \text{ or } 78.7\% \text{ Ans.}$$

(c) *Steam consumption in kg/kWh*

We know that steam consumption

$$= \frac{m}{P} = \frac{36\,000}{3800} = 9.47 \text{ kg/kWh Ans.}$$

**Example 24.3.** *A single row impulse turbine receives 3 kg/s steam with velocity of 425 m/s. The ratio of blade speed to jet speed is 0.4 and the stage output is 170 kW. If the internal losses due to disc friction etc. amount to 15 kW, determine the blading efficiency and the blade velocity coefficient. The nozzle angle is 16° and the blade exit angle is 17°.*

**Solution.** Given : $m = 3$ kg/s ; $V = 425$ m/s ; $V_b / V = 0.4$ ; Stage output = 170 kW ; Internal losses = 15 kW ; $\alpha = 16°$ ; $\phi = 17°$

*Blading efficiency*

We know that blade speed,

$$V_b = V \times 0.4 = 425 \times 0.4 = 170 \text{ m/s}$$

and total power developed, $P$ = Stage output + Internal losses

$$= 170 + 15 = 185 \text{ kW} = 185 \times 10^3 \text{ W}$$

Let $V_w + V_{w1}$ = Change in the velocity of whirl.

We know that power developed ($P$),

$$185 \times 10^3 = m (V_w + V_{w1}) V_b = 3 (V_w + V_{w1}) 170$$

$$\therefore \quad V_w + V_{w1} = 185 \times 10^3 / 3 \times 170 = 363 \text{ m/s}$$

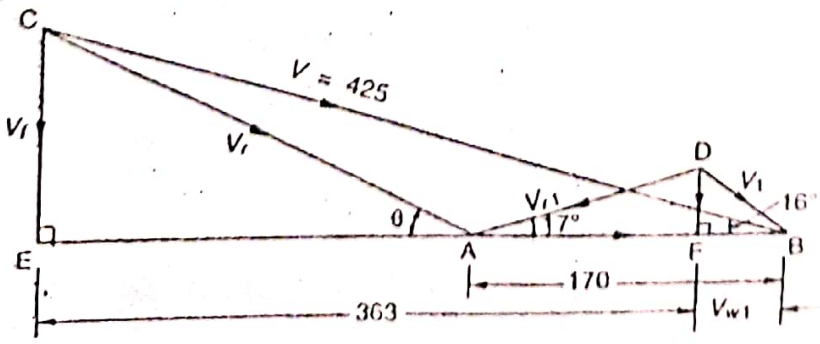



Fig. 24.3

Now draw the combined velocity triangle, as shown in Fig. 24.3, as discussed below :

1. First of all, draw a horizontal line and cut off $AB$ equal to 170 m/s, to some suitable scale, to represent the blade speed ($V_b$).



www.Jntufastupdates.com

Scanned by CamScanner

2. Now draw the inlet velocity triangle $ABC$ on the base $AB$ with $\alpha = 16°$ and $V = 425$ m/s, the scale.

3. Similarly, draw the outlet velocity triangle $ABD$ on the same base $AB$ with $\phi = 17°$ and $+ V_{w1}) = 363$ m/s to the scale.

4. From $C$ and $D$ draw perpendiculars to meet the line $AB$ at $E$ and $F$. From the geometry of figure, we find that $V_{w1}$ is in the opposite direction of $V_w$. Therefore $(V_w - V_{w1}) = 363$ m/s.

