UNIT-III
STEAM TURBINES

Contents:- **(08 Hours)**

Steam Nozzles:- Types and Classification, Equation for velocity and mass flow rate [No numerical treatment] **(01 Hour)**

Steam Turbines:-Classifications (Axial and Radial), Constructional details ,Compounding of steam turbines **(02 Hour)**

Velocity diagrams and analysis of Impulse and Reaction turbines (single and multi stage) **(04 Hours)**

Governing and performance characteristics **(01 Hour)**

STEAM NOZZLES

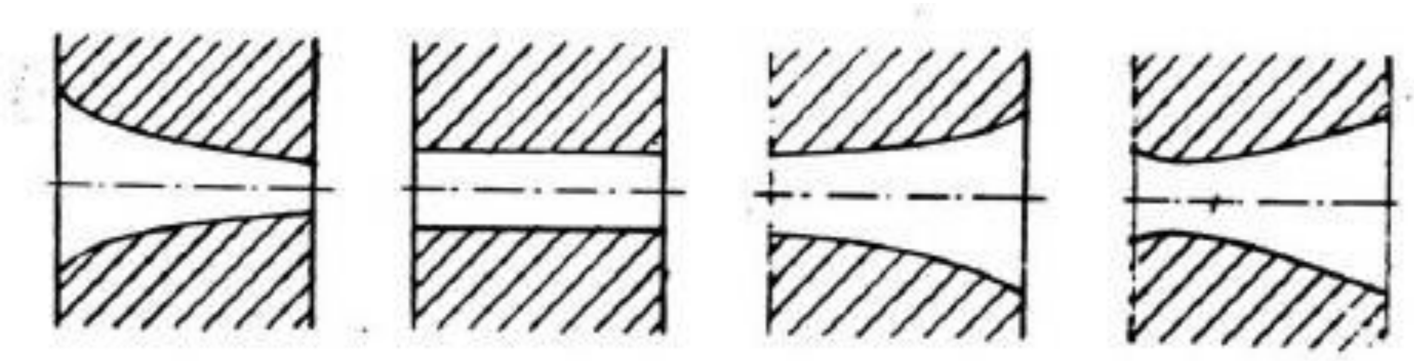
In steam turbines, the overall transformation of heat energy of steam into mechanical work takes place in two stages:-

1) Available steam energy into kinetic energy
2) Kinetic energy into mechanical work.

The first stage is accomplished with the devices called steam nozzles.

A **steam nozzle** is a duct or passage of smoothly varying cross sectional area which converts heat energy of steam into kinetic energy.

The shape of the nozzle is designed such that it will perform this conversion of energy with minimum loss.



The cross section of the nozzles may be circular, rectangular, elliptical or square.

Applications of Nozzles

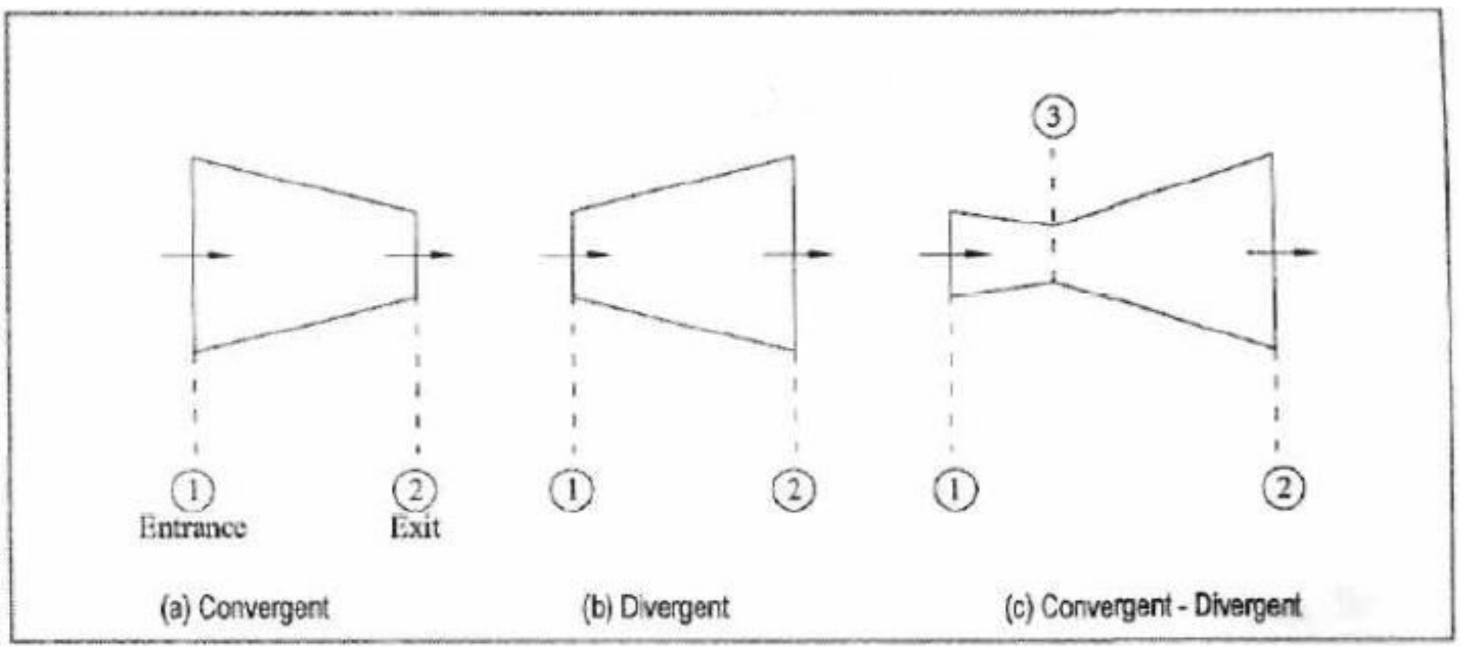
1) Steam and Gas turbines,
2) Jet engines,
3) For propulsion of rocket motors,
4) Flow measurements,
5) In injectors for pumping water ,
6) In ejectors for removing air from condensers .

The nozzles are just located just before the steam turbines.

Types of Steam Nozzles

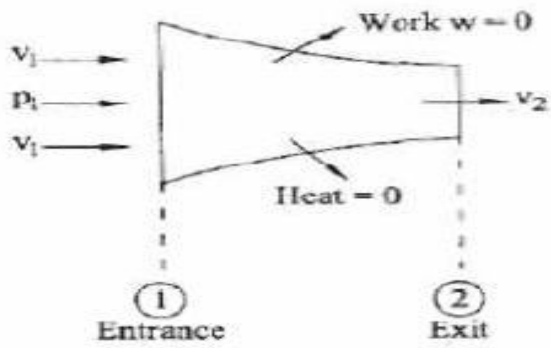
Three important types of steam nozzles are:-

1) Convergent Nozzle,
2) Divergent Nozzle,
3) Convergent-Divergent Nozzle.



Types of Steam Nozzles

Velocity of steam through Nozzle



Consider steady flow of 1 kg of steam through nozzle

Let

P1 and P2 → Pressures at inlet and exit in bar

V1 and V2 → Velocities at inlet and exit in m/sec

Vs1 and Vs2 → specific volumes at inlet at exit in m3/kg

u1 and u2 → Internal energy at inlet and exit in KJ/kg

Z1 and Z2→ Elevation and inlet and exit in m

h1 and h2 → Enthalpy at inlet and exit in KJ/kg

q→ heat supplied if any in KJ/kg and w→ work done if any in KJ/kg

For a steady flow process (without accumulation of any fluid between inlet and exit), by principle of conservation of energy :

Energy at inlet = Energy at exit

Work done in forcing 1 kg steam through nozzle + initial internal energy+ initial kinetic energy + initial potential energy + heat supplied if any from surroundings = work done in sending out 1 kg of steam from nozzle + final internal energy + final kinetic energy + final potential energy + work done if any to the surroundings

$$P1V1 + u1 + V1^2/2 + gZ1 + q = P2V2 + u2 + V2^2/2 + gZ2 + w$$

$P1V1+u1 = h1$ = Enthalpy of steam at inlet

$P2V2+u2 = h2$ = Enthalpy of steam at exit

$$h1 + V1^2/2 + gZ1 + q = h2 + V2^2/2 + gZ2 + w$$

Generally changes in potential energy are negligible $Z1 = Z2$

If no heat is supplied from the surroundings ; then $q = 0$. If no work is done to the surroundings , then $w = 0$

$$h_1 + \frac{V_1^{\ 2}}{2} = h_2 + \frac{V_2^{\ 2}}{2}$$

This is a steady flow energy equation of nozzle.

$$\frac{V_2^{\ 2}}{2} = \frac{V_1^{\ 2}}{2} + (h_1 - h_2)$$

The gain in the K.E. between any two sections is equal to loss of enthalpy. Enthalpy drop $h_d = (h1 - h2)$

$$\frac{V_2^2}{2} = \frac{V_1^2}{2} + h_d$$

Neglecting the velocity of entering steam of velocity of approach ;

$$\frac{V_2^2}{2} = h_d$$

$V2^2 = 2\ h_d = 2000\ h_d$ J/Kg

$$V_2 = \sqrt{2000\ h_d} = 44.72\ \sqrt{h_d}\ m/sec.$$

Equation for mass flow rate

The equation for velocity is obtained in the above part of derivation. When the expansion of steam is isentropic then,

$$W = \frac{n}{n-1}\,(p1\,v1 - p2v2)$$

Isentropic enthalpy drop equals work done during expansion of steam

$$h1 - h2 = \frac{n}{n-1}\,(p1\,v1 - p2v2)$$

$$V2 = \sqrt{2\,(h1 - h2)}$$

$$V2 = \sqrt{\frac{2n}{n-1}\,(p1\,v1 - p2v2)}\quad assuming\,V1 = 0$$

For isentropic expansion

$$p1v1^n = p1v2^n$$

$$\frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}} = \left(\frac{p_2}{p_1}\right)^{-\frac{1}{n}}$$

$$v_2 = v_{1\left(\frac{p_2}{p_1}\right)}^{-\frac{1}{n}}$$

Substituting the value of v2/v1

$$\frac{v_{2^2}}{2} = \frac{n}{n-1}\left(p_1 v_1\right)\left[1 - \frac{p_2}{p_1}\left(\frac{p_2}{p_1}\right)^{-\frac{1}{n}}\right]$$

$$= \frac{n}{n-1}(p_1 v_1)\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n}{n-1}}\right]$$

$$V_2 = \sqrt{2\frac{n}{n-1}p_1 v_1\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n}{n-1}}\right]}$$

