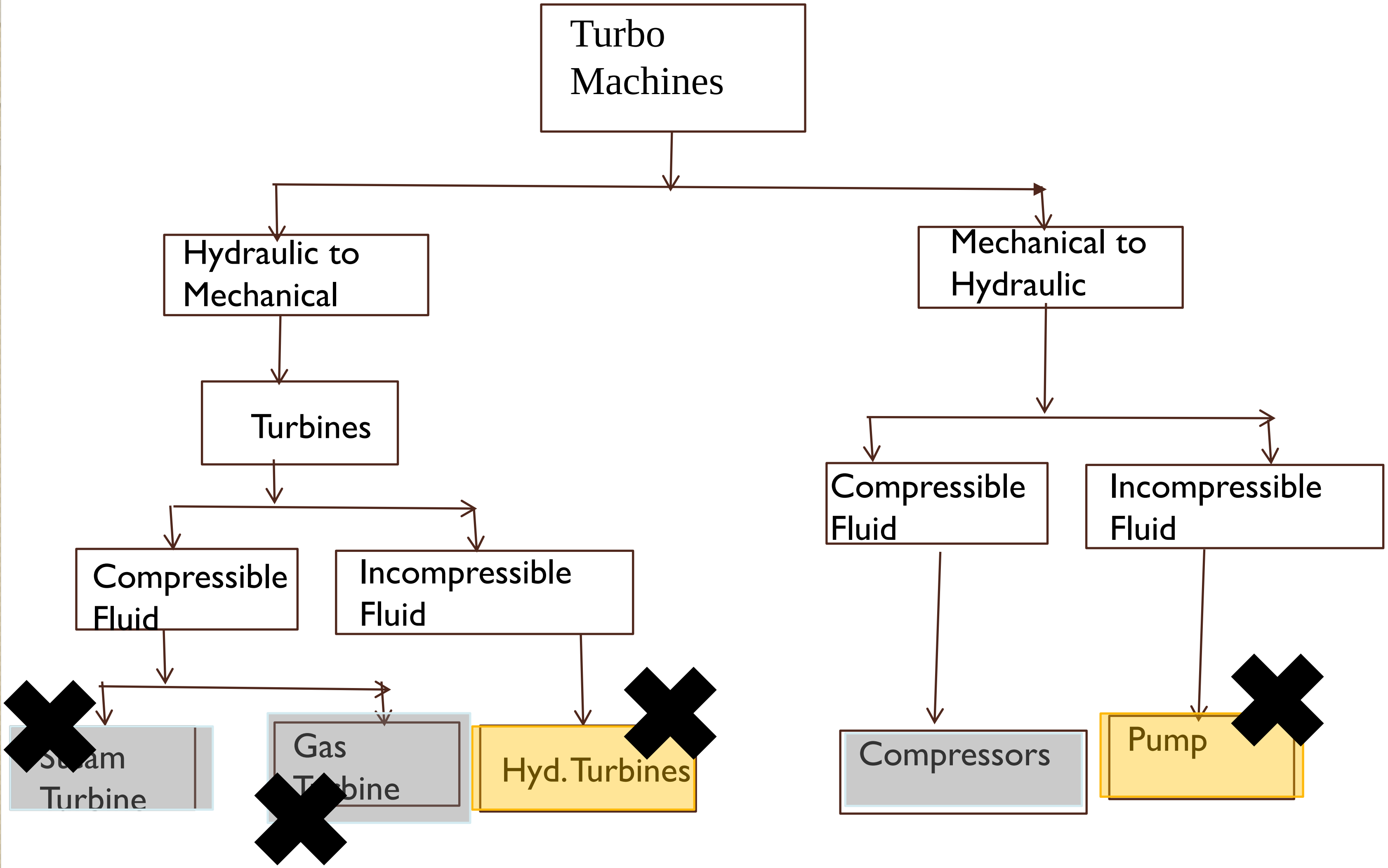
5. Compressor

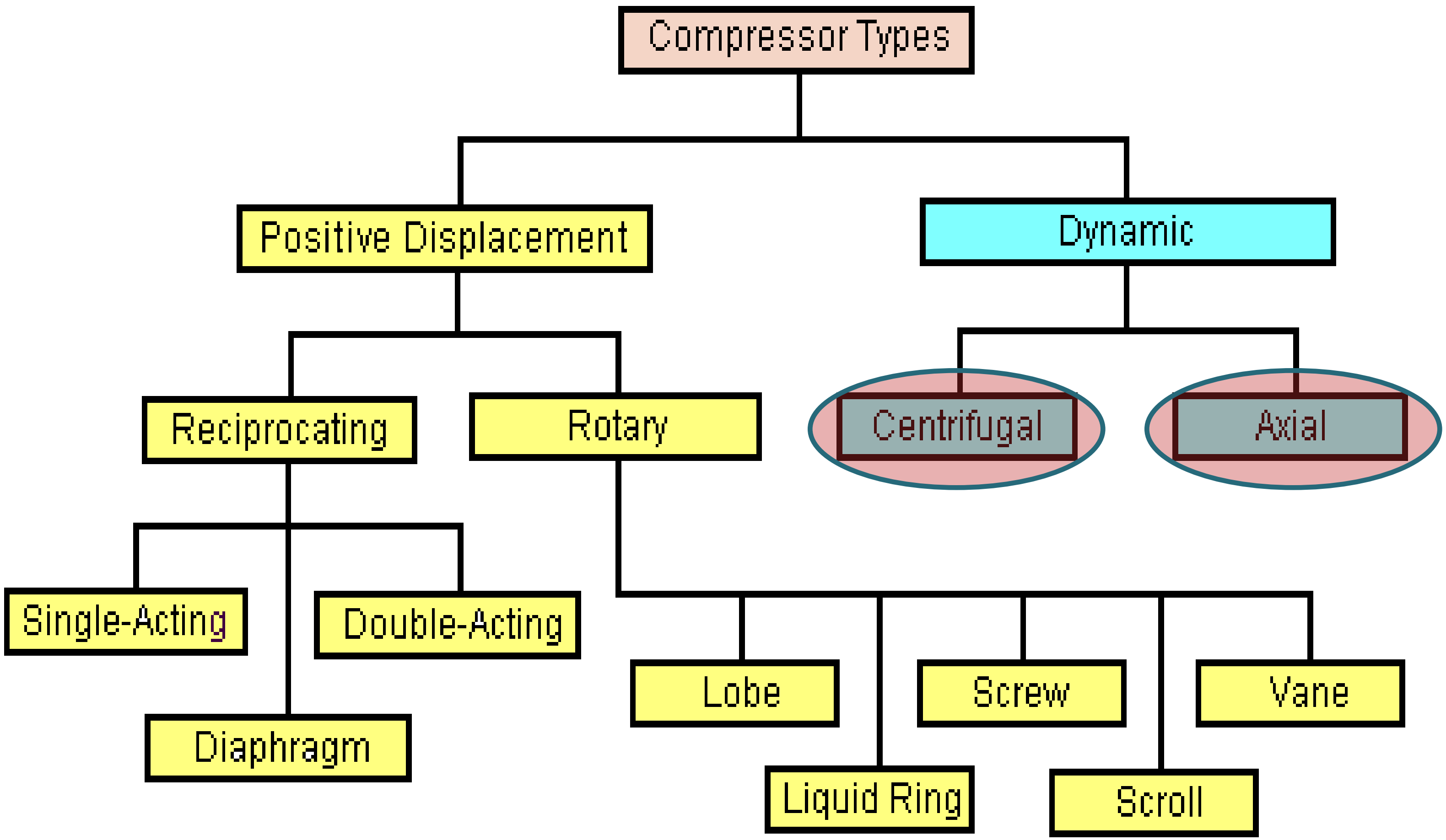
Subject: Turbo Machinery

Overview of Subject



Introduction

Compressor are the work consuming devices in which gas/air pressure is increased.