By *measurement from the velocity diagram, we find that

Relative velocity at inlet, $V_r = 265$ m/s

d relative velocity at outlet, $V_{r1} = 130$ m/s

We know that blading efficiency,

$$\eta_b = \frac{2 (V_w - V_{w1}) V_b}{V^2} = \frac{2 \times 363 \times 170}{(425)^2} = 0.683 \quad \text{or} \quad 68.3\ \%\ \text{Ans.}$$

*ade velocity coefficient*

We know that blade velocity coefficient,

$$K = \frac{V_{r1}}{V_r} = \frac{130}{265} = 0.49\ \text{Ans.}$$

**Example 24.4.** *A two row curtis wheel operates at a blade speed of 150 m/s, when receiving kg of steam per second at 10.5 bar dry and saturated. The ratio of blade speed to the steam speed exit from the nozzle is 0.21 and nozzle efficiency is 90%. The nozzles are inclined at 16° to the lane of the wheel. The outlet angles of the first row moving, fixed and second row moving blades re respectively 20°, 24° and 32° with respective blade velocity coefficients 0.79, 0.83 and 0.88 Determine : (a) The pressure of steam at exhaust; (b) Diagram efficiency ; and (c) Stage efficiency*

**Solution.** Given : $V_b = 150$ m/s; $m = 3$ kg/s ; $p = 10.5$ bar ; $V_b/V = 0.21$ ; $k = 90\% = 0.9$ $= 16°$ ; $\phi = 20°$ ; $\alpha' = 24°$ ; $\phi' = 32°$ ; $V_{r1}/V_r = 0.79$ for first moving blades ; $V'/V_1 = 0.83$ for fixed lades ; $V_{r1}'/V_r = 0.88$ for second moving blades

We know that steam speed at exit from the nozzle,

$$V = V_b / 0.21 = 150 / 0.21 = 714.3\ \text{m/s}$$

---

These values may also be obtained from the geometry of the combined velocity triangle, as discussed below

$$V_f = 425 \sin 16° = 425 \times 0.2756 = 117.1\ \text{m/s}$$

Now $$\tan \theta = \frac{117.1}{425 \cos 16° - 170} = \frac{117.1}{(425 \times 0.9613) - 170} = 0.4909$$

$\therefore$ $\theta = 26.15°$ and $\angle ACB = 26.15° - 16° - 10.15°$

Now in triangle $ABC$,

$$\frac{V_r}{\sin 16°} = \frac{170}{\sin 10.15°}$$

$\therefore$ $$V_r = \frac{170}{\sin 10.15°} \times \sin 16° = \frac{170}{0.1763} \times 0.2756 = 265.8\ \text{m/s}$$

We know that $$AF = 361 - V_r \cos 26.15° = 361 - (265.8 \times 0.8976) = 122.4\ \text{m/s}$$

$$V_{r1} = \frac{122.4}{\cos 17°} = \frac{122.4}{0.9563} = 128\ \text{m/s}$$


www.Jntufastupdates.com

Scanned by CamScanner

(a) *Pressure of steam at exhaust*

Let $p_2$ = Pressure of steam at exhaust, and

$h_d$ = Enthalpy or heat drop from pressure $p_1$ to $p_2$.

We know that the velocity of steam at exit from nozzle ($V$),

$$714.3 = 44.72 \sqrt{k\, h_d} = 44.72 \sqrt{0.9\, h_d}$$

$$\therefore \quad h_d = \left( \frac{714.3}{44.72} \right)^2 \times \frac{1}{0.9} = 283.5 \text{ kJ/kg}$$

Now let us complete the Mollier diagram for the steam flow through the nozzle, as shown in Fig. 24.4. From the Mollier diagram, we find that

$$p_2 = 2 \text{ bar Ans.}$$

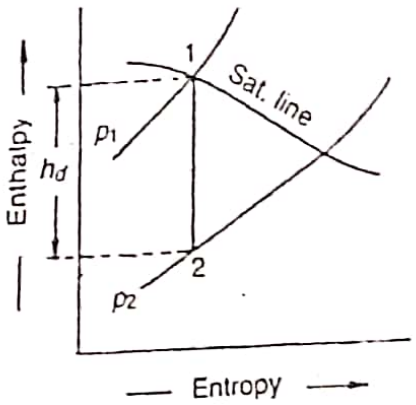



Fig. 24.4

(b) *Diagram efficiency*

Now draw the combined velocity triangle for the two stage impulse turbine, as shown in Fig. 24.5, as discussed below :