Now the volume of steam flowing per second = cross sectional area of nozzle × velocity of steam = A × V2

And volume of 1 kg of steam i.e. specific volume of steam at pressure P_2= V_2 m^3/kg

Mass of steam discharged through nozzle per second

$$m = \frac{volume\,of\ steam\ flowing\ per\sec ond}{volume\,of\,1kg\ of\ steam\,at\ pressure\,P_2}$$

$$= \frac{AV_2}{v_2} = \frac{A}{v_2}\sqrt{2\frac{n}{n-1}p_1 v_1\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

$$m = \frac{A}{v_1}\left(\frac{p_1}{p_2}\right)^{-\frac{1}{n}}\sqrt{\frac{2n}{n-1}p_1 v_1\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

$$= \frac{A}{v_1}\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}\sqrt{\frac{2n}{n-1}p_1 v_1\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

$$= A\sqrt{\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}}\frac{2n}{n-1}\frac{p_1}{v_1}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

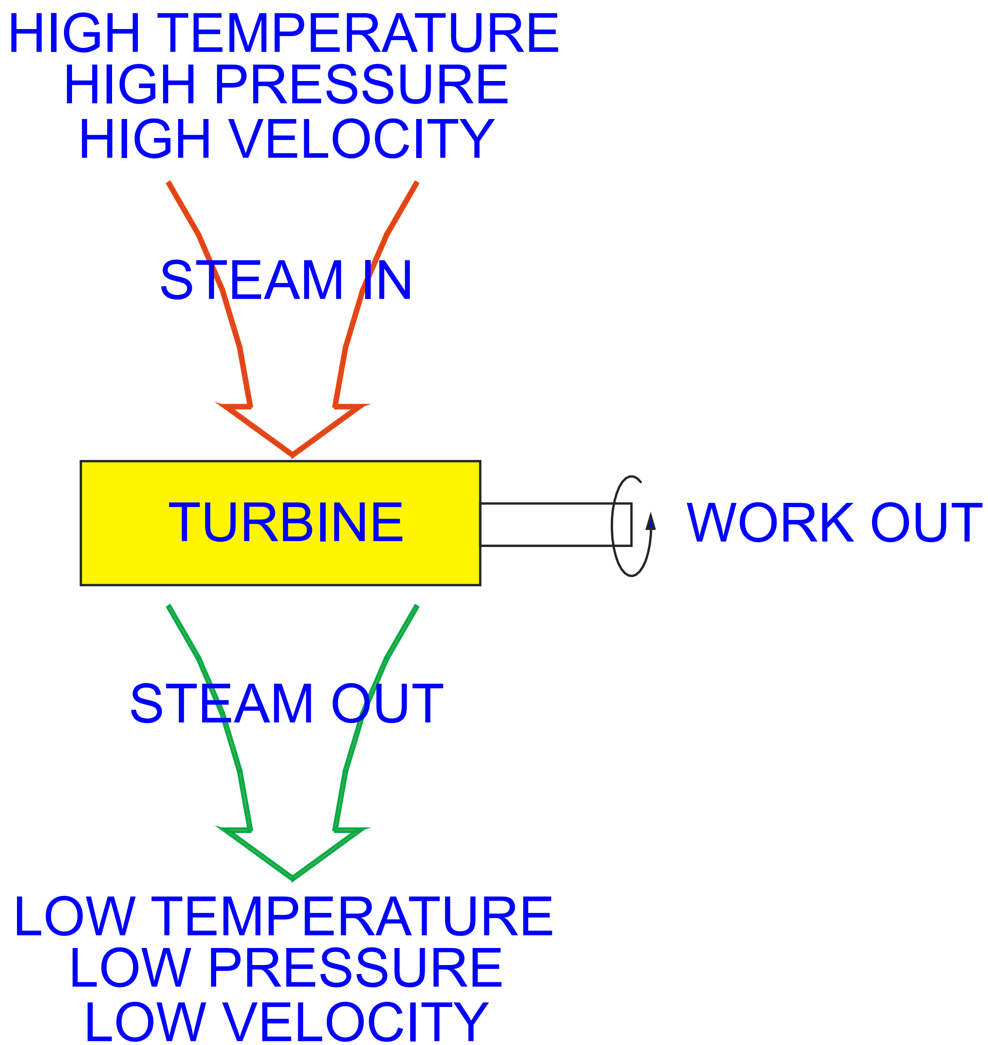
$$= A\sqrt{\frac{2n}{n-1}\frac{p_1}{v_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}}-\left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}}\right]}$$

STEAM TURBINES

A steam turbine is a key unit in a steam power plant from which we get power . A stem turbine is a turbo machine and a prime mover in which energy of stem is transformed into kinetic energy and this kinetic energy is then transformed into mechanical energy of rotation of shaft of turbine.

The modern steam turbine was invented in 1884 by Sir Charles Parsons, whose first model was connected to a dynamo that generated 7.5 kW (10 hp) of electricity. The Parsons turbine also turned out to be easy to scale up. Parsons had the satisfaction of seeing his invention adopted for all major world power stations, and the size of generators had increased from his first 7.5 kW set up to units of 500MW capacity.

WORK IN A TURBINE VISUALIZED



CLASSIFICATION OF STEAM TURBINE

Classification of steam turbines may be done as following:

1. According to action of steam
   (a) Impulse turbine
   (b) Reaction turbine
   (c) Combination of both

2. According to direction of flow:
   (a) Axial flow turbine
   (b) Radial flow turbine

3. According to number of stages
   (a)Single stage turbine
   (b)Multi stage turbine

4 .According to steam pressure at inlet of Turbine:
(a) Low pressure turbine
(b) Medium pressure turbine.
(c) High pressure turbine
(d) Super critical pressure turbine.

5.According to method of governing:
(a) Throttle governing turbine.
(b) Nozzle governing turbine.
(c) By pass governing turbine.

6. According to usage in industry:
(a) Stationary turbine with constant speed.
(b) Stationary turbine with variable speed.
(c) Non stationary turbines.

Description of common types of Turbines

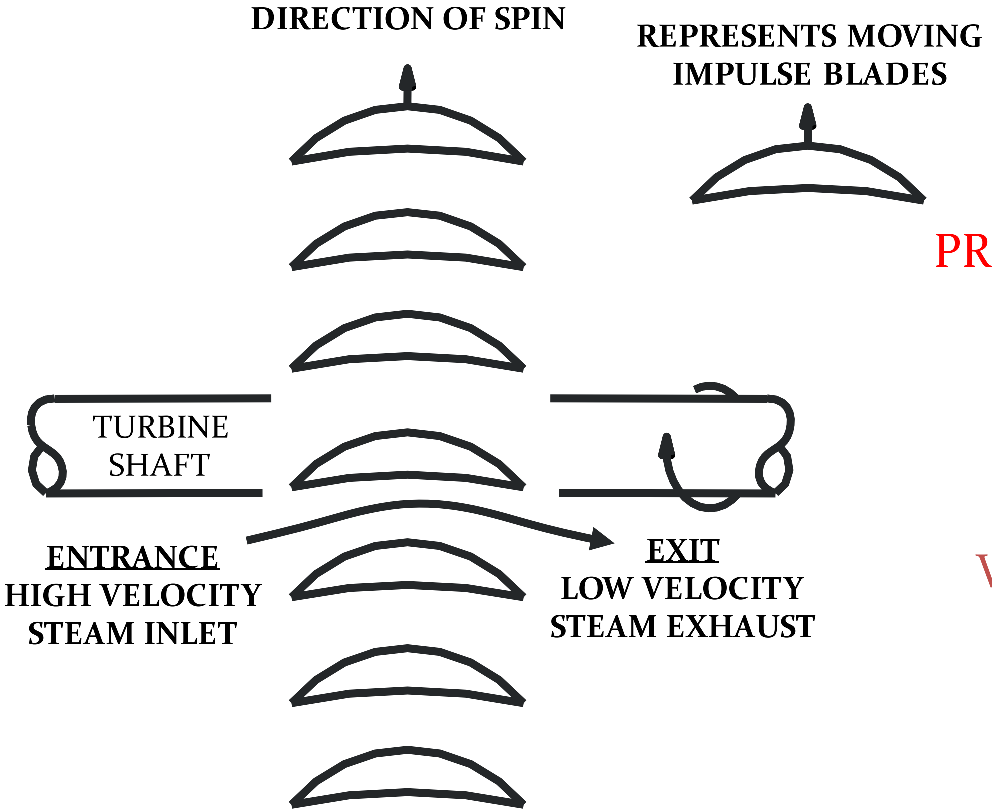
The common types of steam turbine are

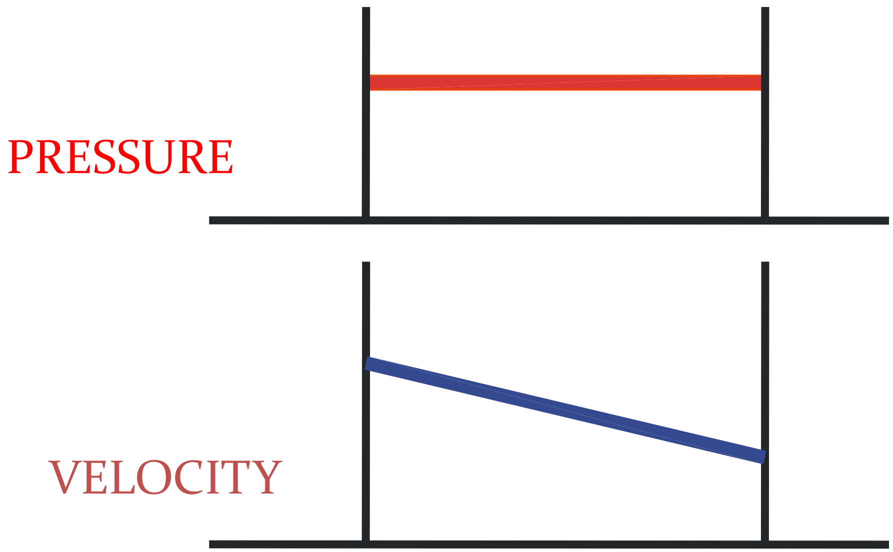
1. Impulse Turbine.
2. Reaction Turbine.

