

Steam Turbines:-

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A steam turbine is a prime mover in which rotary motion is obtained by the gradual change of momentum of the steam between two or more stages.

The basic principle of operation of a steam turbine is the generation of high velocity steam jet by the expansion

of high pressure steam and then conversion of kinetic energy so obtained into mechanical work on rotatory blades.

Classification of Steam Turbines:-

1. According to the mode of steam action

(a) Impulse turbine (b) Reaction turbine

2. According to the direction of steam flow.

(a) Axial flow turbine (b) Radial flow turbine

3. According to the exhaust condition of steam

(a) condensing turbine (b) Non-condensing turbine

4. According to the pressure of steam

(a) H.P. turbine (b) Medium P.T (c) L.P.T

5. According to the number of stages

(a) Single stage turbine (b) Multi-stage turbine

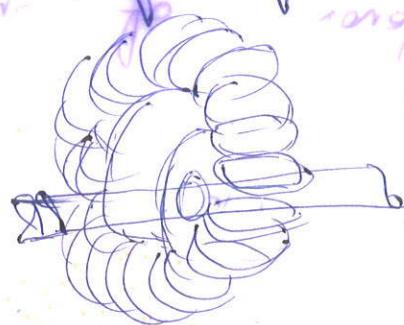
(a)

## Impulse Turbine:-

An impulse turbine, as the name indicates, is a turbine which runs by the impulse of steam jet. In this turbine, the steam is first made to flow through a nozzle. Then the steam jet impinges on the turbine blades and are mounted on the circumference of the wheel. The steam jet after impinging glides over the concave surface of the blades and finally leave the turbine.

It has the following main components:-

1. Nozzle
2. Runner and blades
3. Casing



## Pressure and velocity of steam in an impulse turbine:-

The pressure of steam jet is reduced in the nozzle and remains constant while passing through the moving blade.

→ The velocity of steam is increased in the nozzle, and is reduced while passing through the moving blade.

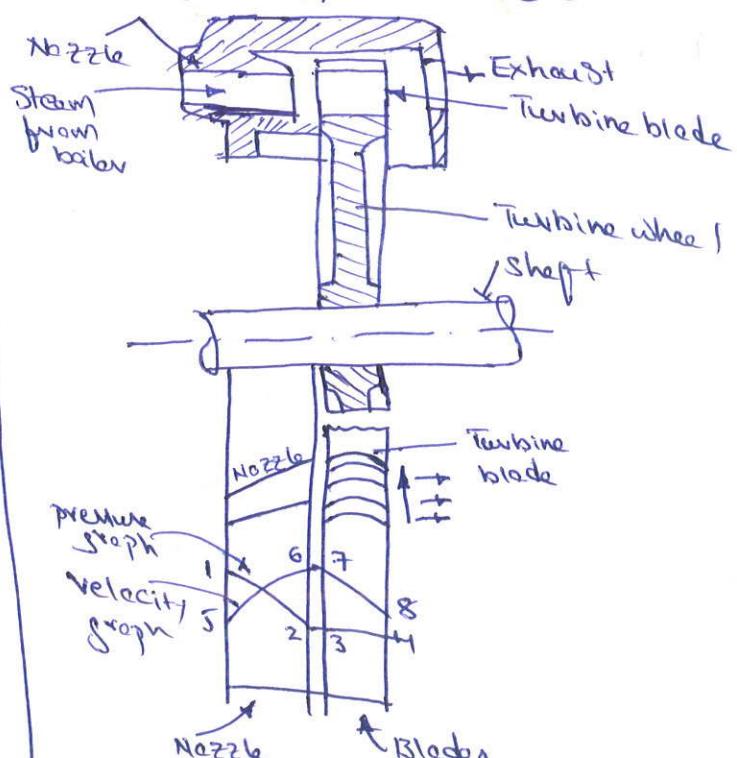
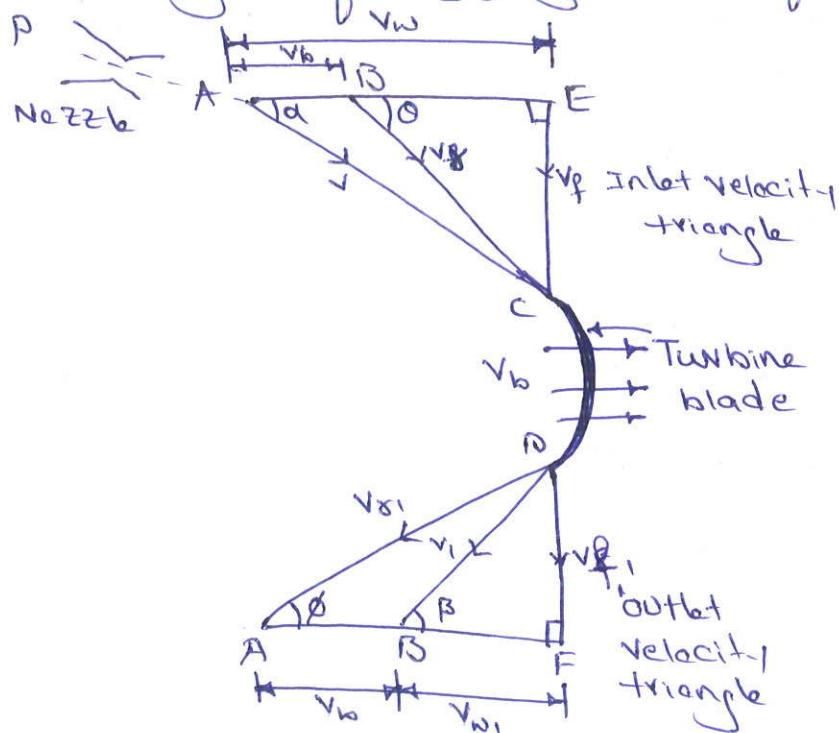


Figure shows the pressure and velocity graphs of the steam in a simple turbine while it flows in the nozzle and blades.

- The pressure graph 1-2-3-4 represents steam pressure at entrance of the nozzle, exit of the nozzle, entrance of the blades and exit of the blades respectively.
- Similarly, velocity graph 5-6-7-8 represents the velocity of steam at entrance of the nozzle, exit of the nozzle, entrance of the blades and exit of the blades respectively.

### Velocity Triangles for Moving Blade of an Impulse Turbine:-



In an impulse turbine, the steam jet after leaving the nozzle impinges on one end of the blade.

- The jet then glides over the inside surface of the blade and finally leaves from the other edge, as shown in figure.
- It may be noted that the jet enters and leaves the blades tangentially for shockless entry and exit.

→ consider a steam jet entering a curved blade after leaving the nozzle at C.

→ Now let the jet glides over the inside surface and leaves the blade at D, as shown in figure.

→ Now let us draw the velocity triangles at inlet and outlet tips of the moving blade, as shown in figure

Let  $V_b$  = Linear velocity of the moving blade (AB)

$V$  - Absolute velocity of steam entering the moving blade (Ac)

$V_r$  - Relative velocity of jet to the moving blade (Bc).  
It is the vectorial difference b/w  $V_b$  and  $V$ .

$V_f$  - Velocity of flow at entrance of the moving blade.  
It is the vertical component of  $V$ .

$V_w$  - Velocity of whist at entrance of the moving blade.  
It is the horizontal component of  $V$ .

$\theta$  - Angle which the relative velocity of jet to the moving blade ( $V_r$ ) makes with the direction of motion of the blade.