Elements of Centrifugal com

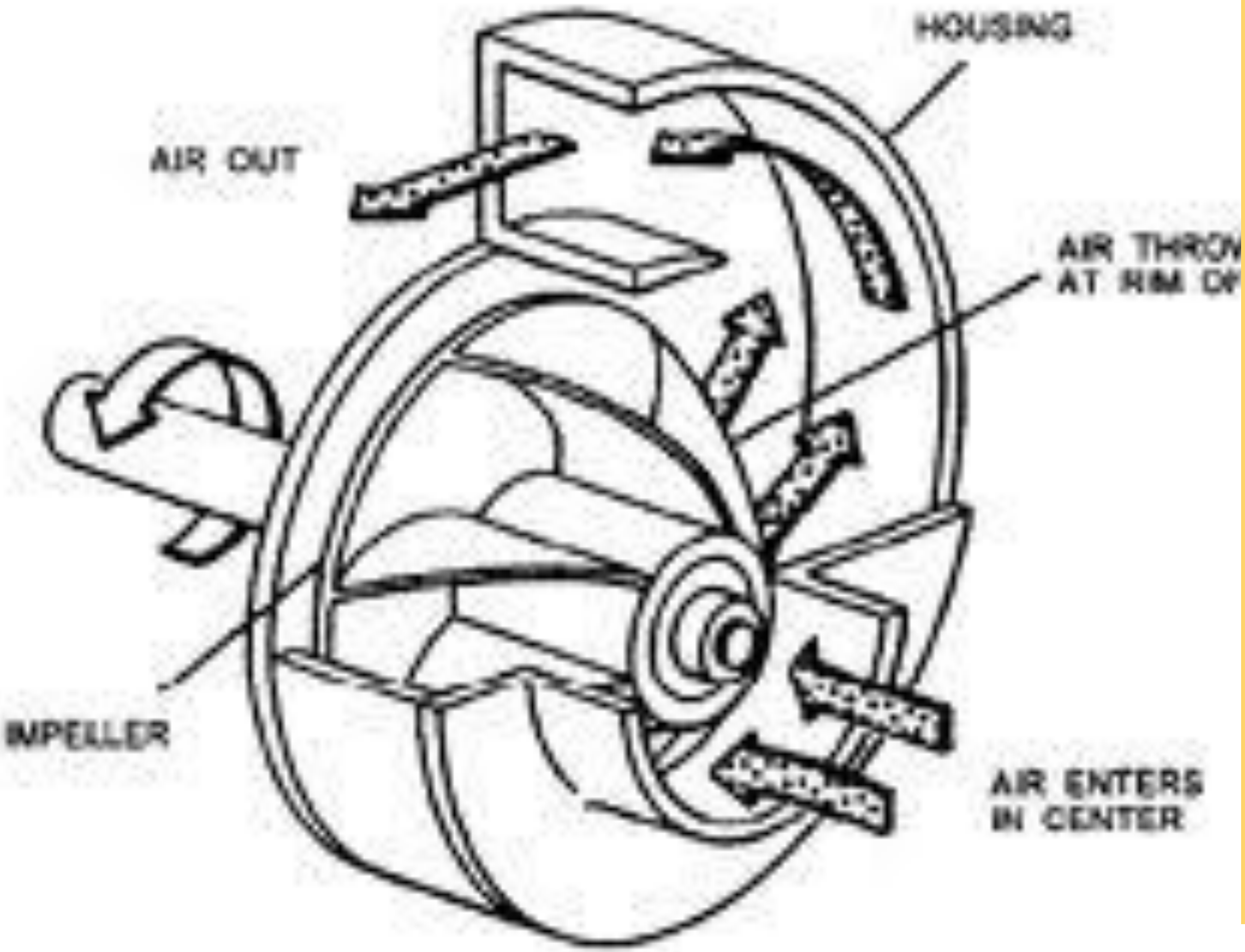


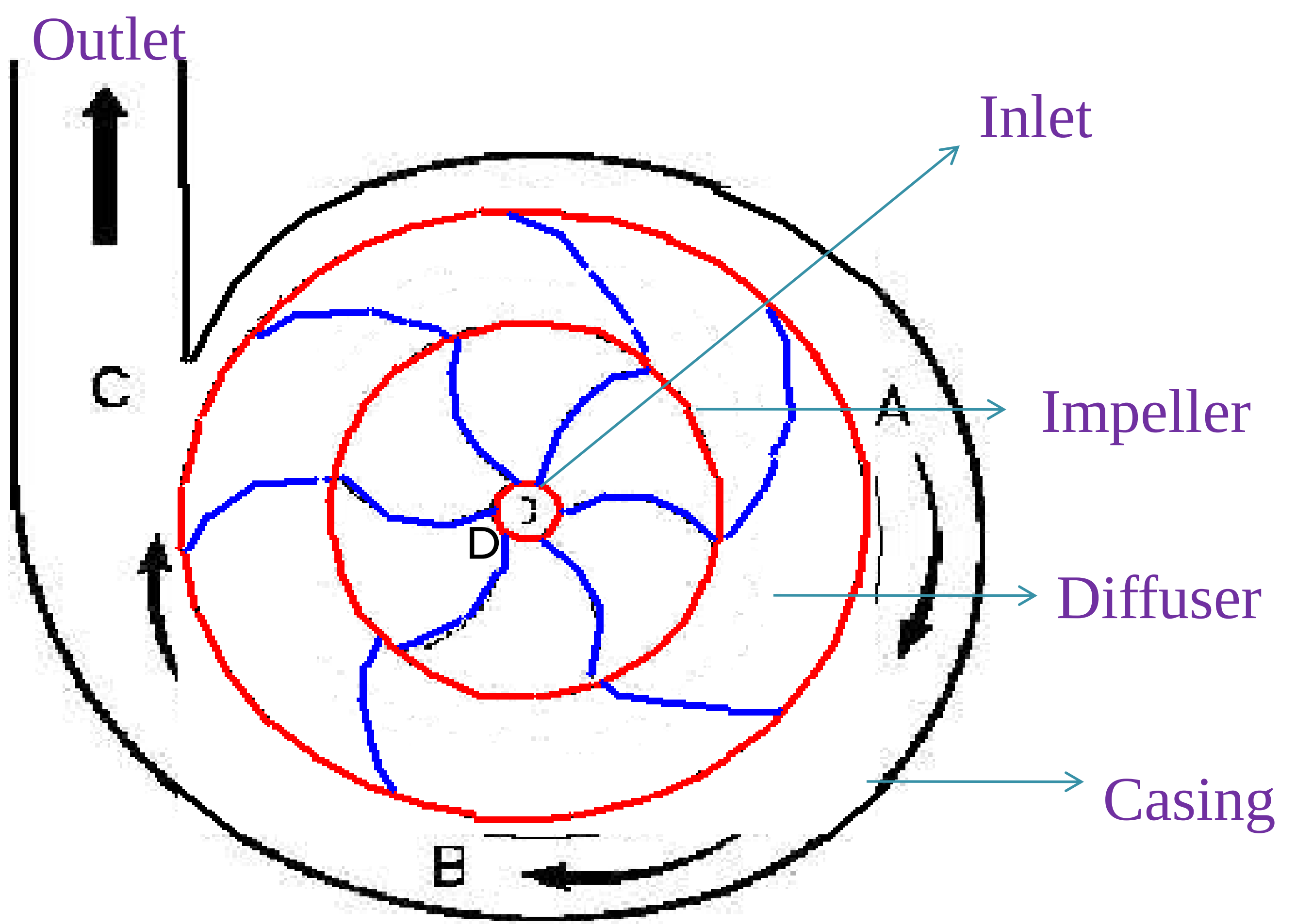
Figure 5-39.—Centrifugal supercharger.

-50% pressure rise occurs in impeller and remaining in diffuser

- The mechanical energy is provided to the rotor from some external source

- As rotor rotates, it suck the air through its eye, increases