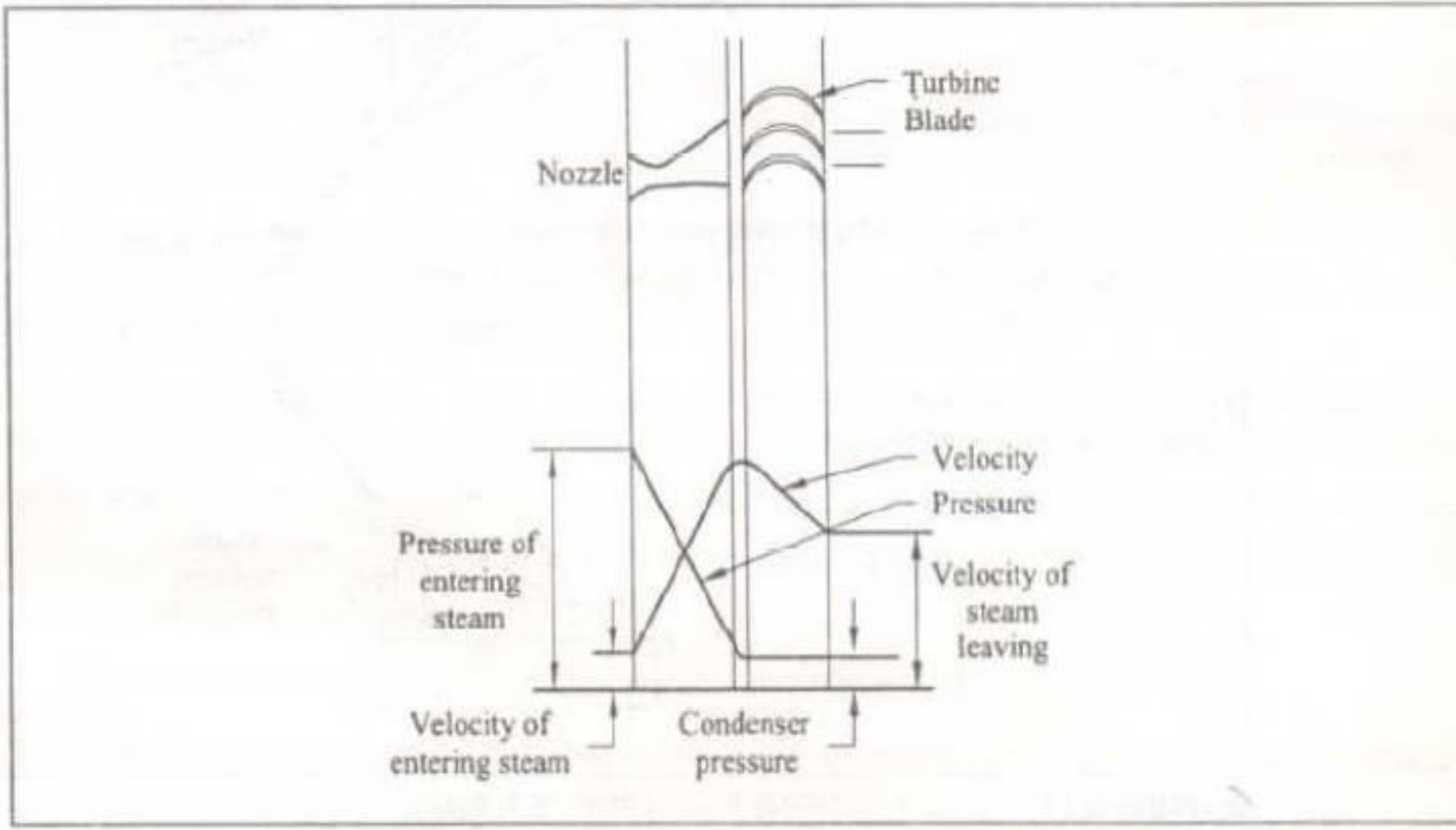
The main difference between these two turbines lies in the way of expanding the steam while it moves through them.

Simple impulse Turbine

In the impulse turbine, the steam is expanded within the nozzle and there is no any change in the steam pressure as it passes over the blades.







VARIATION OF PRESSURE AND VELOCITY IN A SIMPLE IMPULSE TURBINE

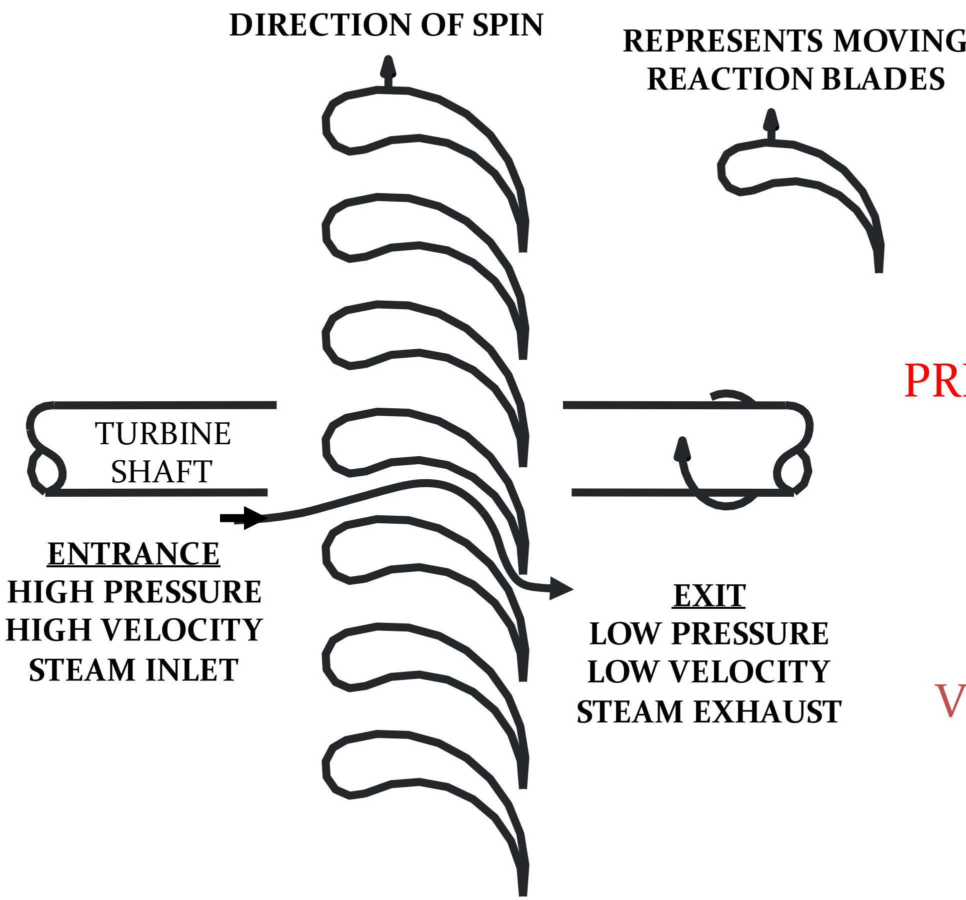
Reaction Turbine

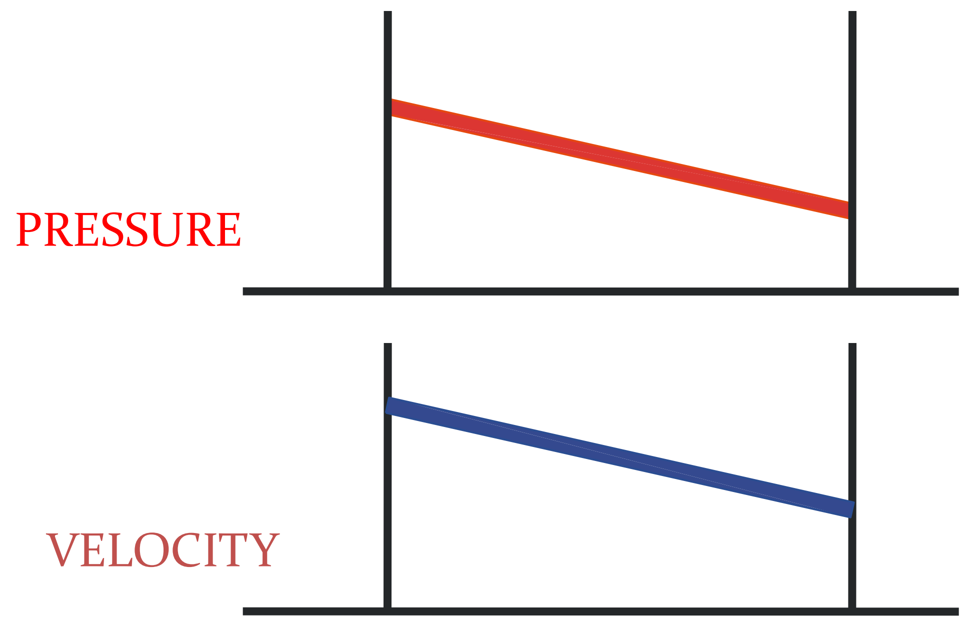
In this type of turbine, there is a gradual pressure drop and takes place continuously over the fixed and moving blades. The rotation of the shaft and drum, which carrying the blades is the result of both impulse and reactive force in the steam. The reaction turbine consist of a row of stationary blades and the following row of moving blades.

The fixed blades act as a nozzle which are attached inside the cylinder and the moving blades are fixed with the rotor.

Because of the pressure drops in each stage, the number of stages required in a reaction turbine is much greater than in a impulse turbine of same capacity.

PRESSURE-VELOCITY DIAGRAM FOR A MOVING REACTION BLADE





Compounding in Steam Turbine

The compounding is the way of reducing the wheel or rotor speed of the turbine to optimum value. It may be defined as the process of arranging the expansion of steam or the utilization of kinetic energy or both in several rings.

There are several methods of reducing the speed of rotor to lower value. All these methods utilize a multiple system of rotors in series keyed on a common shaft, and the steam pressure or jet velocity is absorbed in stages as the steam flow over the blades.