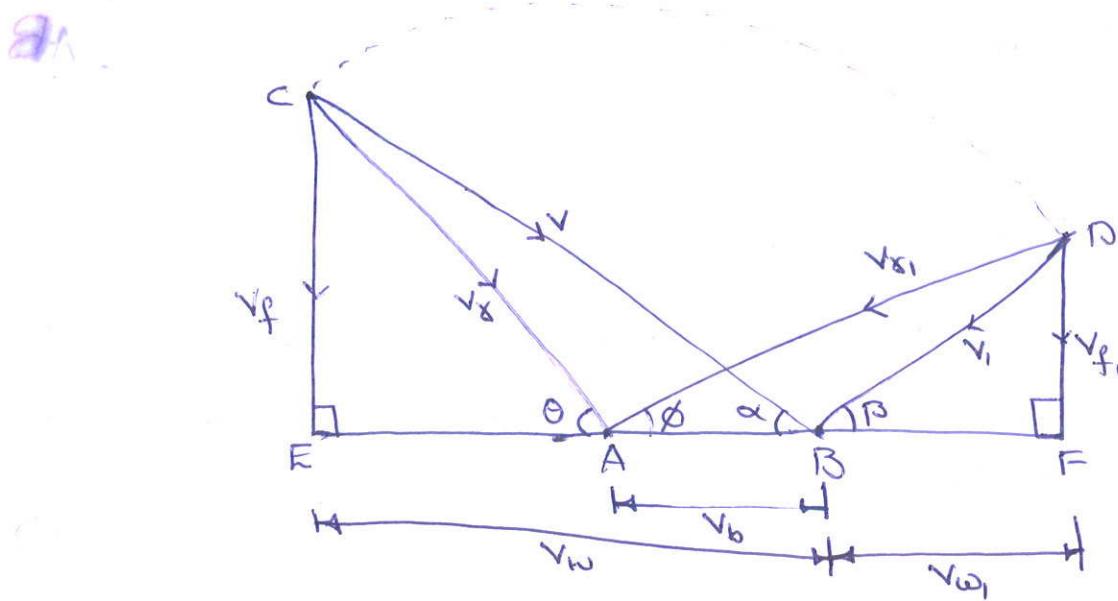
$\alpha$  - Angle with the direction of motion of the blade at which the jet enters the blade

$V_1, V_{s1}, V_{f1}, V_w, \beta, \phi$  - corresponding values at exit of moving blade

→ It may be seen from the above, the original notations (ie  $V, V_r, V_f$  and  $V_w$ ) stand for the inlet triangle.

→ The notations with suffix (ie  $V_1, V_{s1}, V_{f1}, V_{w1}$ ) stand for the outlet triangle.

## Combined velocity triangle for Moving Blades:-



In the last article, we have discussed the inlet and outlet velocity triangles separately.

→ For the sake of simplification, a combined velocity triangle for the moving blade is drawn, for solving problems on steam turbines, as shown in figure.

1. First of all, draw a horizontal line, and cut off AB equal to velocity of blade ( $V_b$ ) to some suitable scale.
2. Now at B, draw a line BC at an angle  $\alpha$  with AB. cut off BC equal to  $V$  (ie velocity of steam jet at inlet of the blade) to the scale.
3. Join AC, which represents the relative velocity at inlet ( $V_s$ ). Now at A, draw a line AD at an angle  $\phi$  with AB.
4. Now with A as centre and radius equal to AC, draw an arc meeting the line through A at D, such that  $AC = AD$   
or  $V_s = V_{s1}$ .

5. Join BD, which represents velocity of jet at exit ( $v_1$ ) to the sea.
6. From C and D, draw perpendiculars meeting the line AB produced at E and F respectively.
7. Now EB and CF represent the velocity of whirl and velocity of flow at inlet ( $v_w$  and  $v_f$ ) to the sea. Similarly, BF and DF represent the velocity of whirl and velocity of flow at outlet ( $v_{w1}$  and  $v_{f1}$ ) to the sea.

### Power Produced by an Impulse Turbine:-

Consider an impulse turbine working under the action of steam jet. Let us draw a combined velocity triangle for the impulse turbine as shown in figure.

Let  $m$  = Mass of the steam flowing through the turbine in kg/s.

$(v_w + v_{w1})$  = change in the velocity of whirl in m/s.

We know that according to the Newton's second law of motion, force in the direction of motion of the blades,

$F_x = \text{Mass of steam flowing per second} \times \text{change in the velocity of whirl}$

$$= m [v_w - (-v_{w1})]$$

$$= m [v_w + v_{w1}]$$

$$= m \times EF \ N \rightarrow ①$$

and work done in the direction of motion of the blades

$$= \text{Force} \times \text{Distance}$$

$$= m [V_w + V_{w1}] \times V_b \text{ N-m/s} \rightarrow \textcircled{II}$$

$$= m \times E_F \times A_B \text{ N-m/s}$$

$\therefore$  Power produced by the turbine

$$P = m \times E_F \times A_B \text{ watt} \quad (\because 1 \text{ N-m/s} = 1 \text{ watt})$$

$$P = m (V_w + V_{w1}) V_b \text{ watt}$$

### Axial thrust:-

Similarly, we can find out the axial thrust on the wheel which is due to the difference of velocities of flow at inlet and outlet. Mathematically, axial thrust on the wheel,

$\therefore F_y = \text{Mass of steam flowing per second} \times \text{change in the velocity of flow.}$

$$= m (V_f - V_{f1})$$

$$= m (CE - DF) N \rightarrow \textcircled{3}$$

### Note:-

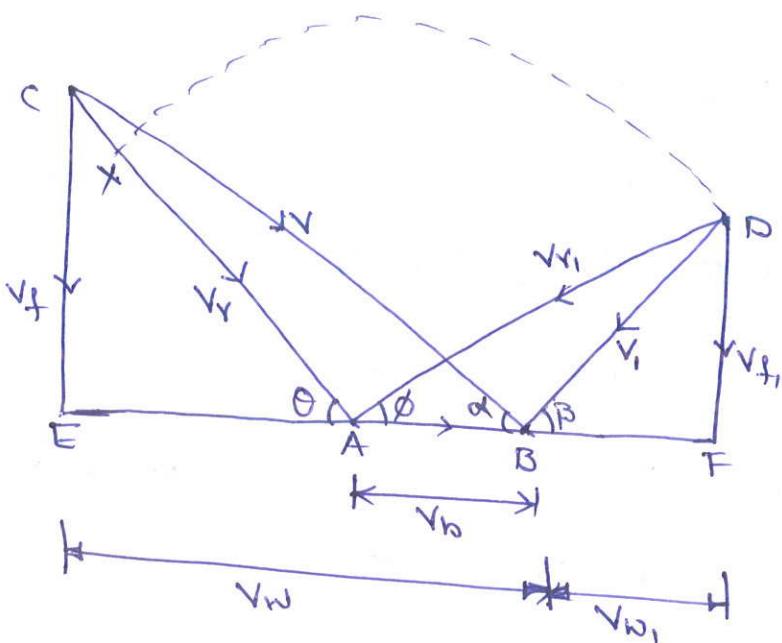
1. In eqn \textcircled{1}, the value of  $V_{w1}$  is taken as negative because of the opposite direction of  $V_w$  with respect to the blade motion. In other words, when point F in the velocity diagram lies on the right of point B, then  $V_{w1}$  is negative. Thus change in velocity of whist.

$$= V_w - (-V_{w1}) = V_w + V_{w1}$$

2. If  $V_{w1}$  is in the same direction with respect to the blade motion, then  $V_{w1}$  is taken as positive. In other words, when point F in the velocity diagram lies on the left of point B, then  $V_{w1}$  is positive. Thus change in velocity of whist

$$= V_w - (+V_{w1}) = V_w - V_{w1}$$

## Effect of friction:-



In the last article, we have discussed that the relative velocity of steam jet is the same at the inlet and outlet tips of the blade.

- In other words, we have assumed that the inner side of the curved blade offers no resistance to the steam jet.
- But in actual practice, some resistance is always offered by the blade surface to the gliding steam jet, whose effect is to reduce the relative velocity of the jet i.e. to make  $V_{r1}$  less than  $V_r$ .
- The ratio of  $V_{r1}$  to  $V_r$  is known as blade velocity coefficient or coefficient of velocity or friction factor, (usually denoted by  $K$ )  
Mathematically, blade velocity coefficient,

$$\therefore K = \frac{V_{r1}}{V_r}$$

- It may be noted that the effect of friction on the combined velocity triangle will be to reduce the relative velocity at outlet ( $V_{r1}$ ) as shown in figure.

- Note:-
1. Since  $V_{r1}$  is decreased due to friction, therefore work done per kg of steam is also reduced.
  2. The value of  $K$  varies from 0.75 to 0.85 depending upon the shape of the blades.