its pressure due to centrifugal force and forces the air to flow over the diffuser

Working Details



Compressor and Diffuser

The centrifugal force utilized by the centrifugal compressor is the same force utilized by the centrifugal pump.

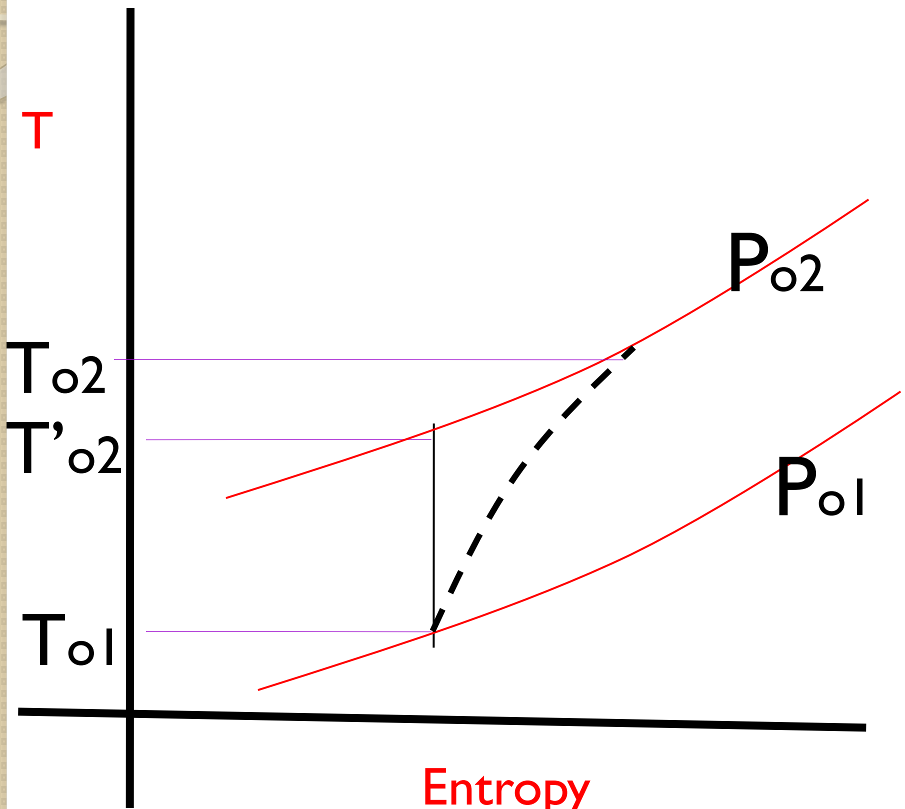
The air particles enter the eye of the impeller, designated D .