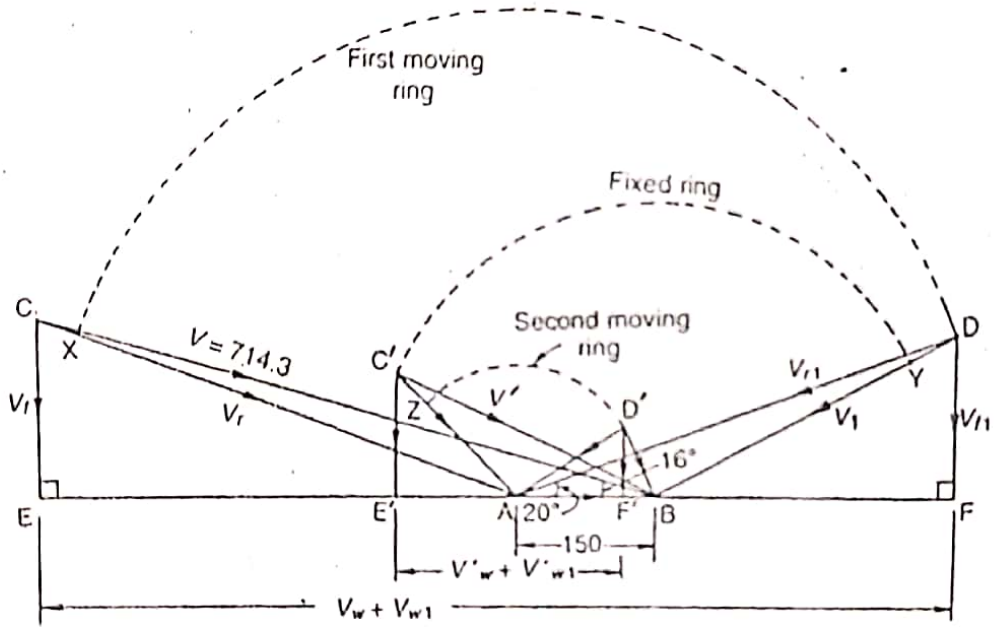



Fig. 24.5

1. First of all, draw a horizontal line, and cut off $AB$ equal to 150 m/s to a suitable scale to represent the blade velocity ($V_b$).

2. Now draw the inlet velocity triangle $ABC$ for the first moving ring on the base $AB$ with nozzle angle for the first moving ring ($\alpha = 16°$) and $V = 714.3$ m/s. By measuring the side $AC$, we find that $V_r = 570$ m/s.

3 Now draw the outlet velocity triangle $ABD$ for the first moving ring on the same base $AB$ with $\phi = 20°$ and $V_{r1} = 0.79\ V_r = 0.79 \times 570 = 450.3$ m/s, to the scale. By measuring the side $BD$, we find that $V_1 = 375$ m/s.

4. Now draw the inlet velocity triangle $ABC'$ for the second moving ring on the same base $AB$ with $\alpha' = 24°$ and $V' = 0.83 \times 375 = 311.2$ m/s, to the scale. By measuring the side $AC'$, we find that $V_r' = 185$ m/s.



www.Jntufastupdates.com

Scanned by CamScanner

5. Now draw the outlet velocity triangle $ABD'$ for the second moving ring on the same base $AB$ with $\phi' = 32^\circ$ and $V_{r1}' = 0.88 \times V_r' = 0.88 \times 185 = 162.8$ m/s to the scale.