In a free level turbine steam issues from the nozzle with a velocity of  $1200 \text{ m/s}$ . The nozzle angle is  $20^\circ$ , the mean blade velocity is  $400 \text{ m/s}$ , and the inlet and outlet angles of blades are equal. The mass of steam flowing through the turbine per hour is  $1000 \text{ kg/h}$ .

calculate

① Blade angle

② Tangential force on the blades

③ Relative velocity of steam entering the blades

④ Power developed.

⑤ Blade efficiency

Take blade velocity coefficient as  $0.8$ .

Sol:-

Absolute velocity of steam entering the blade  $V_1 = 1200 \text{ m/s}$

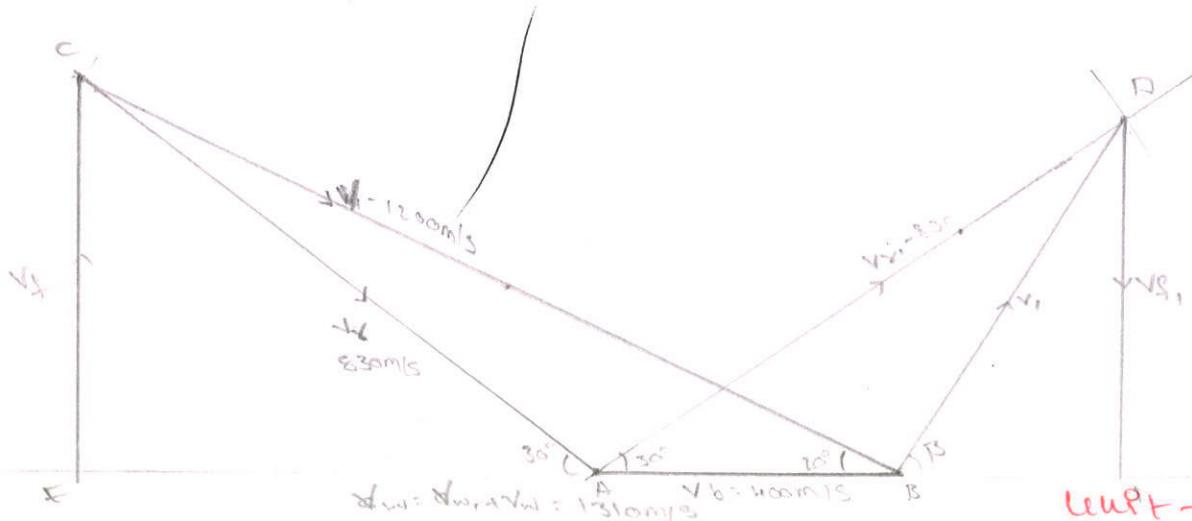
Nozzle blade,  $\alpha = 20^\circ$

Mean blade velocity,  $V_b = 400 \text{ m/s}$

Inlet blade angle,  $\theta = \text{outlet blade angle} = \phi$

Blade velocity coefficient,  $k = 0.8$

Mass of steam flowing through the turbine,  $m_s = 1000 \text{ kg/h}$



By measurement

$$\theta = 30^\circ, V_{x_1} = 830 \text{ m/s}$$

$$\theta = \phi = 30^\circ$$

$$V_{x_f} = KV_x = 0.8 \times 830 = 664 \text{ m/s}$$

① Blade angle,  $\theta, \phi$  :-

As the blades are symmetrical

$$\theta = \phi = 30^\circ$$

② Relative velocity of steam entering the blades,  $V_x$

$$V_x = M_s = 830 \text{ m/s}$$

③ Tangential force on the blades

$$\text{Tangential force} = m_s (V_{w_1} + V_{w_f}) = \frac{1000}{60 \times 60} (1310) = 363.8 \text{ N}$$

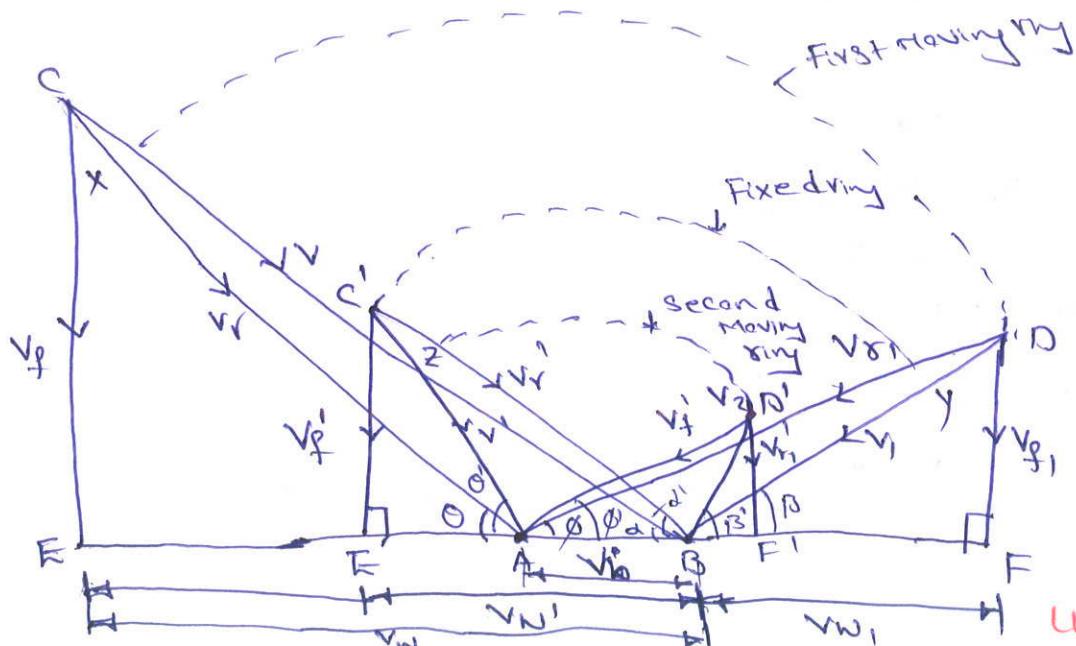
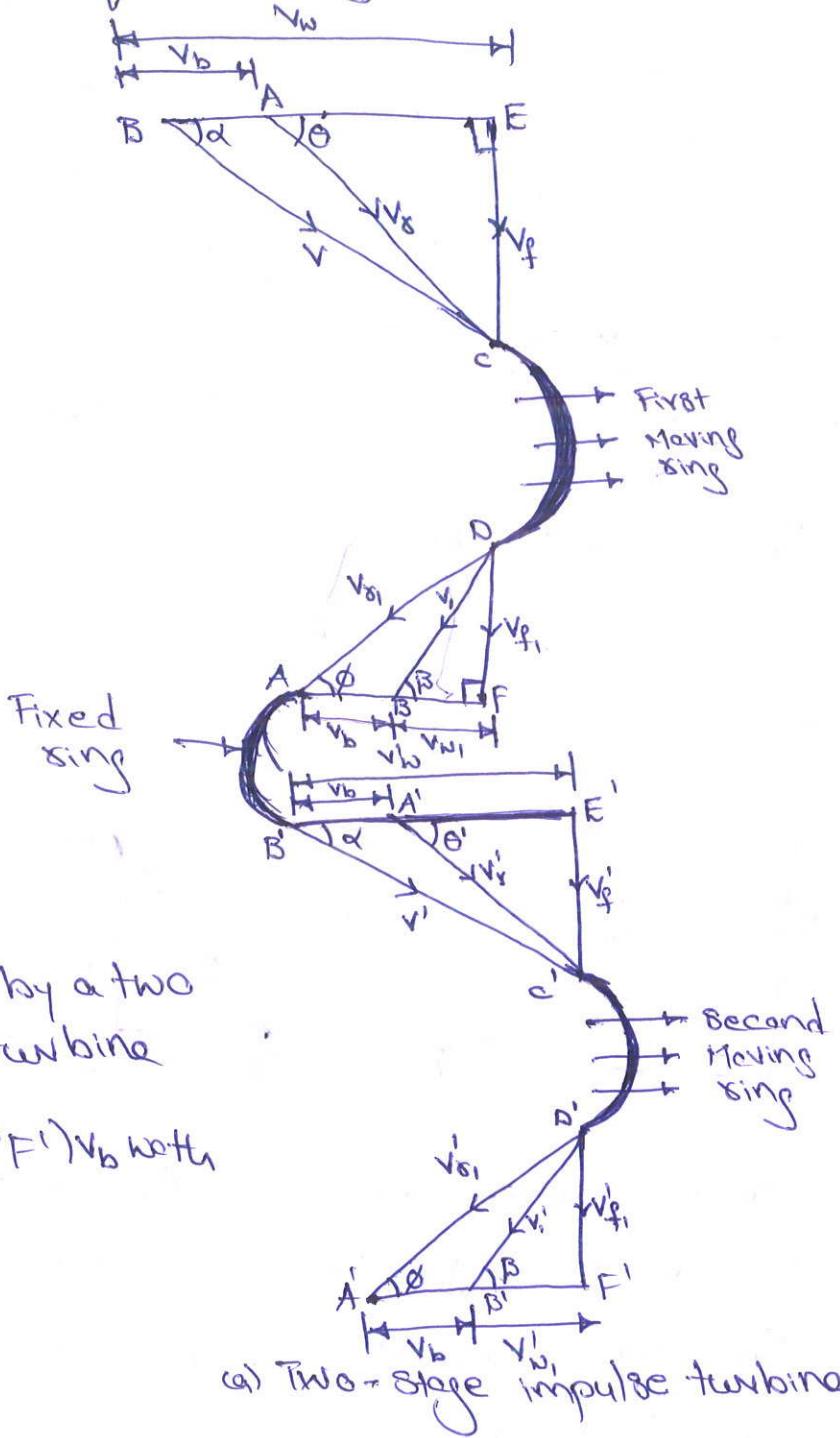
④ Power developed,  $P$