As the impeller rotates, air is thrown against the casing of the compressor. The air becomes compressed as more and more air is thrown out to the casing by the impeller blades.

The air is pushed along the path designated A, B, and C. The pressure of the air increased as it is pushed along this path. Note that the impell er blades curve forward, which is opposite to the backward curve used in typi cal centrifugal liquid pumps.

Centrifugal compressors can use a variety of blade orientation including both forward and backward curves as well as other designs

T-s Diagram



$$\eta_{is} = \frac{T_{o2}' - T_{o1}}{T_{o2} - T_{o1}}$$

During adiabatic compression in rotary compressor, there is friction between air and blade passage

Thus maximum temperature is greater than the adiabatic compression

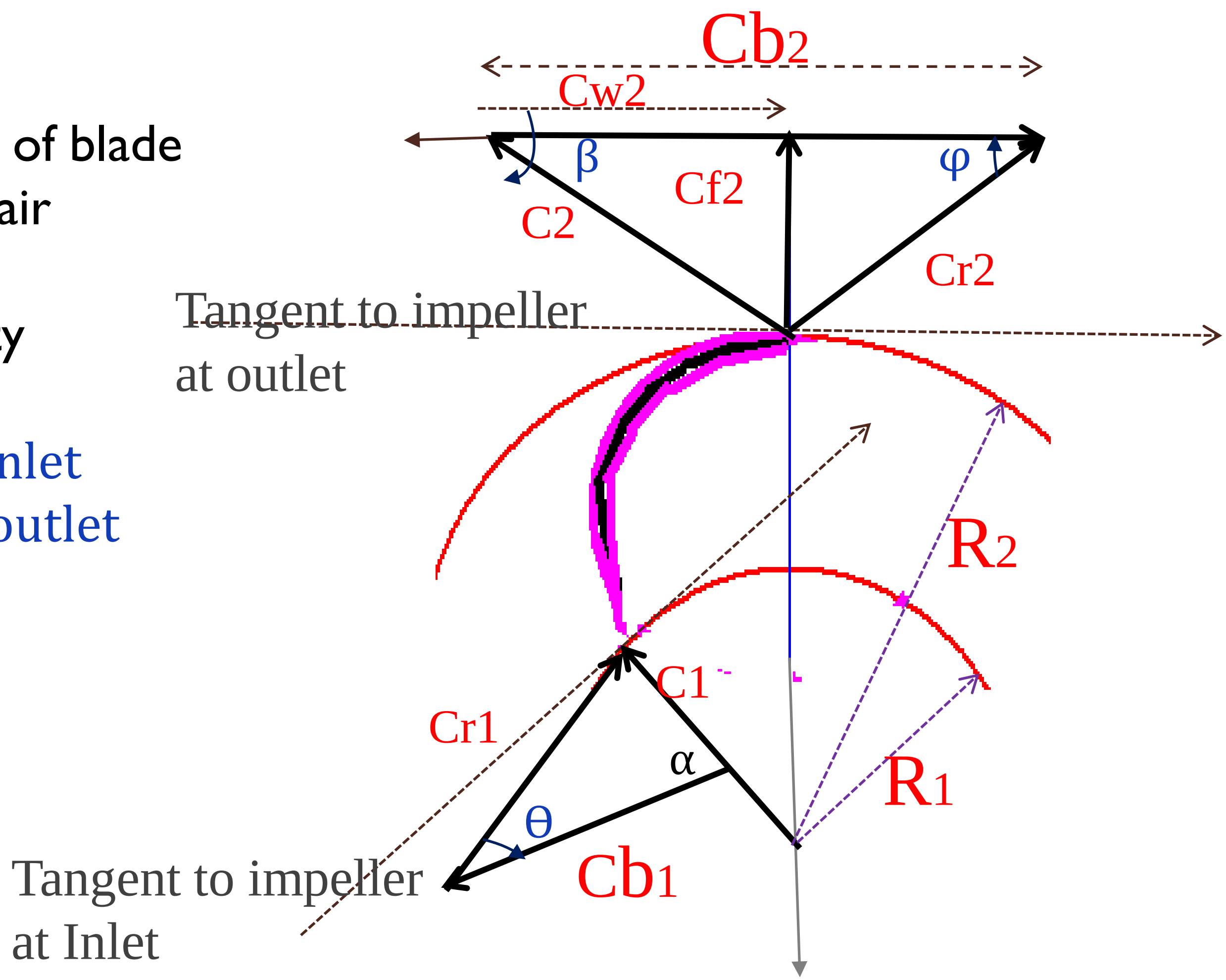
This results in continuous generation of entropy