Different methods of compounding are:

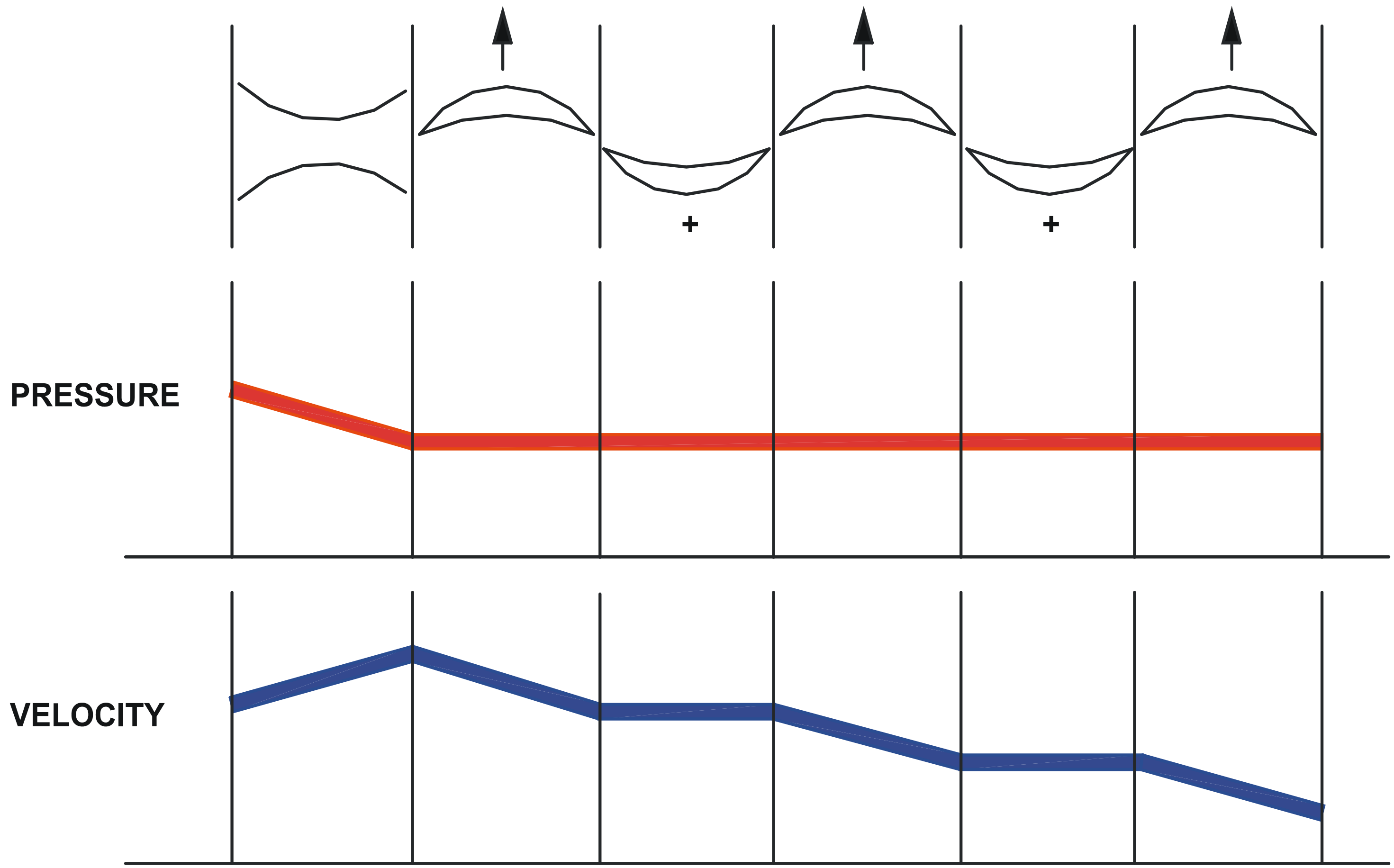
1. **Velocity Compounding**
2. **Pressure Compounding**
3. **Pressure Velocity Compounding**

Velocity Compounding

There are number of moving blades separated by rings of fixed blades. All the moving blades are keyed on a common shaft. When the steam passed through the nozzles where it is expanded to condenser pressure. It's Velocity becomes very high. This high velocity steam then passes through a series of moving and fixed blades.

When the steam passes over the moving blades it's velocity decreases. The function of the fixed blades is to re-direct the steam flow without altering it's velocity to the following next row moving blades where a work is done on them and steam leaves the turbine with allow velocity as shown in diagram.

VELOCITY COMPOUNDED TURBINE



VISUALIZATION OF A VELOCITY COMPOUNDED TURBINE

Pressure Compounding

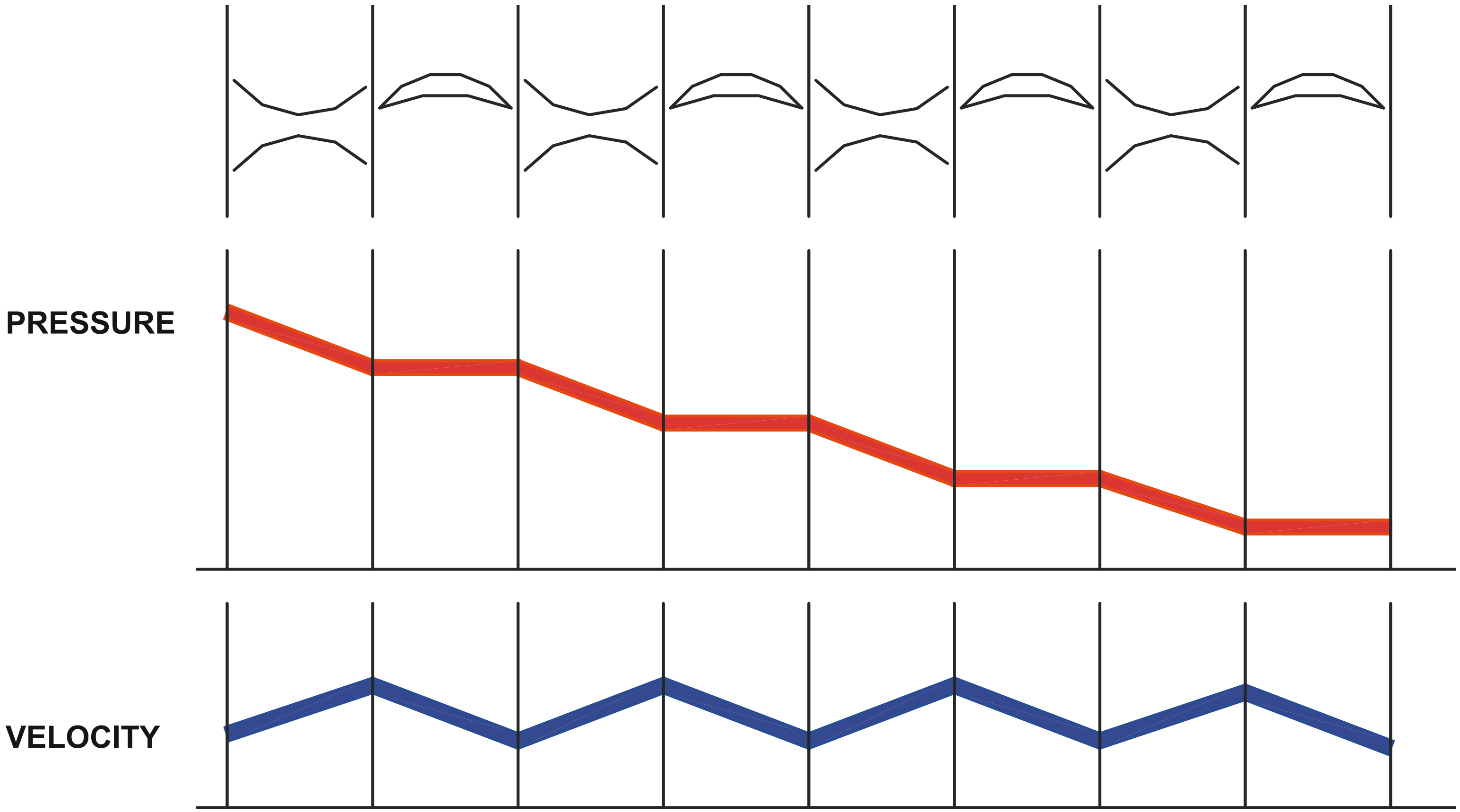
There are the rings of moving blades which are keyed on a same shaft in series, are separated by the rings of fixed nozzles.

The steam at boiler pressure enters the first set of nozzles and expanded partially. The kinetic energy of the steam thus obtained is absorbed by moving blades.

The steam is then expanded partially in second set of nozzles where it's pressure again falls and the velocity increase the kinetic energy so obtained is absorbed by second ring of moving blades.

This process repeats again and again and at last, steam leaves the turbine at low velocity and pressure. During entire process, the pressure decrease continuously but the velocity fluctuate as shown in diagram.