$$P = m_s (V_{w_1} + V_{w_f}) V_b = \frac{1000}{60 \times 60} \times \frac{1310 \times 600}{1000} \text{ kW} = 145.5 \text{ kW}$$

⑤ Blade efficiency,  $n_b$

$$\therefore n_b = \frac{2V_b(V_{w_1} + V_{w_f})}{V_i^2} = \frac{2 \times 600 \times 1310}{1200^2} = 72.8\%$$

# Velocity Diagram for two stage Impulse turbine



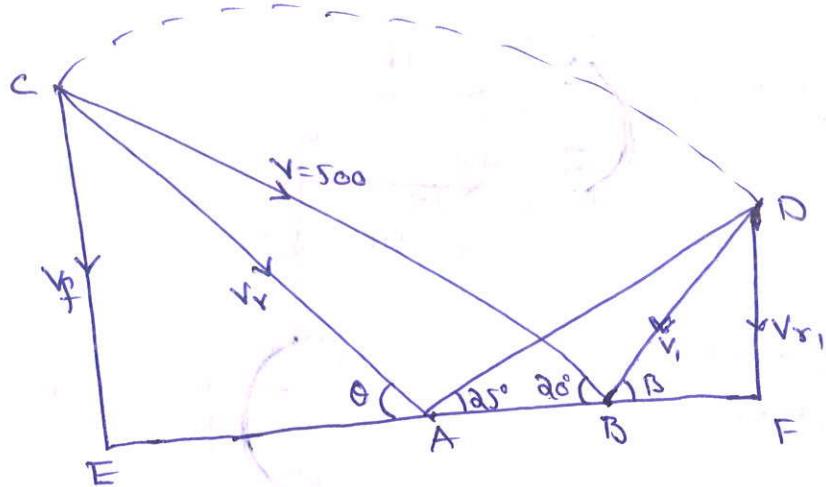
(3)

In a De-level turbine, the steam enters the wheel through a nozzle with a velocity of 500 m/s and at an angle of  $20^\circ$  to the direction of motion of the blade. The blade speed is 200 m/s and the exit angle of the moving blade is  $25^\circ$ . Find the inlet angle off the moving blade, exit velocity of steam and its direction and workdone per kg of steam.

Sol:-

Given  $V = 500 \text{ m/s}$ ;  $\alpha = 20^\circ$ ;  $V_b = 200 \text{ m/s}$ ;  $\phi = 25^\circ$

Sol:-



The following values are measured from the velocity diagrams

$$\theta = 32^\circ; \beta = 59^\circ; V_i = BA = 165 \text{ m/s}$$

$$V_w = BE = 170 \text{ m/s} \text{ and } V_{w1} = BF = 90 \text{ m/s}$$

Inlet angle of moving blade

$$\theta = 32^\circ$$

Exit velocity of steam

$$V_i = 165 \text{ m/s}$$

Direction of the exit steam

$$\beta = 59^\circ$$

Workdone per kg of steam

$$= m(V_w + V_{w1})$$

$$= 1 (170 + 90)$$

$$= 560 \text{ N-m}$$

$$m = 1 \text{ kg}$$

## Efficiencies of Steam Turbine:-

### 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

$\therefore$  Energy supplied to the blade per second

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

We know that workdone on the blades per second

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

### 2. 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 workdone on the turbine blades may also be obtained from the kinetic energy at 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

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

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

$$P = \frac{m(V^2 - V_1^2)}{2} \text{ watts} \quad \therefore 1 \text{ J/s} = 1 \text{ watt}$$

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

2. Gross or stage efficiency:-

It is the ratio of the work done on the blade 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.

$\therefore$  Enthalpy or heat drop in the nozzle ring of an impulse wheel,

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

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

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

$$= I(V_N + V_{W1}) V_b \text{ J/kg of steam}$$

$\therefore$  Gross or stage efficiency

$$\eta_s = \frac{(V_N + V_{W1}) V_b}{1000 h_d} = \frac{(V_N + V_{W1}) V_b}{1000 (h_1 - h_2)}$$

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

$$= \frac{V^2}{2} \quad (\text{J})$$

$$\therefore \text{Nozzle efficiency, } n_n = \frac{V^2/2}{1000 \text{ hd}} = \frac{V^2}{2000 \text{ hd}}$$

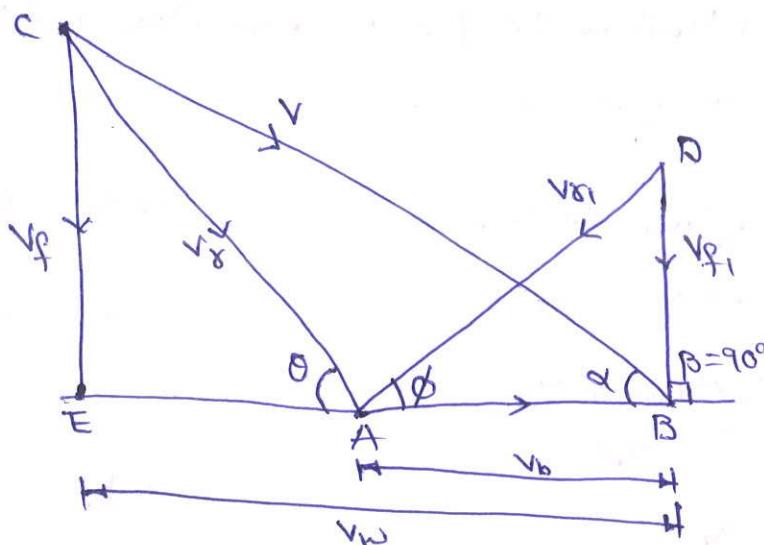
Note:- we know that stage efficiency

$$n_s = \frac{(V_w + V_{w1})V_b}{1000 \text{ hd}} = \frac{2(V_w + V_{w1})V_b}{V^2} \times \frac{V^2}{2000 \text{ hd}}$$

$$n_s = n_b \times n_n$$

$\therefore$  stage efficiency = Bleeding efficiency  $\times$  Nozzle efficiency.

Condition for Maximum efficiency of an Impulse Turbine :-



The blading efficiency (or diagram efficiency) of an impulse turbine

$$\eta_b = \frac{V^2 - V_i^2}{V^2} = \frac{2(V_w + V_{w_i})V_b}{V^2}$$

→ It may be noted that the blading efficiency will be maximum when  $V_i$  is minimum

→ From the combined velocity triangle, we see that the value of  $V$ , will be minimum, when  $\beta$  is equal to  $90^\circ$ .