Thus the isentropic efficiency is the ratio of isentropic temperature rise to the actual temperature rise

$$\eta is = \frac{\text{Isentropic Temp rise}}{\text{Actual Temp rise}}$$

Velocity Triangle

Cb-Linear velocity of blade
C-Abs. Velocity of air entering the blade
Cr-Relative velocity
Cf-Flow velocity
θ- Vane angle at inlet
Φ- Vane angle at outlet



Let,
m- mass of air compressed in kg/s

Thus

Force F= Mass (Change in Velocity)

$F = m\,(C_{w1} + C_{w2})$

As

$C_{w1} = 0$

Thus

$F = m\,C_{w2}$

The work done in the direction of blades

$W = \text{Force} \times (\text{Distance/time}) = m\,C_{w2} \times C_{b2}$

where $C_{b2} = \pi D_2 N/60$

Also Work done by the compressor= $m c_p (T_{o2} - T_{o1})$

The Power required= $m\,C_{w2} \times C_{b2}$ Watt

Slip Factor

Due to inertia, the air trapped between the impeller vanes does not move round the impeller

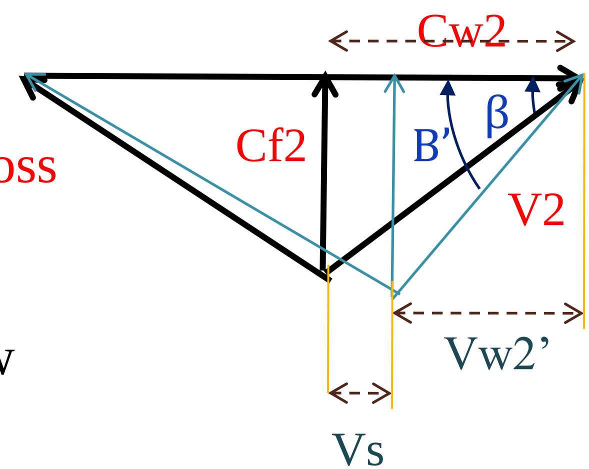
It results in difference of pressure across the vane

High pressure in leading edge and low pressure in trailing edge

It results in velocity gradient across the channel

Thus air will discharge at B2' instead of B2

The velocity get reduce to (Cw2-Cw2')



Dimensionless Parameters

Flow Coefficients Φ-

It is a ratio of actual mass flow rate and the mass flow rate referred to the tip of the impeller [0.28-0.32]

$$\varphi = \frac{M_{actual}}{M_{theoretical}} = \frac{\rho_2 A_2 C_{f2}}{\rho_2 A_2 C_{b2}}$$

Power Input Factor (P_{if}):

The actual energy transfer to the air from the impeller is less than that given by the equation

$$P = \mu C_{w2} C_{b2} = \mu C_{b2}^{2}$$

There is loss of friction between the casing and the air moving around the vanes and in disc friction.

This is taken in to consideration by a factor known as power input factor [1.035-1.04]

$$P = P_{if}\, \mu C_{b2}^{2}$$

Pressure Coefficient ψ:

It is the ratio of isentropic enthalpy rise to the work done

$$\psi = \frac{(\nabla h)_{isen}}{V_{b2} V_{w2}}$$

For radial vaned impeller

Vw2=Vb2

Thus

$$\psi = \frac{(\nabla h)_{isen}}{V_{b2}^{2}} = \psi = \frac{C_p (T_{o2} - T_{o1}) \eta_{isen}}{V_{b2}^{2}}$$

$$= \frac{P_{if}\, \mu V_{b2}^{2} \eta_{isen}}{V_{b2}^{2}}$$

Hence $\psi = P_{if}\, \mu \eta_{isen}$

Numerical-1

A rotary air compressor is working between 1 bar and 2.5 bar has internal and external diameter of impeller as 300mm and 600mm resp. the vane angle at inlet and outlet are 30 and 45 resp. if the air enters the impeller at 15m/s. find speed of impeller in rpm and work done per kg of air

Given

Po1- 1 bar

Po2-2.5 bar

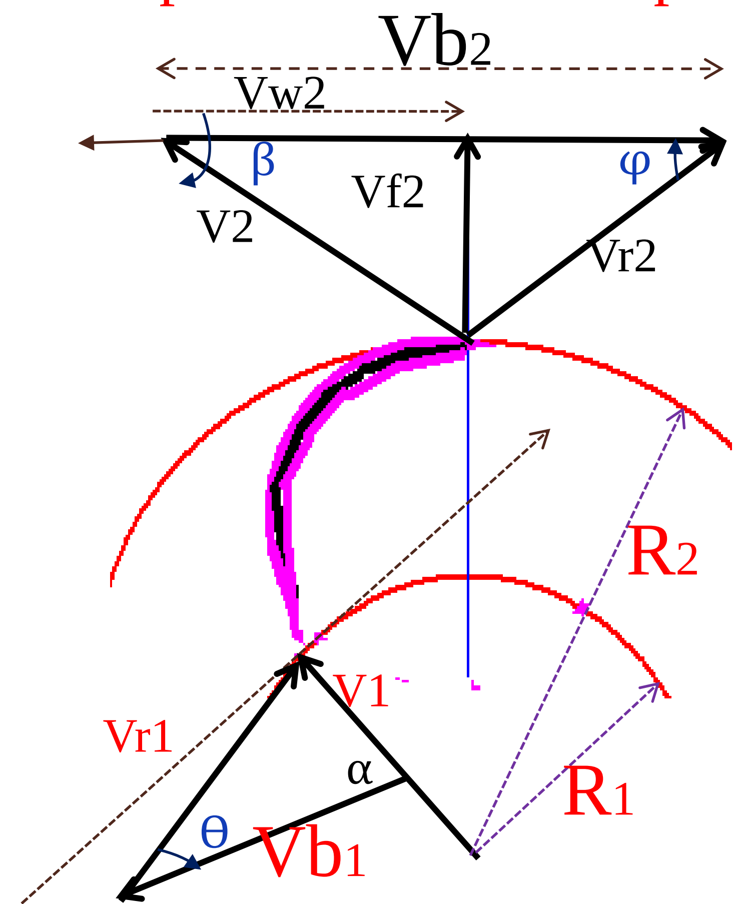
D1=300mm=0.3m

D2=600mm=0.6m

θ=30

Φ= 45

V1=15m/s



Numerical-2

A single sided centrifugal compressor is to deliver 15 Kg/s of air when operating at an stagnation pressure ratio of 4:1 and speed of 12000 rpm. The inlet stagnation conditions are 288 K and 1 bar. Assuming slip factor of 0.9, a power input factor of 1.04 and overall isentropic efficiency of 0.8, estimate the overall diameter of the impeller