The following values are measured from the combined velocity diagram :

$$EF = (V_w + V_{w1}) = 1020 \text{ m/s}$$

$$E'F' = (V_w' + V_{w1}') = 275 \text{ m/s}$$

We know that diagram efficiency,

$$\eta_b = \frac{2\,AB\,(EF + E'F')}{V^2} = \frac{2 \times 150\,(1020 + 275)}{(714.3)^2} = 0.761 \text{ or } 76.1\% \text{ Ans.}$$

(c) *Stage efficiency*

We know that stage efficiency,

$$\eta_s = \frac{AB\,(EF + E'F')}{1000\,h_d} = \frac{150\,(1020 + 275)}{1000 \times 283.5} = 0.685 \text{ or } 68.5\% \text{ Ans.}$$

**Example 24.5.** *In an impulse turbine, there are two rings of moving blades separated by fixed blades. The tips of the moving blades are inclined at 30° to the plane of motion. The steam enters the wheel chamber through a nozzle to which the steam is supplied at 240° C and 11.5 bar. The pressure in the wheel chamber is 5 bar. Find the speed of the blades, so that the steam finally discharged is axial. Assume a 10% loss in velocity, while passing through a blade ring. Also determine the blade tip angles of the fixed blade and diagram efficiency.*

**Solution.** Given : $\phi$, $\phi'$, $\theta$ and $\theta' = 30^\circ$ ; $T = 240^\circ$ C ; $p_1 = 11.5$ bar ; $p_2 = 5$ bar ; Loss in velocity = 10%

From the Mollier diagram, as shown in Fig. 24.6, we find that enthalpy drop from 11.5 bar and 240° C to 5 bar,

$$h_d = h_1 - h_2 = 2915 - 2760 = 155 \text{ kJ/kg}$$

∴ Velocity of steam at the wheel chamber,

$$V = 44.72 \sqrt{155} = 556.6 \text{ m/s}$$

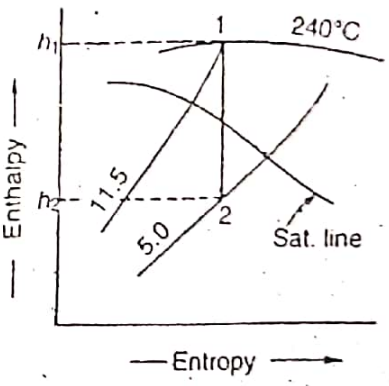


Fig. 24.6

*Blade speed*

From the given data, we find that it is not sufficient to draw inlet velocity triangle for the first moving ring. Therefore we have to start the diagram from the outlet velocity triangle for the moving ring.

Now draw the combined velocity diagram for the two stages of the turbine, as shown in Fig. 24.7, as discussed below :

1. First of all, draw a horizontal line and mark $AB$ equal to 15 mm to represent the blade velocity (which is required to be found out).

2. Now draw the outlet velocity triangle $ABD'$ for the second moving ring on the base $AB$ with $\phi' = 30^\circ$ and $\beta' = 90^\circ$. From the geometry of the figure, we find that $D'B$ represents $V_f'$ and $D'A$ represents $V_{r1}'$. By measurement, we find that $V_{r1}' = 17.3$ mm. Since there is a 10% loss in velocity due to friction, therefore, $V_r' = V_{r1}' / 0.9 = 17.3 / 0.9 = 19.2$ mm.

3. Now draw the inlet velocity triangle $ABC'$ for the second moving ring on the same base $AB$ with $\theta' = 30^\circ$ and $V_r' = 19.2$ mm. From the geometry of the figure, we find that $C'A$ and $C'B$ represents $V_r'$ and $V'$ respectively to the scale. By measurement, we find $C'B = 33$ mm. Since there is a 10% loss in velocity due to friction, therefore $V_1 = V'/0.9 = 33/0.9 = 36.7$ mm.


www.Jntufastupdates.com

Scanned by CamScanner

4. Now draw the outlet velocity triangle $ABD$ for the first moving ring on the same base $AB$ with $\phi = 30°$ and $V_1 = 36.7$ mm. From the geometry of the figure, we find that $DF$ and $DA$ represent $V_{f1}$ and $V_{r1}$ respectively to the scale. By measurement, we find that $V_{r1} = 49$ mm. Since there is 10% loss in velocity due to friction, therefore $V_r = V_{r1} / 0.9 = 49 / 0.9 = 54.4$ mm

5. Now draw the inlet velocity triangle $ABC$ for the first moving ring on the same base $AB$ with $\theta = 30°$ and $V_r = 54.4$ mm.