→ In other words, for maximum efficiency the steam should leave the turbine blades at right angles to their motion.

→ The modified combined velocity triangle for maximum efficiency is shown in figure.

→ It may also be noted that for maximum efficiency,  $V_{w_i}$  is zero

: For maximum efficiency, substituting,  $V_{w_i} = 0$  in the general expression for efficiency of an impulse turbine, we have

$$\eta_{max} = \frac{2xV_w \times V_b}{V^2}$$

W.K.T in free-bend turbine,  $\theta = \phi$ , considering  $V_\infty = V_\infty$  (or in other words, neglecting blade friction)

$$\begin{aligned} V_b &= \frac{1}{2}V_w = 0.5V_w \\ &= 0.5V \cos\phi \end{aligned}$$

$$\therefore \Delta EAC = \Delta ADB$$

$$\therefore V_w = V \cos\phi$$

$$\therefore \eta_{max} = \frac{2xV_w \times 0.5V_w}{V^2}$$

$$\therefore V_w/V = \cos\phi$$

$$= \frac{V_w^2}{V^2} = \cos^2\phi$$

$$\therefore \eta_{max} = \cos\phi$$

A single row impulse turbine develops 132.4 kW at a blade speed of 175 m/s using 2 kg of steam per sec. Steam leaves the nozzle at 400 m/s. Velocity coefficient of the blades is 0.9. Steam leaves the turbine blades axially. Determine nozzle angle, blade angles at entry and exit, assuming no shock.

Sol:-

Ans:-

Power developed,  $P = 132.4 \text{ kW}$

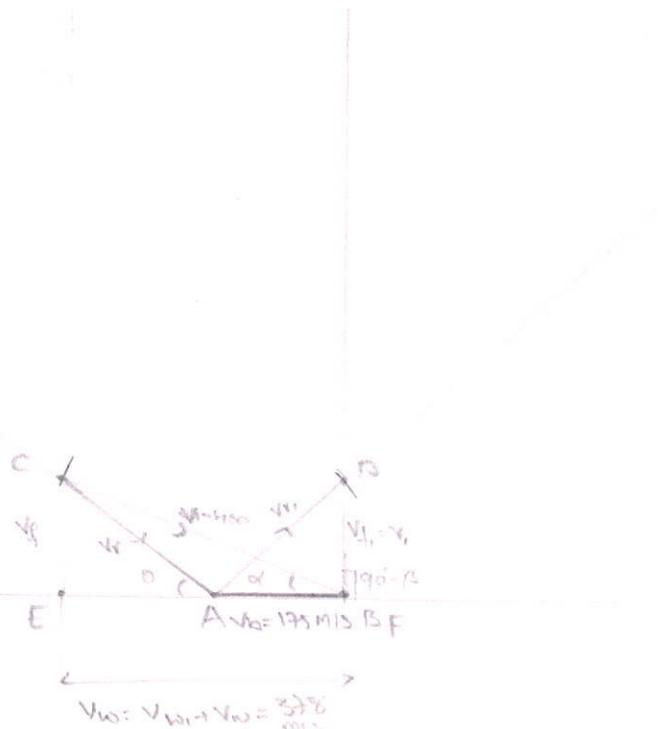
Blade speed  $V_b = 175 \text{ m/s}$

Steam used  $m_s = 2 \text{ kg/s}$

$$V_{b_1} = 0.9 \times 220$$

Velocity of steam leaving the nozzle,  $V_1 = 400 \text{ m/s}$

Blade velocity coefficient,  $\kappa = 0.9$



$$\text{power developed, } P = m_s \frac{(V_{w1} + V_w) \times V_b}{1000}$$

$$= 132.4 = 2 \frac{(V_{w1} + V_w) \times 175}{1000} \quad \text{or } (V_{w1} + V_w) = \frac{132.4 \times 1000}{2 \times 175} = 378 \text{ m/s}$$

$\therefore C_w = 0$ , since the discharge is axial.

$$\therefore \frac{\alpha}{\gamma} = 0.9$$

$\beta = 90^\circ$  since the discharge is axial

$$V_{w1} + V_w = 378 \text{ m/s}$$

$\alpha = 21^\circ$ , Nozzle angle  
 $\beta = 36^\circ$ , Blade inlet angle  
 $\phi = 32^\circ$ , Blade outlet angle b

b) Steam with absolute velocity of 300 m/s is supplied through a nozzle to a single stage impulse turbine. The nozzle angle is  $25^\circ$ . The mean diameter of the blade row is 1 metre and it has a speed of 2000 rpm. Find suitable blade angles for zero axial thrust. If the blade velocity coefficient is 0.9 and the steam flow rate is 10 kg/s, calculate the power developed.

Ans:- Absolute velocity of steam entering the blade,  $V_A = 300 \text{ m/s}$

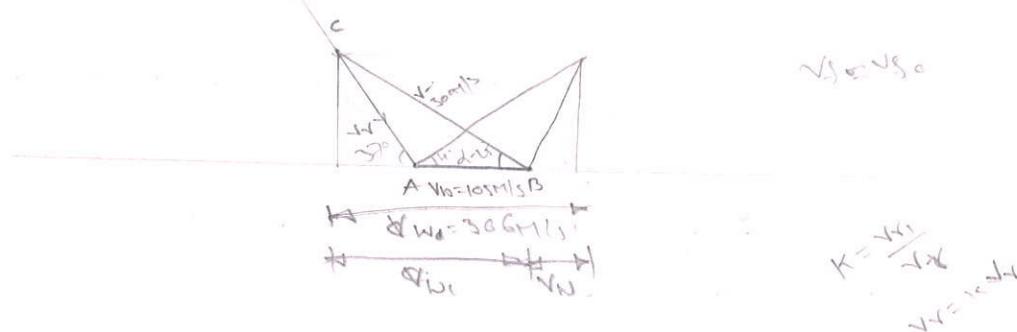
Nozzle angle,  $\alpha = 25^\circ$

Mean diameter of the nozzle blade,  $D = 1 \text{ m}$

Speed of the rotor,  $N = 2000 \text{ rpm}$

Blade velocity coefficient,  $k = 0.9$

Steam flow rate,  $m_s = 10 \text{ kg/s}$



Blade angles:-

$$\text{Blade speed } d, V_b = \frac{\pi \times D \times N}{60} = \frac{\pi \times 1 \times 2000}{60} = 105 \text{ m/s}$$

$$V_A = 300 \text{ m/s}; V_b = 105 \text{ m/s} \text{ and } \alpha = 25^\circ$$

$$\therefore Q V_f = V_f,$$

$$\theta = 37^\circ \text{ and } \phi = 42^\circ$$

Power developed,  $P$

$$\therefore P = \frac{m_s (V_{w1} + V_{w2}) \times V_b}{1000} = \frac{10 \times 306 \times 105}{1000} = 321.3 \text{ kW}$$

$$V_x = 750 \text{ m/s}$$

$$\phi = 24^\circ, V_{x1} = 0.9V_x = 0.9 \times 750 = 675 \text{ m/s}; V_1 = 540 \text{ m/s}$$