PRESSURE COMPOUNDED TURBINE



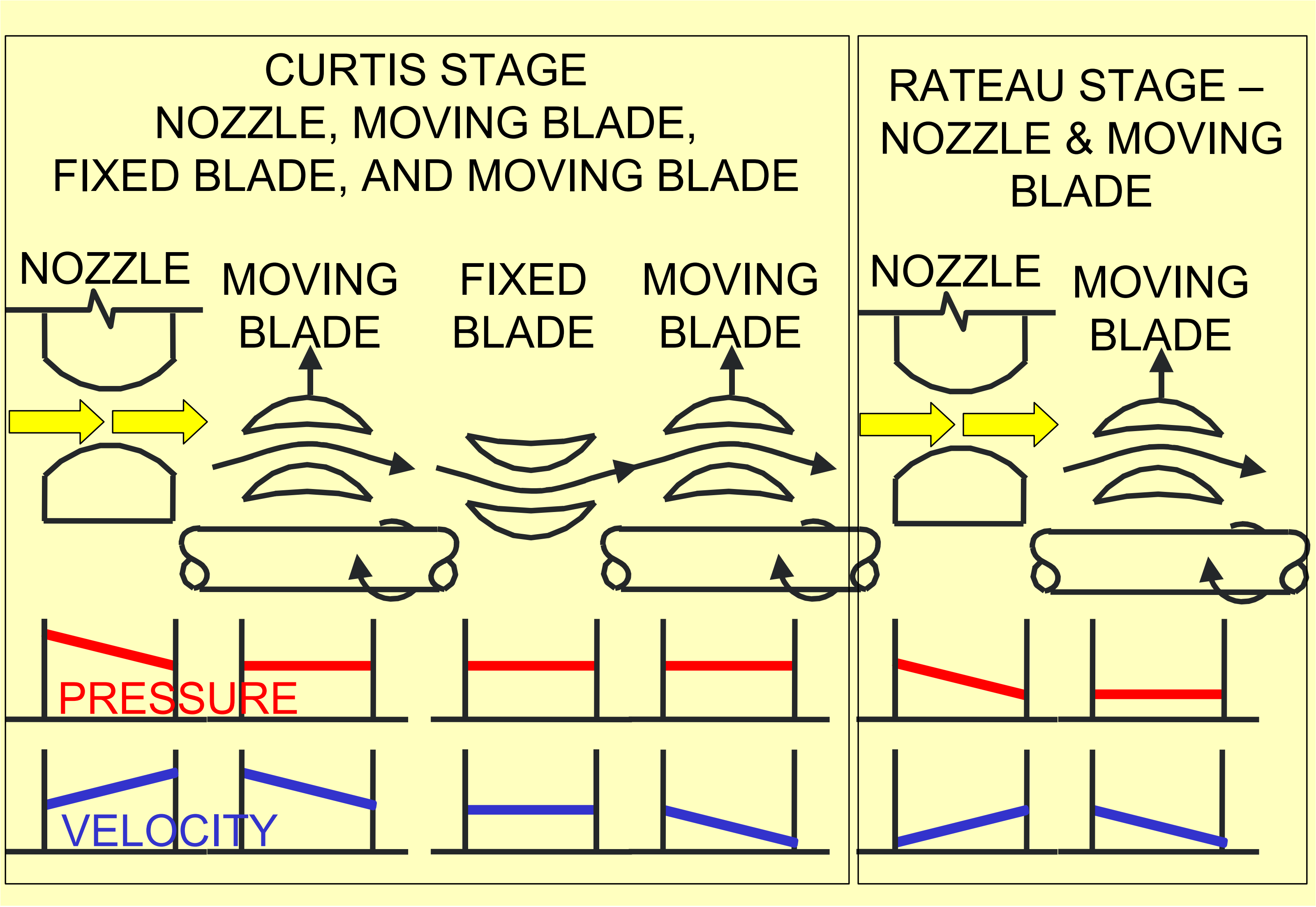
VISUALIZATION OF A PRESSURE COMPOUNDED TURBINE

Pressure velocity compounding

This method of compounding is the combination of two previously discussed methods. The total drop in steam pressure is divided into stages and the velocity obtained in each stage is also compounded. The rings of nozzles are fixed at the beginning of each stage and pressure remains constant during each stage as shown in figure.

The turbine employing this method of compounding may be said to combine many of the advantages of both pressure and velocity staging By allowing a bigger pressure drop in each stage, less number stages are necessary and hence a shorter turbine will be obtained for a given pressure drop.

PRESSURE-VELOCITY COMPOUNDED IMPULSE TURBINE

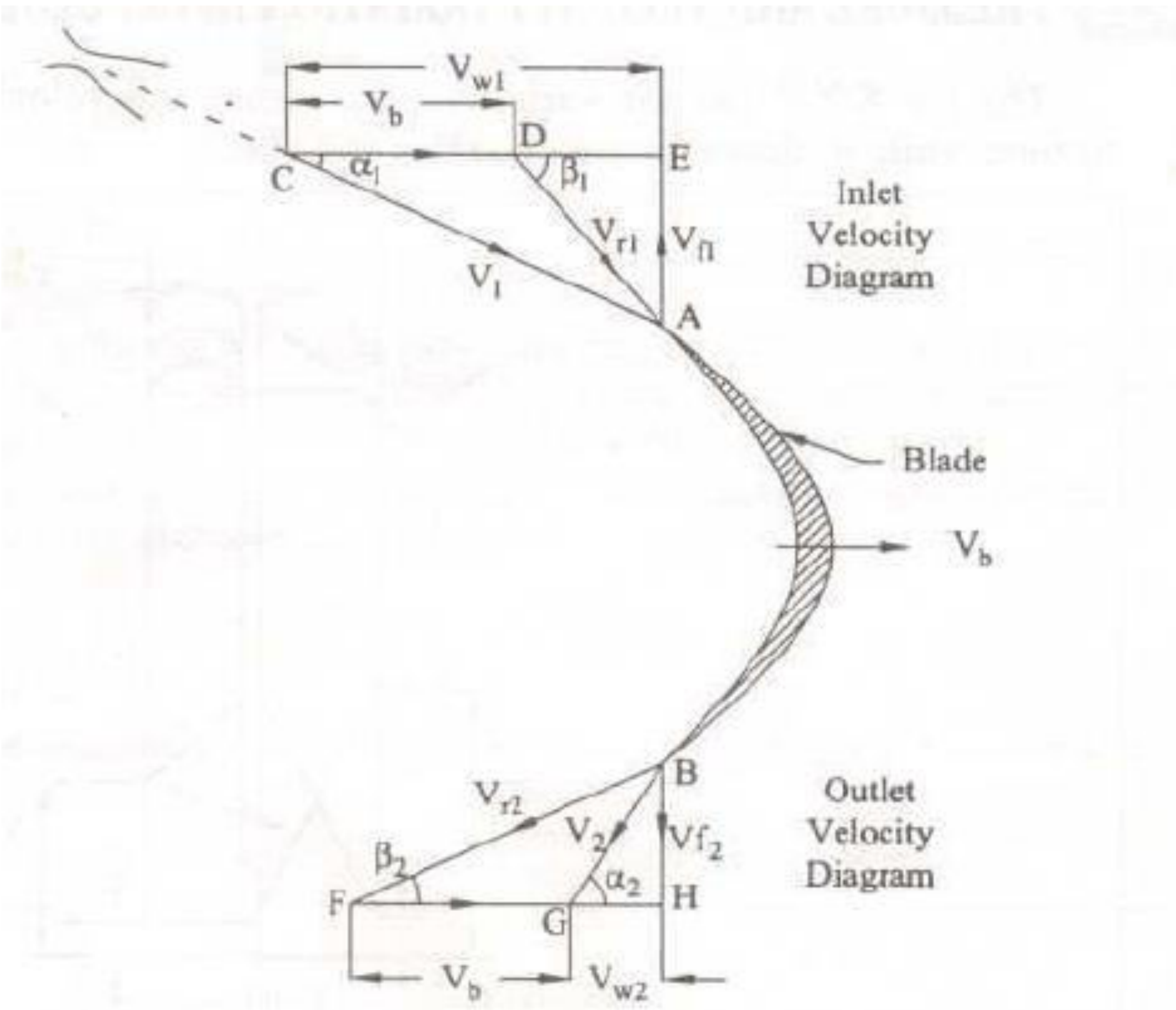


Velocity Diagram and Analysis of Impulse and Reaction Turbines

We should be able to calculate the propelling force applied to the turbine rotor. We can estimate work done and hence power.

Since the force is due to change of momentum mainly caused by change in direction of flow of steam, it is essential to draw velocity diagram that shows how velocity of the steam varies during its passage through the blades.

Velocity is vector quantity as it has magnitude and direction. So we can represent velocity by a straight line and its length indicates its magnitude and direction is indicated by direction of line with reference to some fixed direction.



Velocity diagram for Impulse Turbine

Let:- V_b = linear velocity of moving blade

V_1= absolute velocity of steam at inlet to moving blade; i. e. exit velocity of nozzle

V_{w1}= Tangential component of entering steam , also known as velocity of whirl at entrance

V_{r1}= relative velocity of steam wrt tip of blade at inlet , it is the vectorial difference between V_b and V_1

V_{f1}= velocity of flow = axial velocity at entrance to moving blades. It is the vertical component of V_1

α_1= angle of nozzle= angle which the entering steam makes with the moving blade at entrance with tangent to the wheel at entrance

β_1= angle which the relative velocity makes with tangent of the wheel – direction of motion of blade . Also known as blade angle at inlet.

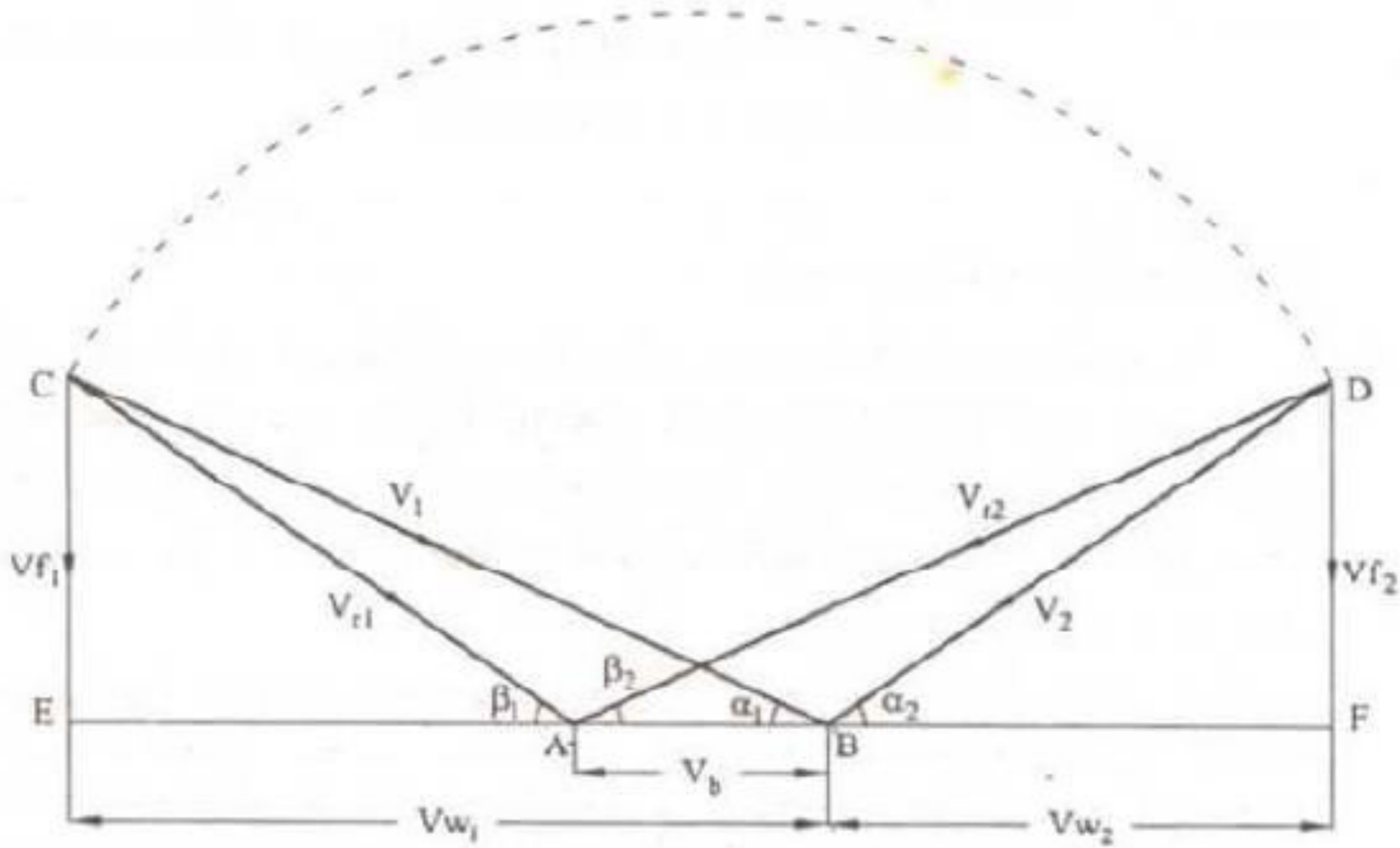
V_2, V_{w2}, V_{f2}, V_{r2}, α_2, β_2 are corresponding values at exit of the moving blade. They stand outlet velocity triangle.