Given

$m = 15 Kg/s$ $\mu = 0.9$

$P_{o1} = 1 bar$ $P_{if} = 1.04$

$P_{o2}/P_{o1} = 4$ $\eta_{is} = 0.8$

$T_{o1} = 288 K$

$N = 12000$ rpm

Numerical-3

A centrifugal compressor delivers 12m^3/s of free air while running at 10000 rpm. The air compressed from 1 bar, 20 deg cen. To 4 bar with an isentropic efficiency of 81%. Blades are radial at the outlet of the impeller and the flow velocity is 60m/s which is constant through out. The ratio of outer and inner radii of the impeller is 2 and the slip factor 0.9. The blades area coefficient at inlet is 0.92. Determine

1. Temperature of air discharge
2. Theoretical power required
3. Impeller diameter at inlet and outlet

Losses

Shock in rotor losses. This loss is due to shock occurring at the rotor inlet. The inlet of the rotor blades should be wedgelike to sustain a weak oblique shock, and then gradually expanded to the blade thickness to avoid another shock. If the blades are blunt, a bow shock will result, causing the flow to detach from the blade wall and the loss to be higher.

Incidence loss. At off-design conditions, flow enters the inducer at an incidence angle that is either positive or negative,

A positive incidence angle causes a reduction in flow. Fluid approaching a blade at an incidence angle suffers an instantaneous change of velocity at the blade inlet to comply with the blade inlet angle. Separation of the blade can create a loss associated with this phenomenon.

Disc friction loss. This loss results from frictional torque on the back surface of the rotor

Diffusion-blading loss. This loss develops because of negative velocity gradients in the boundary layer. Deceleration of the flow increases the boundary layer and gives rise to separation of the flow. The adverse pressure gradient that a compressor normally works against increases the chances of separation and causes significant loss.

Skin friction loss. Skin friction loss is the loss from the shear forces on the impeller wall caused by turbulent friction. This loss is determined by considering the flow as an equivalent circular cross section with a hydraulic diameter. The loss is then computed based on well-known pipe flow pressure loss equations.

Axial Flow Compressor

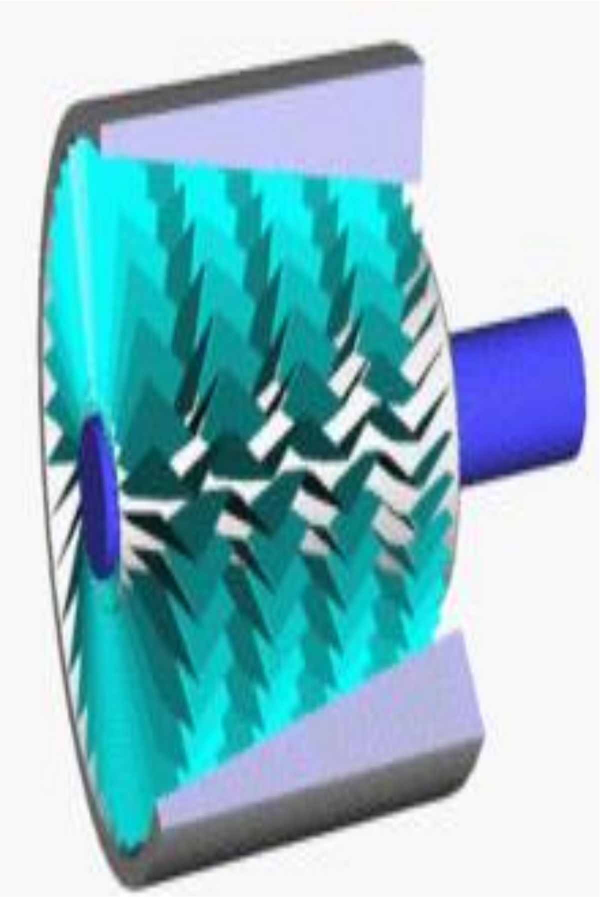
In axial flow compressor, the pressure of gas continuously increases in the axial direction

The increase of pressure of gas or air is obtained by the action of rotor blades which exerts a torque on the fluid

The torque is supplied by an external source

The efficiency is higher than centrifugal compressor and drops drastically at lower than designed mass flow rate