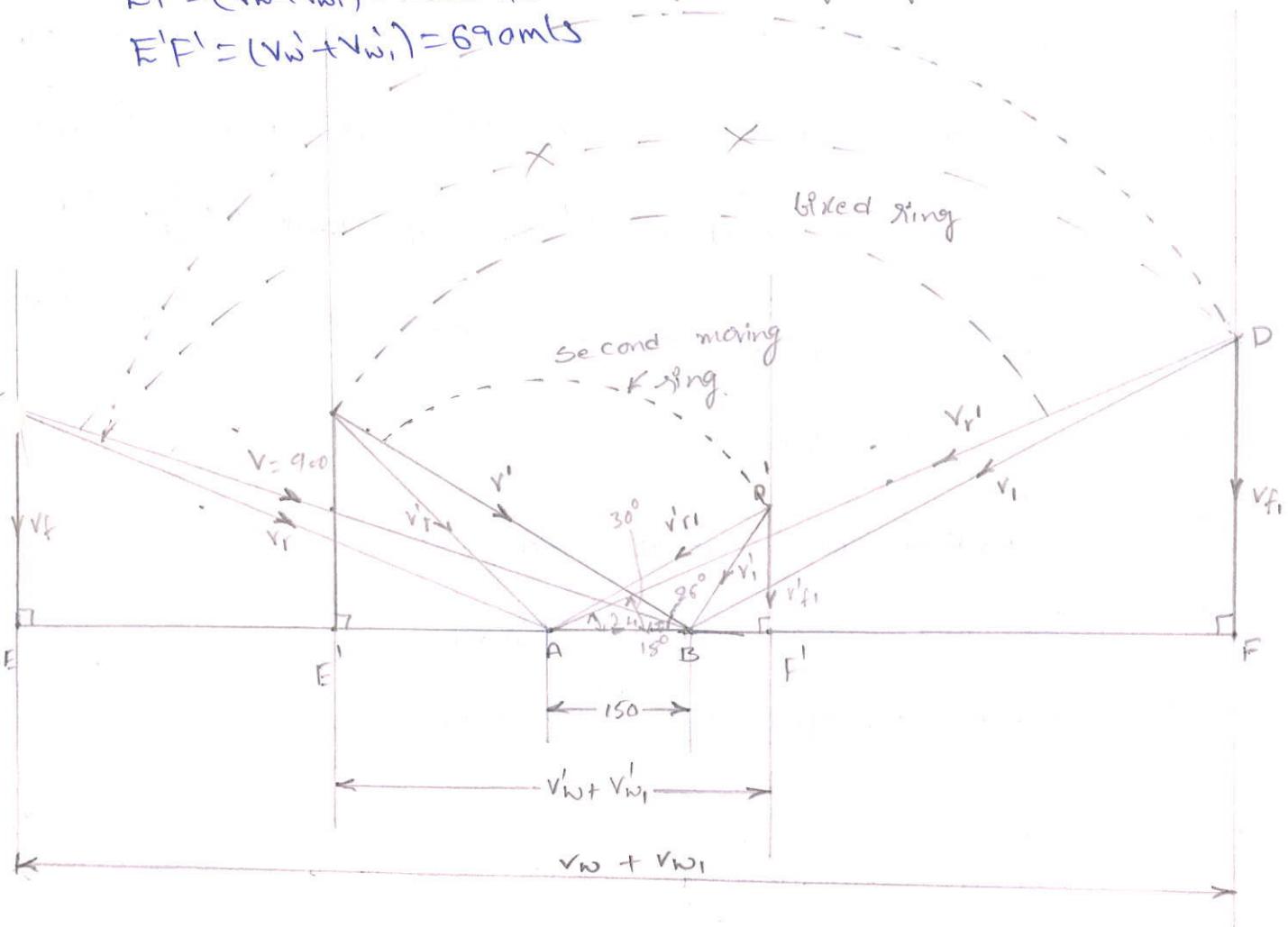
$$\alpha = 26^\circ, V' = 0.9V_1 = 0.9 \times 540 = 486 \text{ m/s}; V_x' = 350 \text{ m/s}$$

$$\phi = 30^\circ; V_{x1}' = 0.9V_x' = 0.9 \times 350 = 315 \text{ m/s}$$

$$EF = (V_w + V_{w1}) = 1400 \text{ m/s}$$

$$E'F' = (V_w' + V_{w1}') = 690 \text{ m/s}$$

1st moving ring



(a)

Tangential force on the rotor

We know that tangential force on the rotor

$$\begin{aligned} F_x &= m \cdot (EF + E'F') = 1.25 (1400 + 690) \\ &= 2612.5 \text{ N Ang} \end{aligned}$$

(b)

Total work done on the blade

We know that tangential force on the blade

$$\begin{aligned} W.D &= m(CEF + C'E'F')V_D = 1.25 (1400 + 690) 150 \\ &= 391.88 \text{ kN-m/s Ans} \end{aligned}$$

E1-228 A velocity compounded impulse turbine has two rows of moving blades with a fixed row of guide blades. The steam leaves the nozzle at  $900 \text{ m/s}$  in a direction of  $18^\circ$  to the plane of rotation. The blade speed is  $150 \text{ m/s}$  and the blade outlet angles are  $24^\circ$ ,  $26^\circ$  and  $30^\circ$  for the first moving, 1<sup>st</sup> fixed and 2<sup>nd</sup> moving respectively. The friction factor is 0.9 for all rows. The steam supply is  $4500 \text{ kg/h}$  per hour. Determine :-

- (a) Tangential force on the rotor
- (b) Total work done on the blades
- (c) Power developed by the turbine

Sol:-

Given data

$$V = 900 \text{ m/s}$$

$$\alpha = 18^\circ$$

$$V_b = 150 \text{ m/s}$$

$$\phi = 24^\circ$$

$$\alpha' = 26^\circ$$

$$\phi' = 30^\circ$$

$$k = \frac{V_{r1}}{V_r} = \frac{V_{r1}}{V'_r} = \frac{V'}{V_1} = 0.9$$

$$m = 4500 \text{ kg/h} = 1.25 \text{ kg/sec.}$$

(c) Power developed by the turbine

we know that power developed by the turbine

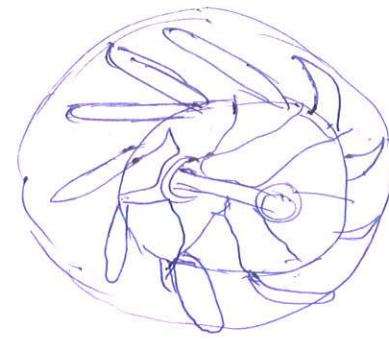
$$P = m (\dot{E}_F + \dot{E}_F') v_b = 391.88 \text{ kW Ans.}$$



(b)

## Reaction Turbine:-

- In a reaction turbine, the steam enters the wheel under pressure and flows over the blades.
- The steam, while gliding, propels the blades and make them to move.
- As a matter of fact, the turbine runner is rotated by the reactive force of steam jets.
- The backward motion of the blades is similar to the recoil of a gun. It may be noted then an absolute reaction turbine is rarely used in actual practice.
- The main components of Parsons' Reaction turbine
  - \* Casing
  - \* Guide mechanism
  - \* Turbine runner
  - \* Draft tube.



## Impulse Turbine

1. The steam flows through the nozzle and impinges on the moving blades.
2. The steam impinges on the buckets with kinetic energy.
3. The steam may or may not be admitted over the whole circumference.
4. The steam pressure remains constant during its flow through the moving blades.
5. Relative velocity of steam constant.
6. Blades are symmetrical.
7. Noft steps required for power delivery.

## Reaction Turbine

1. The steam flows first through guide mechanism and then through the moving blades.
  2. The steam glides over the moving vanes with pressure and kinetic energy.
  3. The steam must be admitted over the whole circumference.
  4. The steam pressure is reduced during its flow through the moving blades.
  5. Relative velocity of steam increases.
  6. Blades are not symmetrical.
- 1, 2, 3, 4, 5, 6, 7, N, H, G, 3, 19 - 22/31

## Pressure and velocity of steam in a Reaction Turbine?

It will be interesting to know that the pressure in a reaction turbine is reduced in the fixed blades as well as in moving blades.

→ The velocity of steam is increased in the fixed blades, and is reduced while passing through the moving blades.

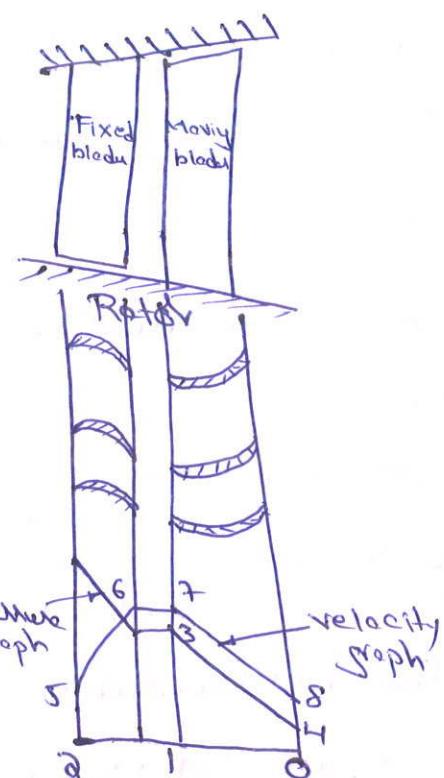
→ Figure shows the pressure and velocity graphs of the steam while it flows in the fixed and moving blades of a reaction turbine.