The absolute velocity V_2 can be considered as two components.

The tangential component called whirl component $V_{w1} = V_1 \cos \alpha_1$ is parallel to direction of rotation of blades and axial or flow component $V_{f1} = V_1 \sin \alpha_1$ is perpendicular to the direction of rotation of blades.

Tangential component does work on the blade because it is in the same direction as the motion of the blade. The axial component doesn't work on the blades because it is perpendicular to the direction of motion of blades . It is responsible for flow of steam through the turbine. Change of velocity in this component causes axial thrust on the rotor.

Combined Velocity diagram for Impulse Turbine

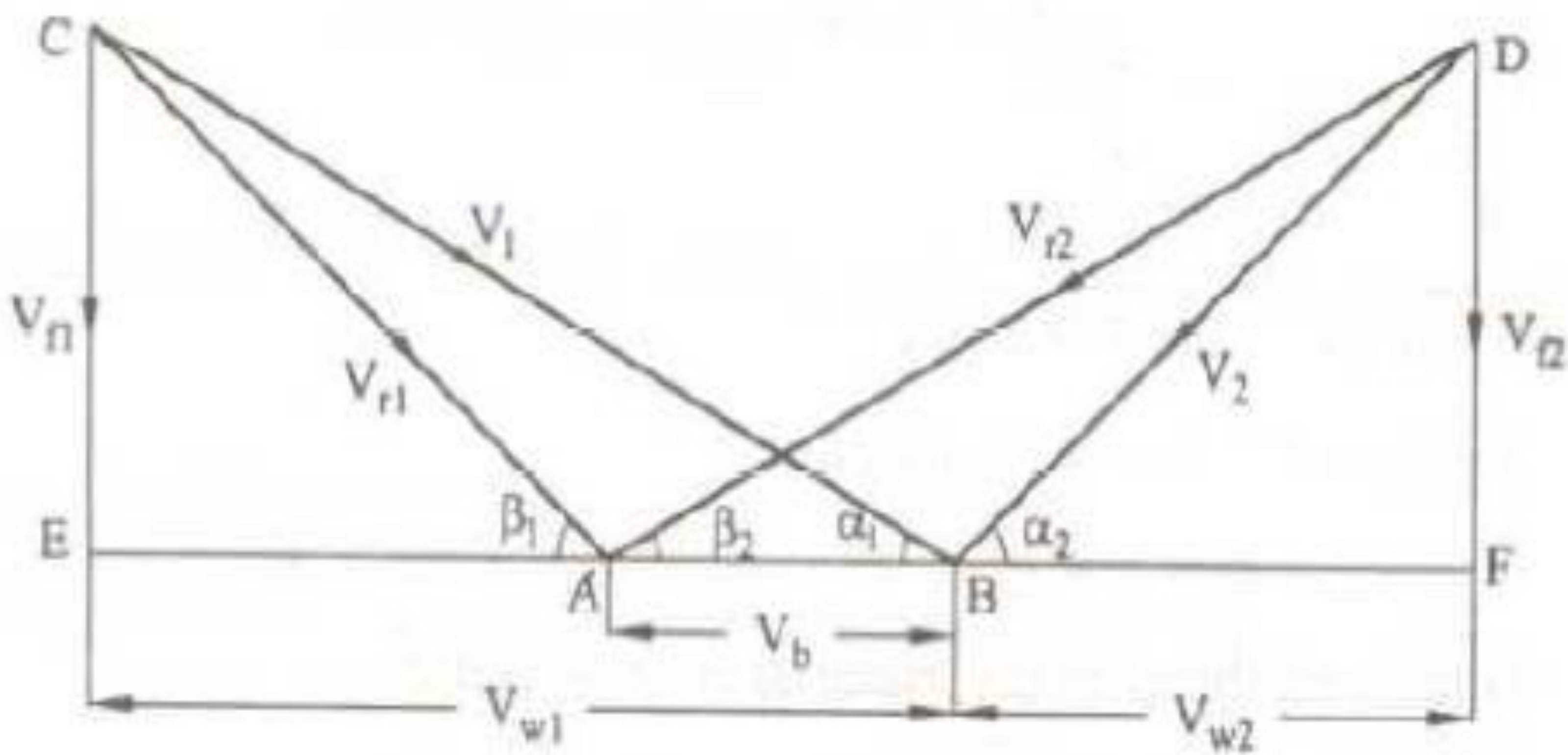


1) Draw horizontal line and cut off AB equal to velocity of blade
2) Draw line BC at an angle $\alpha 1$, with AB. Cut off BC equal to V1
3) Join AC. It represents Vr1
4) From A, draw line AD at an angle $\beta 2$ with AB. With A as centre and radius equal to AC , draw an arc that meets the line through A at D such that AC=AD or V1= Vr2
5) Join BD. It represents absolute velocity at exit.
6) From C and D draw perpendiculars to meet the line AB produced at E and F.
7) Now to scale- EB→ velocity of whirl at entrance,

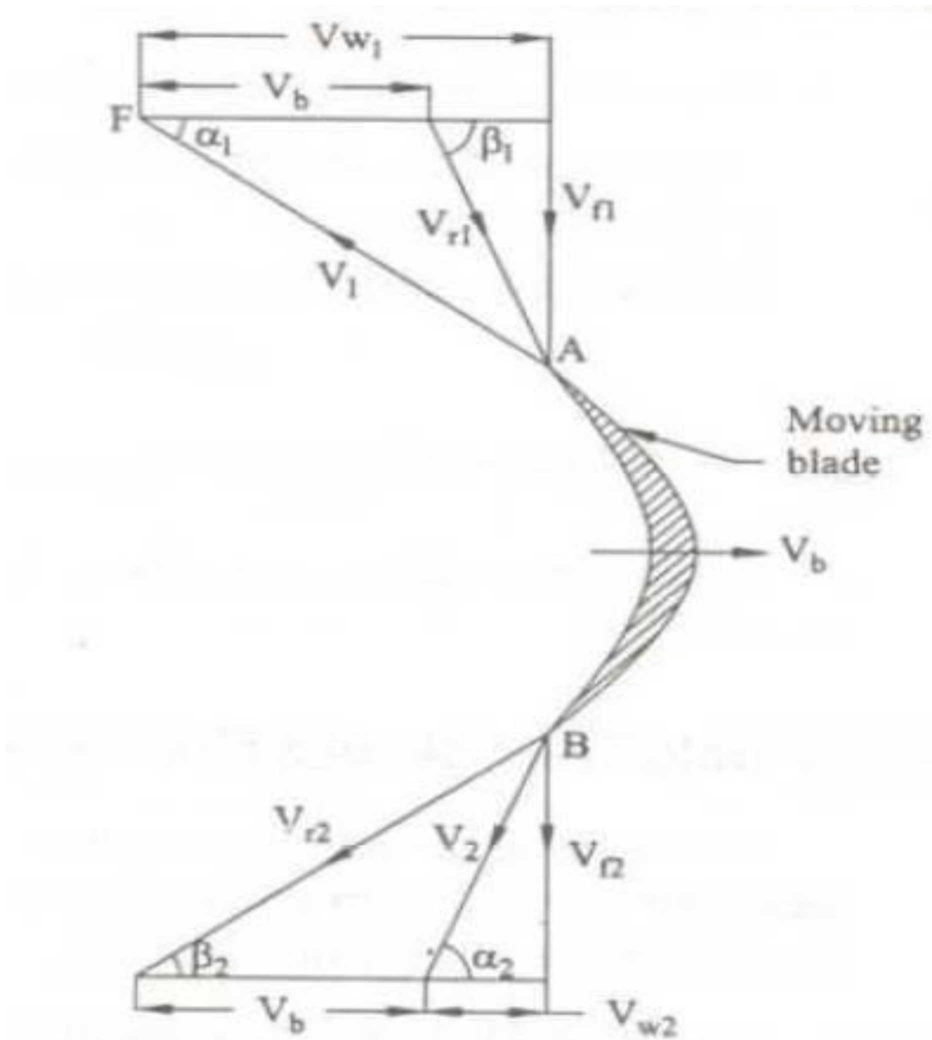
BF→ velocity of whirl at exit, CE--> velocity of flow at inlet,

DF→ velocity of flow at outlet.

When friction is neglected:- Vr1= Vr2, Vf1= Vf2 and $\beta 1 = \beta 2$



Velocity diagram for Reaction Turbine



In Parsons reaction turbine, both the fixed and moving blades are made identical.

So , $\alpha1= \beta2$ and $\alpha2= \beta1$.

So velocity diagram for parsons reaction turbine will be symmetrical about about vertical centre line and

Vf1= Vf2 ; V1= Vr2;

V2= vr1

Forces on blade and WD by the blades

1. Force on rotor= mass × tangential acceleration

$$= m \times (V_{\omega 1} - V_{\omega 2})$$

Where m = mass flow rate of steam in kg/sec

Actually Vw2 is negative as the steam is discharged in opposite direction to blade motion , so Vw1 and Vw2 are added together. Generally,

$$F_t = m\,(V_{\omega 1} \pm V_{\omega 2}) \text{ Newton.}$$

2. Work done on blade = force ×distance

= tangential force × distance moved in unit time in the direction of force

$$= F_t \, . \, V_b \; N-m/sec$$

$$= m \, . \, (V_{\omega 1} \pm V_{\omega 2}) \, . \, V_b \; N-m/sec$$

3. Power developed by the turbine = rate of doing work

$$= m \, . \, (V_{\omega 1} \pm V_{\omega 2}) \, . \, V_b \text{ watts.}$$

4. Axial thrust on the rotor = Fa= mass × axial acceleration

= mass × change in velocity of flow

$$= m \cdot (V_{f1} - V_{f2}) \text{ Newtons.}$$

Efficiencies:- Following efficiencies are common to both impulse and reaction turbines:-

1) Blading or diagram efficiency

2) Gross or stage efficiency

3) Nozzle efficiency

1. Diagram efficiency or blading efficiency

$$\eta_{bl} = \frac{\text{Work done on blade}}{\text{Energy supplied blade}}$$

$$= \frac{m \,.\, (V_{\omega 1} \pm V_{\omega 2} \,.\, V_b}{\frac{1}{2} m V_1^{\;2}}$$

$$= \frac{2 V_b \,.\, (V_{\omega 1} \pm V_{\omega 2})}{V_1^{\;2}}$$

This is called diagram efficiency because the quantities involved in it are obtained from velocity diagram.