Thus it is ideal for constant flow application such as air craft



Working Principle of Axial Flow Compressor

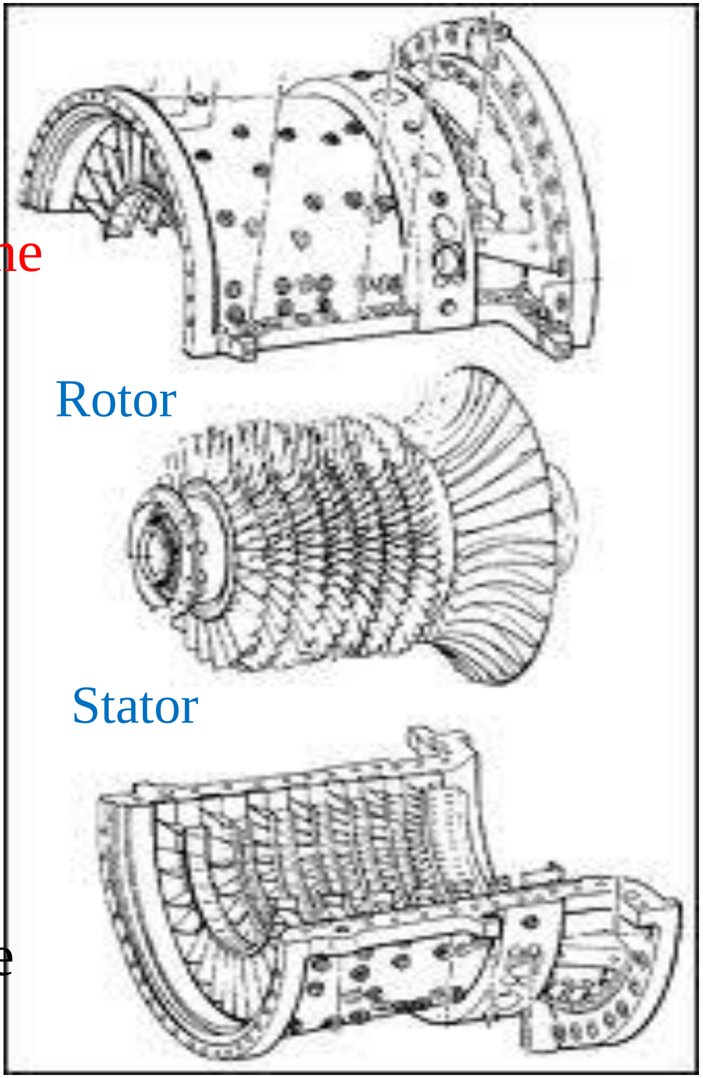
It consists of alternate sequence of fixed and moving blades (Stator & Rotor)

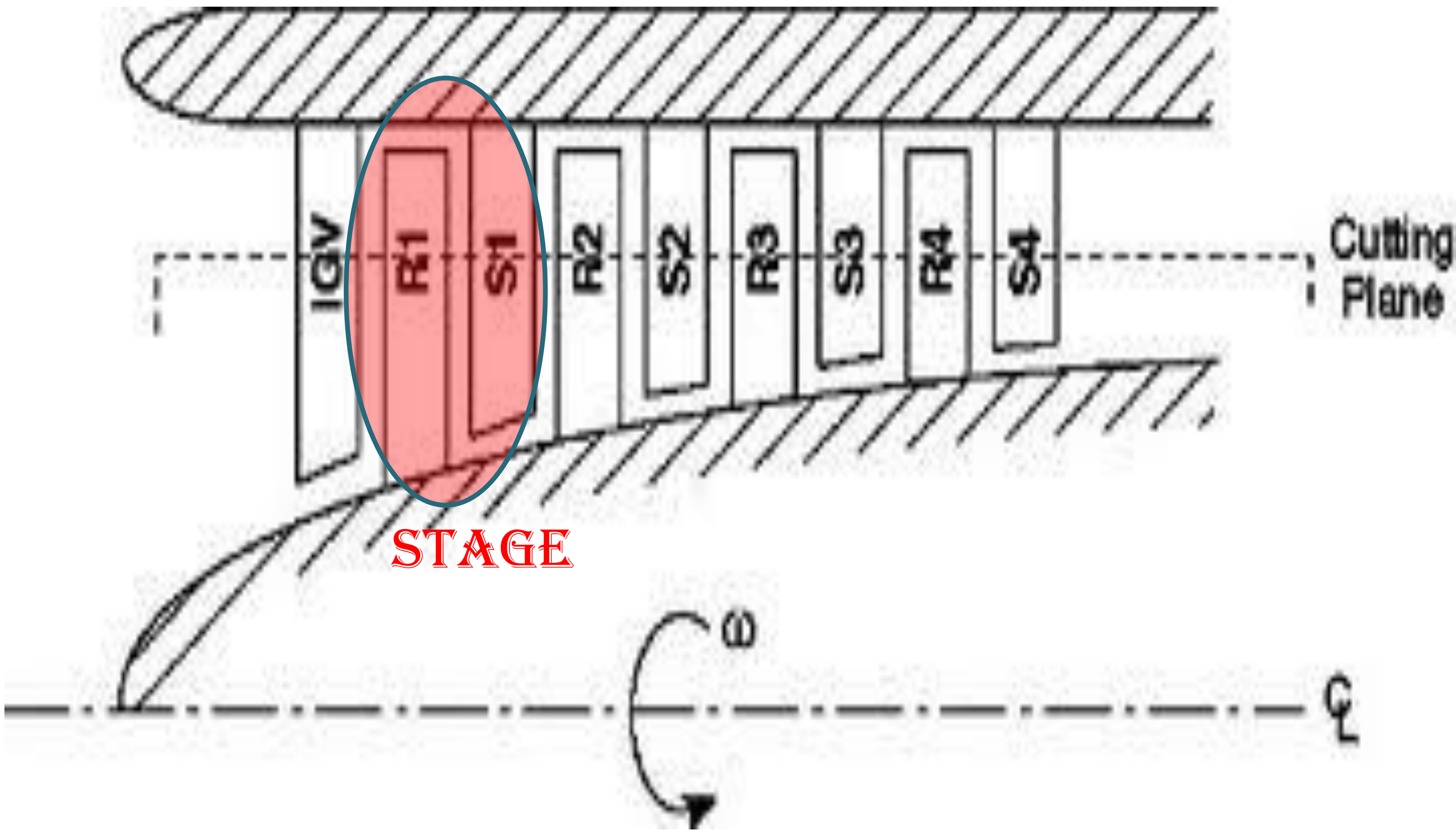
Each stage is separated by an inlet guide vanes which are fixed and use to guide the air with an correct angle on next stage

The height of blades decreases along the length of fluid travel to maintain the constant axial velocity