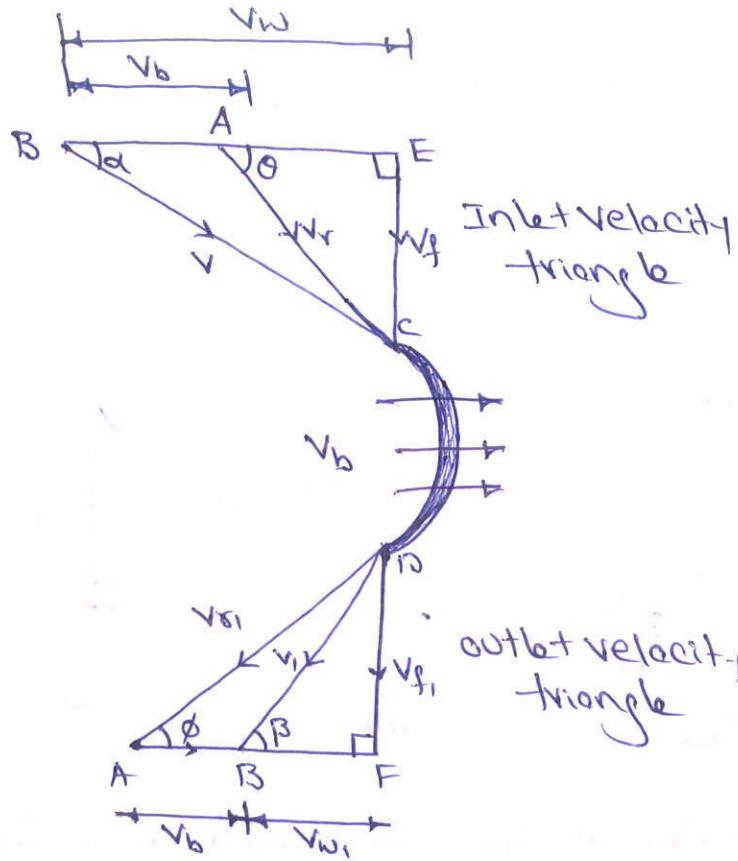
→ The pressure graph 1-2-3-4 represents steam pressure at entrance of the fixed blades, exit of the fixed blades, entrance of moving blades and exit of the moving blades respectively.

→ Similarly velocity graph 5-6-7-8 represents the velocity of steam at entrance of the fixed blades, exit of the fixed blades, entrance of the moving blades and exit of the moving blades respectively.

## Velocity Triangles for Moving Blades of a Reaction Turbine:

Consider steam, in the form of a jet, entering the curved blade (after leaving the fixed blade) at C. Let the jet glide over the inside surface and leave the blade at D, as shown in figure. Now let us draw the velocity triangles at inlet and outlet tip of the moving blade as shown in figure.





Let

$V_b$  - Linear velocity of the moving blade (AB)

$V$  - Absolute velocity of steam entering the moving blade (BC)

$V_r$  - Relative velocity of jet to the moving blade (AC). It is the vectorial difference of  $V_b$  and  $V$ .

$V_f$  = Velocity of flow at entrance (Ec). It is the vertical component of  $V$ .

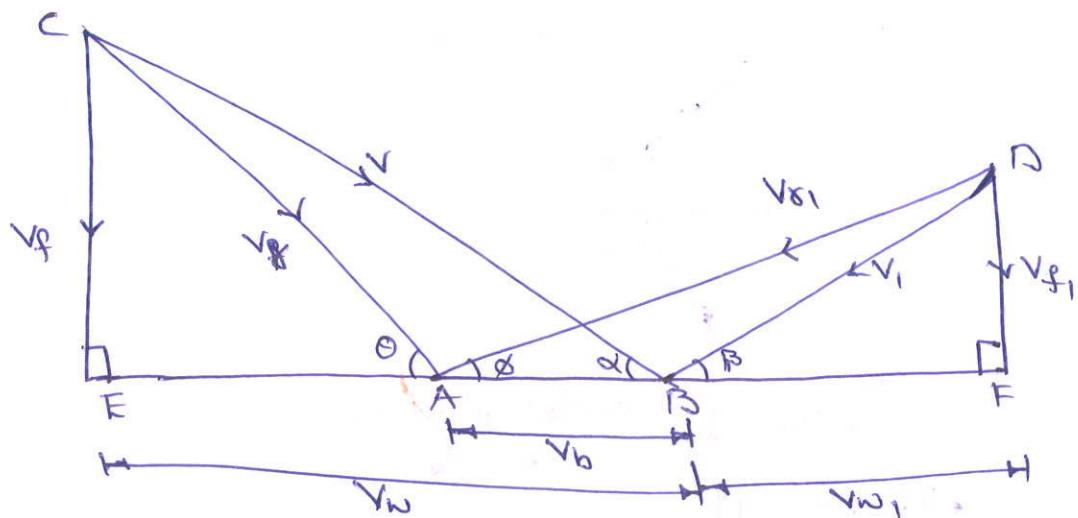
$V_w$  - Velocity of whirl at entrance (BE). It is the horizontal component of  $V$ .

$\alpha$  - Angle with the direction of motion of the blade at which the steam enters the blade.

$\theta$  - Angle which the relative velocity of jet ( $V_r$ ) makes with the direction of motion of the blade

$V_1, V_{r1}, V_{f1}, V_{w1}, \beta, \phi$  = corresponding values at exit of the moving blade.

## Combined Velocity Triangle for Moving Bladed:-



Note:- A careful study of the combined velocity diagram of parson's reaction turbine will reveal that it is symmetric about the central line. Therefore following relations exist the combined velocity diagram

$$V_f = V_{f1}; V = V_{\theta1}; V_\theta = V_1; EA = BF$$

## Power produced by a Reaction Turbine:-

Consider a reaction turbine working under the action of steam pressure. Let us draw a combined velocity triangle for the reaction turbine, as shown in figure.

Let  $m$  = Mass of the steam flowing through the turbine in kg/s and

$(V_w + V_{w1})$  = change in the velocity of whist in m/s.

We know that according to the Newton's second law of motion, force in the direction of motion of blader,

$F_x = \text{Mass of steam flowing/second} \times \text{change in the Velocity}$   
of which

$$F_x = m [v_w - (-v_{w_i})]$$

$$= m [v_w + v_{w_i}]$$

$$= m \times EF N \rightarrow ①$$

and work done in the direction of motion of the blades

$$= Force \times Distance$$

$$= m(v_w + v_{w_i}) v_b$$

$$= m \times EF \times AB \text{ N-m/s} \rightarrow ②$$

$\therefore$  Power produced by the turbine

$$P = m(v_w + v_{w_i}) v_b \text{ watts} \quad \because 1 \text{ N-m/s} = 1 \text{ watt}$$

Similarly, we can find out the axial thrust on the wheel, which is due to difference of velocities of flow at inlet and outlet  
Mathematically, axial thrust,

$F_y = \text{Mass of steam flowing/second} \times \text{change in the Velocity}$   
of flow

$$= m(v_f - v_{f_i})$$

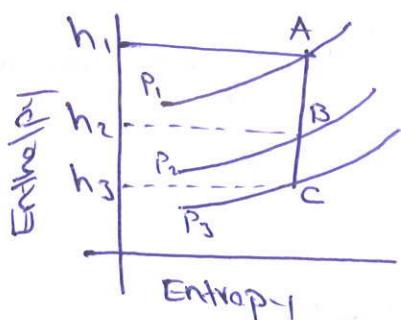
$$= m(CE - DF)N \rightarrow ③$$

Note:- In equation (i) the value of  $v_{w_i}$  is taken as negative because of the opposite directions of  $v_w$  with respect to the blade motion

## Degree of Reaction:-

In a reaction turbine, the pressure drop take place in both the fixed and moving blades.