2. Gross or Stage Efficiency

$$\text{Stage efficiency} = \frac{\text{Work done on blade}/kg \text{ of steam}}{\text{Total energy supplied}/\text{stage}/kg \text{ of steam}}$$

$$\eta_{stage} = \frac{(V_{\omega 1} \pm V_{\omega 2} \cdot V_b}{h_1 - h_2}$$

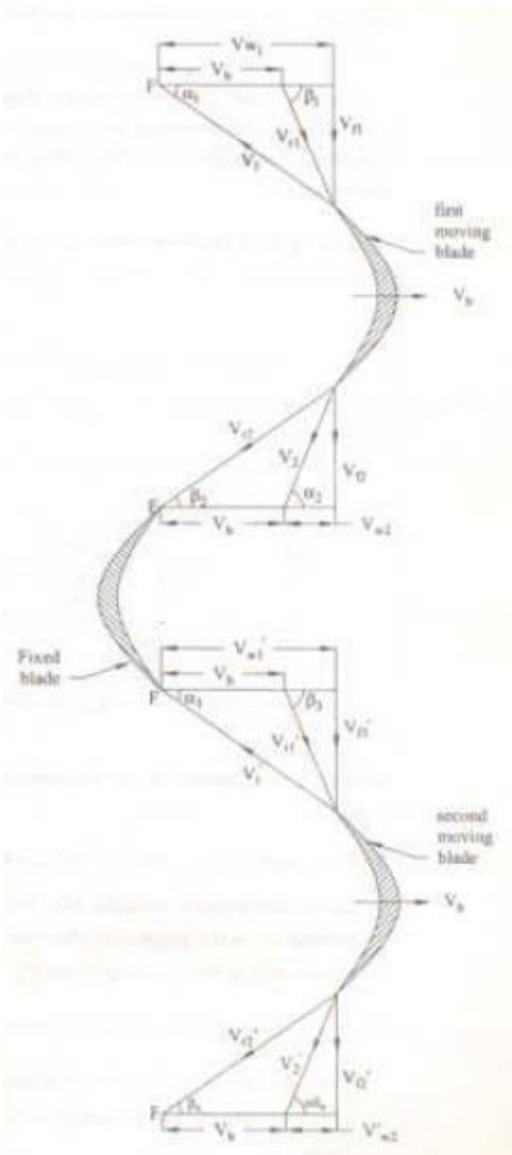
3. Nozzle Efficiency

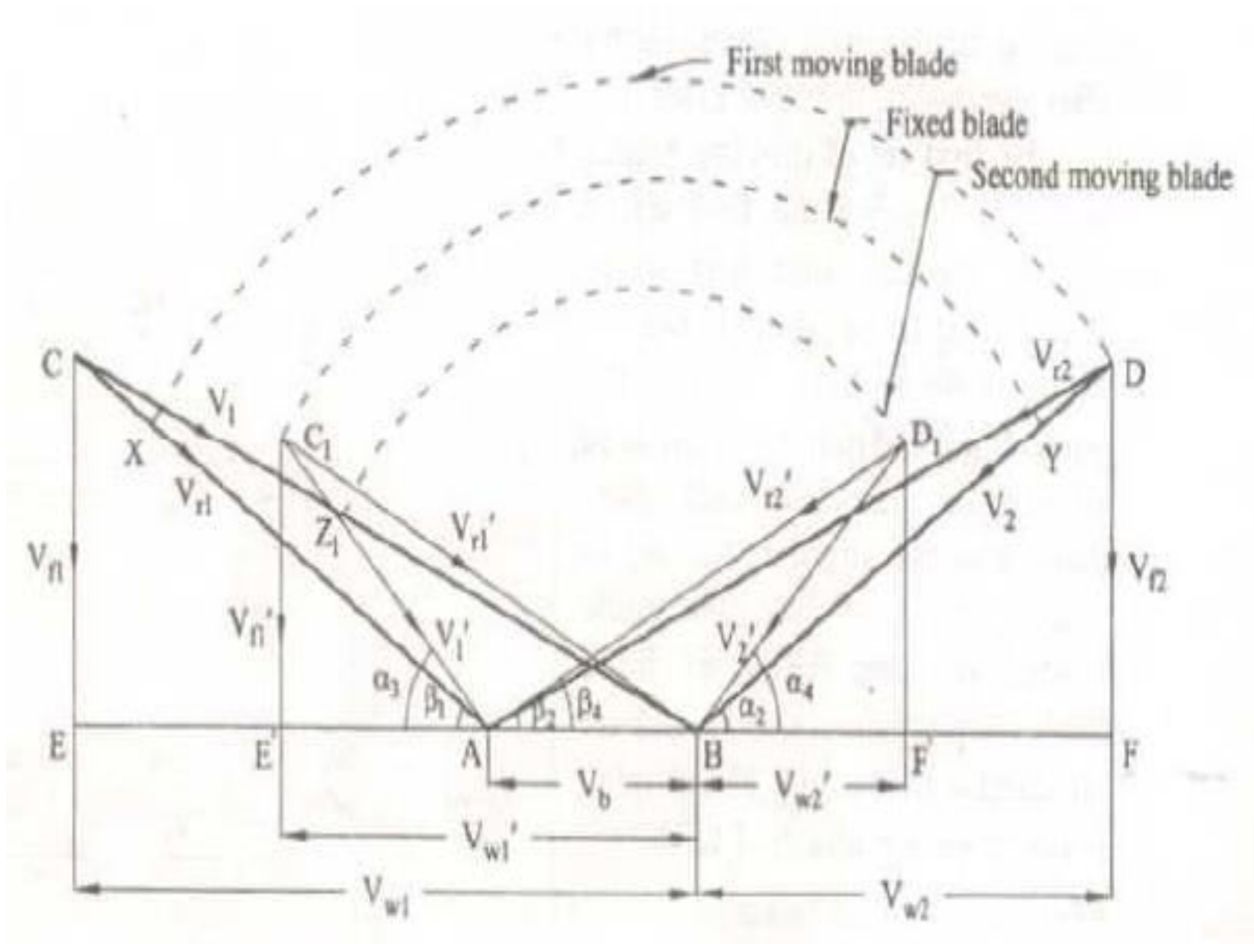
$$\text{Nozzle efficiency} = \frac{\text{Energy availbale at entrance}/kg}{\text{Enthalpy drop through a stage}/kg \text{ of steam}}$$

$$\eta_{nozzle} = \frac{\frac{1}{2} V_1^{\ 2}}{(h_1 - h_2)}$$

$$= \frac{V_1^{\ 2}}{2\,(h_1 - h_2)}$$

Multi Stage Turbines





Calculations

1. WD per kg of steam passing through both the stages (Wt)

   Wt = WD in first moving blade stage + WD in second moving blade stage

$$= 2\,V_b\,.\,(V_1 \cos\alpha_1 - V_b) + 2\,V_b\,(V_1\,.\cos\alpha_1 - 3\,V_b).$$

$$= 4\,V_b\,(V_1\,.\cos\alpha_1 - 2\,V_b).$$

2. Blading or Diagram Efficiency for two stage turbine

$$\eta_{bl} = \frac{\text{Work done}}{\text{Energy supplied}}$$

$$= \frac{\omega_t}{\frac{1}{2}\,.\,m\,.\,V_1{}^2} = \frac{\omega_t}{\frac{1}{2}\,V_1{}^2} \qquad [m = 1\ kg]$$

$$= \frac{4\,V_b \cdot (V_1 \cos \alpha_1 - 2\,V_b)\,.\,2}{V_1^{\,2}}$$

$$= \frac{8V_b}{V_1^{\,2}} (V_1 \cos \alpha_1 - 2\,V_b)$$

$$= 8\,.\,\frac{V_b}{V_1}\left(\cos \alpha_1 - 2\,.\,\frac{V_b}{V_1}\right)$$

$$= 8\,\rho\,(\cos \alpha_1 - 2\,\rho) \text{ where}$$

$$\rho = \frac{V_b}{V_1} = \text{blade speed ratio.}$$

For maximum efficiency, $\rho_{opt} = \dfrac{\cos \alpha_1}{4}$

Maximum efficiency $\eta_{bl(max)} = \cos^2 \alpha_1$.

3. Maximum work done

$$\omega_t = 4\ V_b\ .\ (V_1 \cos\alpha_1 - 2\ V_b)$$

$$\text{Optimum value of } \rho = \frac{\cos\alpha_1}{4}$$

$$\frac{V_b}{V_1} = \frac{\cos\alpha_1}{4}$$

$$V_1 = \frac{4V_b}{\cos\alpha_1}$$

$$\omega_{t(max)} = 4V_b\left(\frac{4V_b}{\cos\alpha_1} . \cos\alpha_1 - 2V_b\right)$$