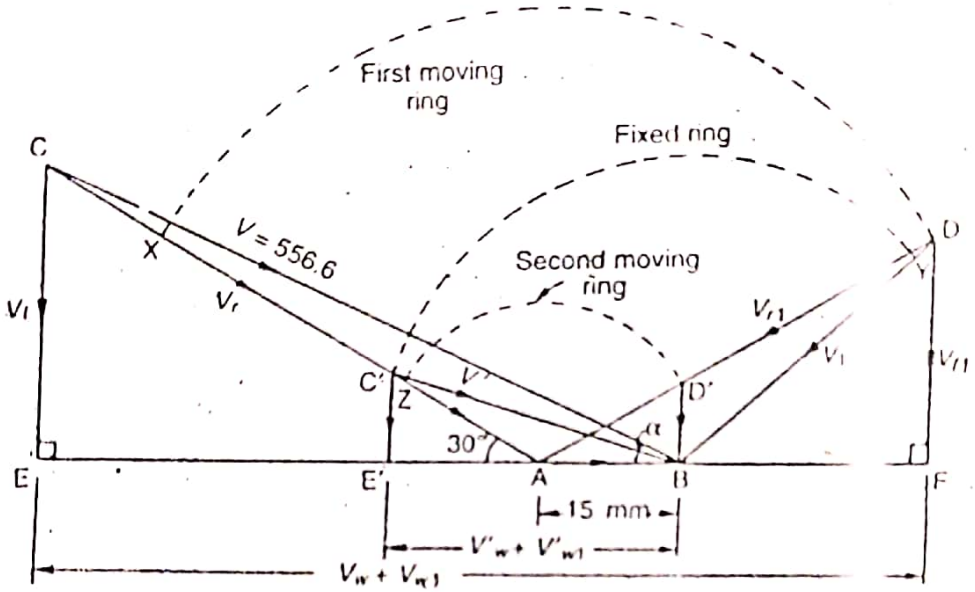



Fig. 24.7

From the combined velocity diagram, we find that the length of $BC$ = [illegible] mm.

$$\therefore \quad \text{Scale, 1 mm} = \frac{556.6}{67} = 8.31 \text{ m/s}$$

and blade speed, $V_b = 15 \times 8.31 = 124.6$ m/s

*Blade tip angles*

By measurement from the velocity diagram, we find that

$$\alpha' = 17° \text{ and } \beta = 43° \text{ Ans.}$$

*Diagram efficiency*

By measurement from the velocity diagram, we find that $EF = V_w + V_{w1} = 88$ mm, and $E'F' = V_w' + V_{w1}' = 31$ mm.

We know that diagram efficiency,

$$\eta_b = \frac{2AB\,(EF + E'F')}{V^2} = \frac{2 \times 15\,(88 + 31)}{67^2} = 0.79 \text{ or } 79.5\% \text{ Ans.}$$

**Example 24.6.** *A reaction turbine with a mean blade diameter of 1 m runs at a speed of 50 rev/second. The blades are designed with exit angles of 50° and inlet angles of 30°. If the turbine is supplied with steam at the rate of 20 kg/s and gross efficiency is 85%, determine : (a) power output of the stage; (b) specific enthalpy drop in the stage; and (c) percentage increase in relative velocity in the moving blades due to steam expansion.*

**Solution.** Given : $d_m = 1$ m ; $N = 50$ r.p.s. ; $\theta = \beta = 50°$ ; $\phi = \alpha = 30°$ ; $m = 20$ kg/s ; $\eta_g = 85\% = 0.85$


www.Jntufastupdates.com

Scanned by CamScanner