→ In other words, there is an enthalpy drop in both the fixed and moving blades as shown on h-s diagram in figure.



→ The ratio of the enthalpy or heat drop in the moving blades to the total enthalpy or heat drop in the stage is known as degree of reaction.

Mathematically,

$$\therefore \text{Degree of reaction} = \frac{\text{Enthalpy or heat drop in the moving blades}}{\text{Total enthalpy or heat drop in the stage}}$$

$$= \frac{h_2 - h_3}{h_1 - h_3}$$

The enthalpy drop in the fixed blade per kg of steam is given by

$$h_1 - h_2 = \frac{V^2 - V_1^2}{2000} \text{ kJ/kg}$$

and enthalpy drop in the moving blades,

$$h_2 - h_3 = \frac{V_{01}^2 - V_0^2}{2000} \text{ kJ/kg}$$

∴ Total enthalpy drop in the stage

$$h_1 - h_3 = (h_1 - h_2) + (h_2 - h_3)$$

$$\begin{aligned}
 &= \frac{V^2 - V_1^2}{2000} + \frac{V_{81}^2 - V_1^2}{2000} \\
 &= \frac{2(V_{81}^2 - V_1^2)}{2000} \\
 &= 2(h_2 - h_3) \text{ kJ/kg}
 \end{aligned}$$

$\therefore$  For Person's reaction turbine  
 $V = V_{81}$  and  $V_1 = V_8$

We know that degree of reaction

$$\begin{aligned}
 &= \frac{h_a - h_3}{h_i - h_3} = \frac{h_a - h_3}{2(h_2 - h_3)} \\
 &= \frac{1}{2} = 0.5 \text{ or } 50\%
 \end{aligned}$$

Thus we see that a Person's reaction turbine is a 50% reaction turbine.

Condition for Maximum Efficiency of a Reaction Turbine:-

We know that work done by a Reaction turbine per kg of steam

$$\begin{aligned}
 &= AB \times EF = V_b(EB + AF - AB) \\
 &= V_b(V \cos \delta d + V_{81} \cos \delta \phi - V_b)
 \end{aligned}$$

We know that in a Person's reaction turbine,

$$\alpha = \phi, V = V_{81}, V_1 = V_8$$

$\therefore$  Work done per kg of steam

$$= V_b(\alpha V \cos \delta d - V_b)$$

$$= V_b \times V^2 \left( \frac{\alpha \cos \delta d}{V} - \frac{V_b}{V^2} \right) \quad \text{Multiplying & dividing by } V^2$$

$$= V^2 \left( \frac{2V_b \cos \alpha}{V} - \frac{V_b^2}{V^2} \right)$$

$$= V^2 (2\beta \cos \alpha - \beta^2) \quad \therefore \text{substituting } \frac{V_b}{V} = \beta$$

We know that kinetic energy supplied to the fixed blade per kg of steam  $= \frac{V^2}{2}$

and kinetic energy supplied to the moving blade per kg of steam

$$= \frac{(V_{r1})^2 - (V_r)^2}{2} = \frac{V^2 - V_1^2}{2} \quad \therefore (V_{r1} = V \text{ & } V_r = V_1)$$

$\therefore$  Total energy supplied to the turbine

$$= \frac{V^2}{2} + \frac{V^2 - V_1^2}{2}$$

$$= \frac{2V^2 - V_1^2}{2}$$

From the combined velocity triangle, we find that

$$V_1 = V_r = \sqrt{V^2 + V_b^2 - 2V V_b \cos \alpha}$$

$\therefore$  Total energy supplied to the turbine

$$= \frac{2V^2 - (V^2 + V_b^2 - 2V V_b \cos \alpha)}{2}$$

$$= \frac{V^2 - V_b^2 + 2V V_b \cos \alpha}{2}$$

$$= \frac{V^2}{2} \left( 1 - \frac{V_b^2}{V^2} + \frac{2V_b}{V} \cos \alpha \right)$$

$$= \frac{V^2}{2} (1 - \beta^2 + 2\beta \cos \alpha) \quad \left( \because \frac{V_b}{V} = \beta \right)$$

We know that diagram of blading efficiency

$$\eta_b = \frac{\text{Work done}}{\text{Energy Supplied}} = \frac{V^2(2\beta \cos\alpha - \rho^2)}{\frac{V^2}{2}(1 - \rho^2 + 2\beta \cos\alpha)}$$

$$\eta_b = \frac{2(\beta \cos\alpha - \rho^2)}{(1 - \rho^2 + 2\beta \cos\alpha)} \rightarrow ①$$

It may be noted that the efficiency of the turbine will be maximum when  $(1 - \rho^2 + 2\beta \cos\alpha)$  is minimum. Now  $(1 - \rho^2 + 2\beta \cos\alpha)$  to be minimum, differentiate this expression with respect to  $\rho$  and equate the same to zero. i.e.

$$\frac{d}{d\rho}(1 - \rho^2 + 2\beta \cos\alpha) = 0$$

$$2\rho - 2\cos\alpha = 0$$

$$\therefore \rho = \cos\alpha \text{ or } \frac{V_b}{V} = \cos\alpha$$

$$\therefore \rho = \frac{V_b}{V}$$

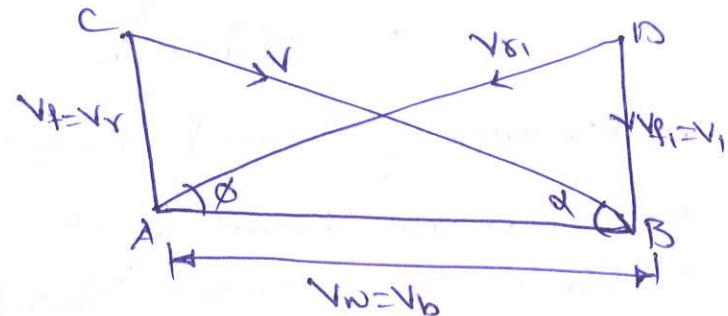
$$\therefore V_b = V \cos\alpha$$

It may be noted that when  $V_b = V \cos\alpha$ , the value of  $V_w$  will be zero (a condition for maximum efficiency of impulse turbine also) as shown in figure. In such a case  $V_b = V_w$ .

Now substituting  $\rho = \cos\alpha$  in equation (i) for Max efficiency

$$\therefore \eta_{\max} = \frac{2(\cos^2\alpha - \cos^2\alpha)}{(1 - \cos^2\alpha + 2\cos^2\alpha)}$$

$$\eta_{\max} = \frac{2\cos^2\alpha}{1 + \cos^2\alpha}$$



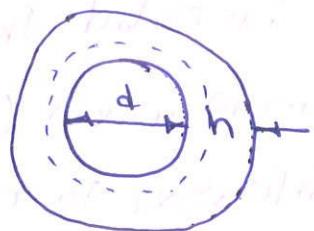
## Height of Blades of a Reaction Turbine:-

In a reaction turbine the steam enters the moving blades over the whole circumference. As a result of this, the area through which the steam flows is always full of steam. Now consider a reaction turbine whose end view of the blade ring is shown in figure.

Let  $d$  - Diameter of rotor drum

\*  $h$  = Height of blade

$v_f$  = Velocity of flow at exit



∴ Total area available for the steam to flow

$$A = \pi(d+h)h$$

and volume of steam flowing =  $\pi(d+h)h v_f$

We know that Volume of 1 kg of steam at the given pressure is  $v_g$  (from Steam tables). Therefore mass of steam flowing.

$$m = \frac{\pi(d+h)h v_f}{v_g} \text{ kgs}$$

If the steam has a dryness fraction of  $x$  then mass of steam flowing

$$m = \frac{\pi(d+h)h v_f}{x v_g} = \frac{\pi dm h v_f}{x v_g} \text{ kgs}$$

where  $dm$  is the mean blade diameter and is equal to  $(d+h)$

Note:- In most of the reaction turbines, the velocity of flow is constant at inlet and outlet (ie  $v_f = v_f'$ ). Therefore we can use the value of  $v_f$  instead of  $v_f'$  in the above relation.