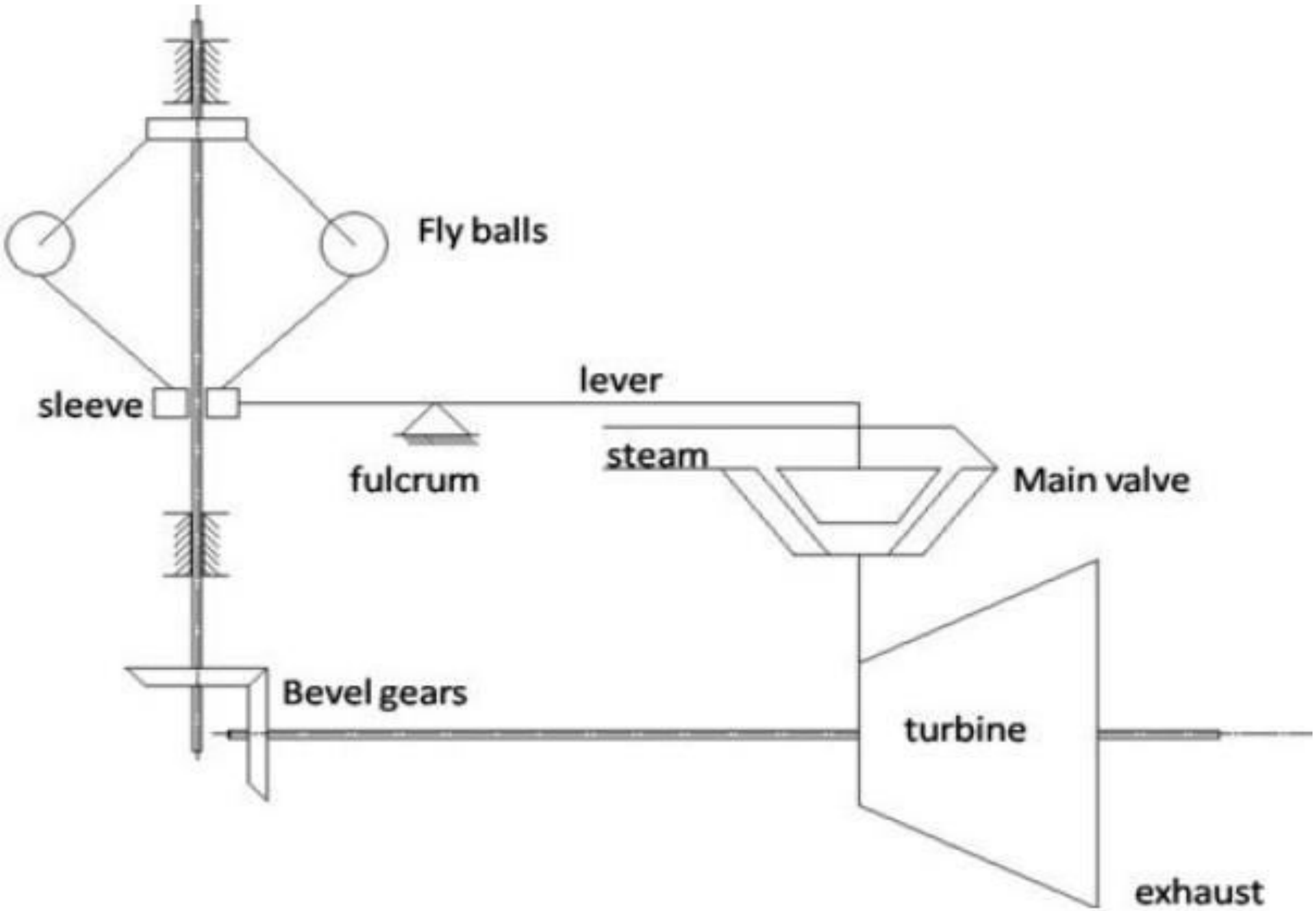
$$= 8V_b{}^2$$

Governing of Steam Turbines

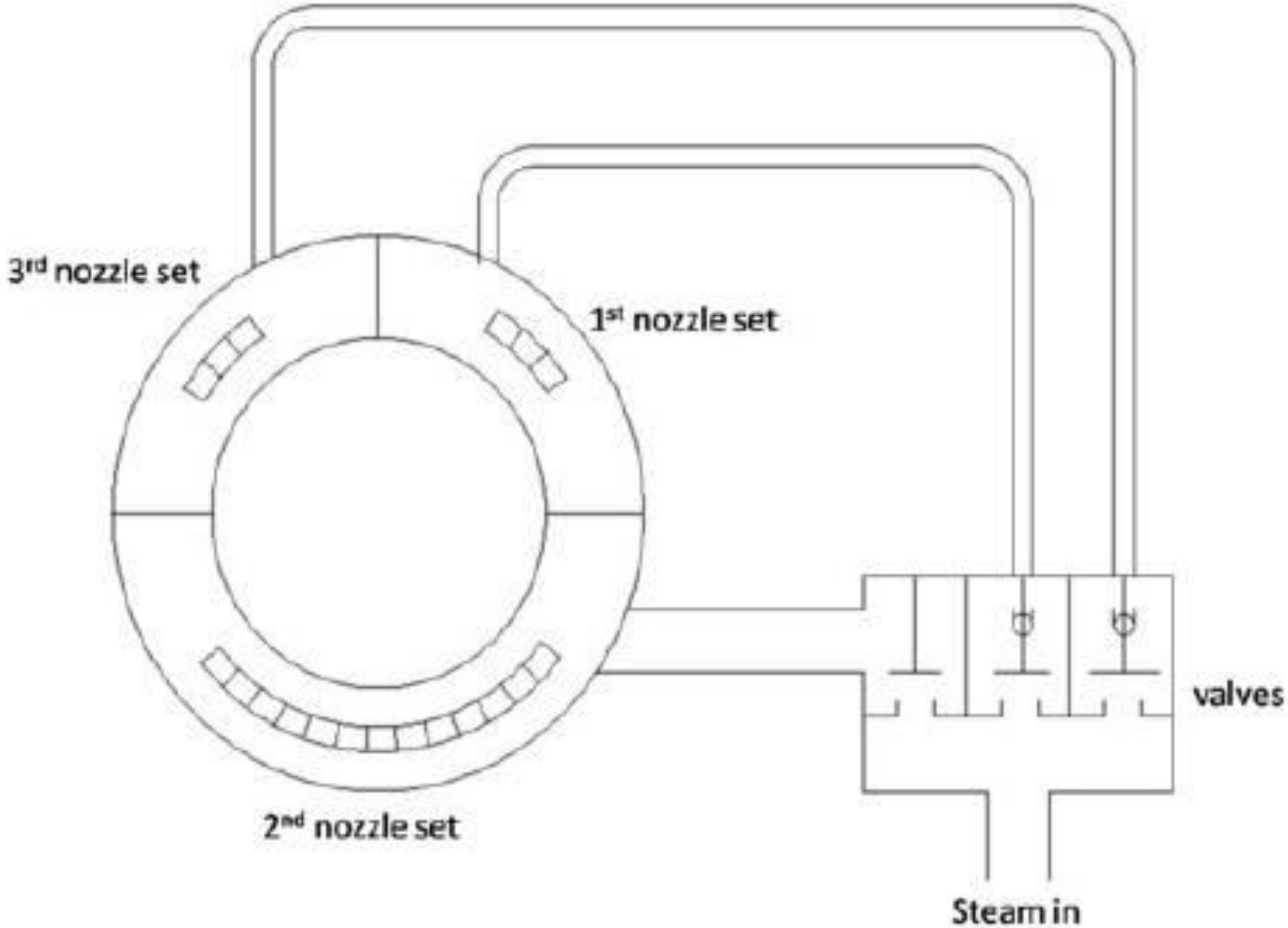
The main function of the governing is to maintain the speed constant irrespective of load on the turbine. The different methods which are commonly used for governing the steam turbines are listed below:-

1) Throttle governing
2) Nozzle control governing
3) By-pass governing

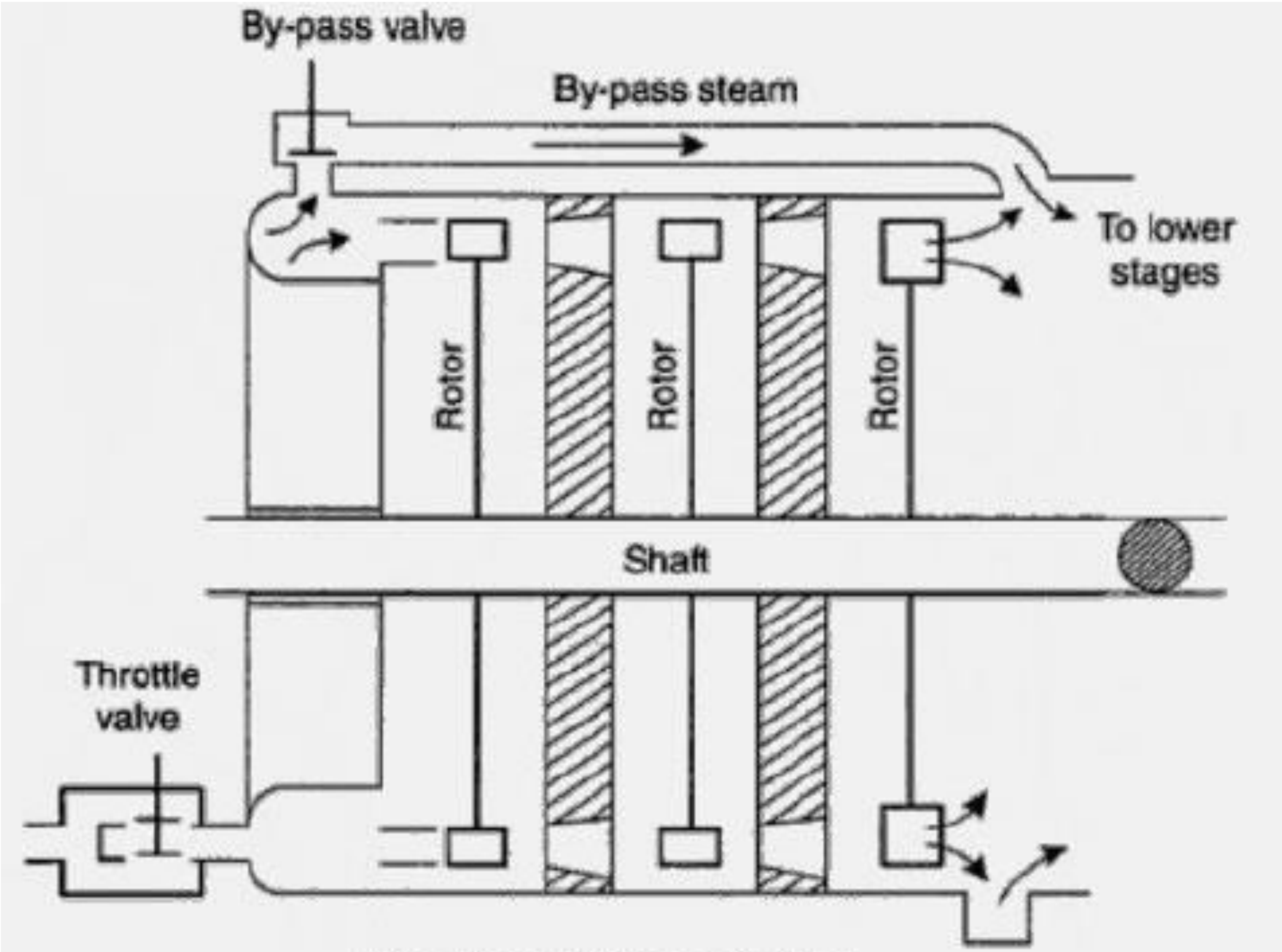
Throttle Governing



Nozzle Control Governing



Bypass Governing



By-Pass Governing