Air enters axially on to the inlet guide vanes and deflected on to the first stage

While air passing through the stages,,,the pressure increases de to diffusion



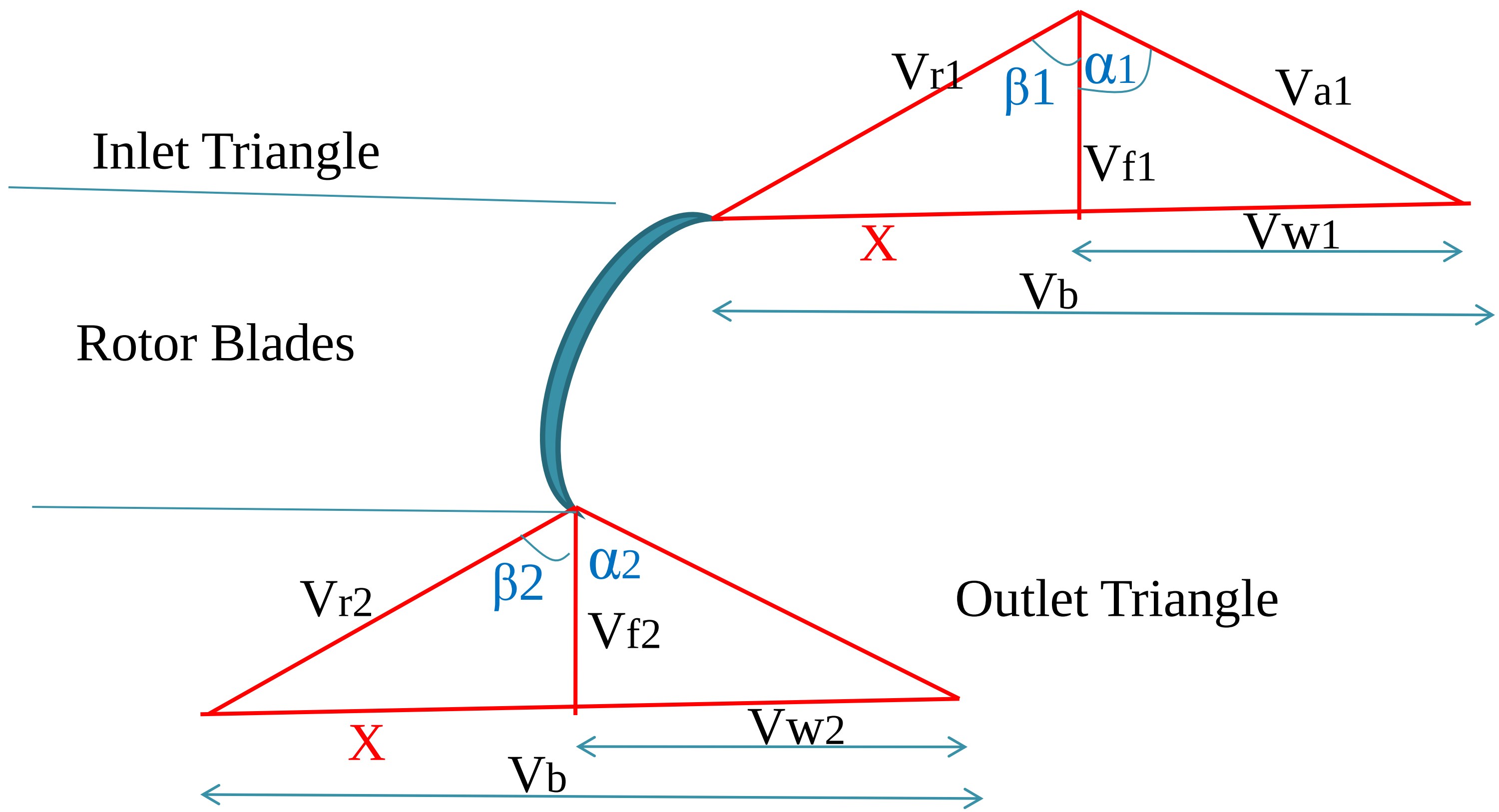


IGV
R1
S1
R2
S2
R3
S3
R4
S4
Cutting Plane
ω
STAGE

Comparison Between Centrifugal and Axial Flow Compressor

Points	Centrifugal	Axial Flow
Direction of Flow	Perpendicular to axis	Parallel to axis
Pressure rise per stage	High 4:1	Low1.2:1
Isentropic Efficiency	80-82%	4 % Higher
Range of Operation	Greater flexibility	Narrow range
Starting Torque	lower	Higher
Working Fluid	Can handled contaminated fluid	Sensitive to contaminated fluid
Frontal Area	more	less
Construction	Simple	Complicated
Multi staging	difficult	More suitable
Application	Steel mills, supercharger	Gas turbine plant, air craft

Velocity Triangle for Axial Flow Compressor



From Inlet Velocity Triangle

$$V_{f1} = V_{a1}\cos\alpha_1 = V_{r1}\cos\beta_1$$

$$V_{w1} = V_{a1}\sin\alpha_1 = V_{f1}\tan\alpha_1$$

Now,

$$V_b = V_{w1} + x$$

Where as

$$x = V_{f1}\tan\beta_1$$

Thus

$$V_b = V_{f1}[\tan\alpha_1 + \tan\beta_1]$$

Similarly from Outlet Velocity Triangle

$$V_b = V_{f2}[\tan\alpha_2 + \tan\beta_2]$$

Work Input to the Compressor

Now,

$$V_b = V_{f1}[\tan\alpha_1 + \tan\beta_1] = V_{f2}[\tan\alpha_2 + \tan\beta_2]$$

Work input/Kg=Vb (Vw2-Vw1)= Cp(To2-To1)

$$= V_b(V_f\ \tan\alpha_2 - V_f\ \tan\alpha_1)$$

$$= V_b V_f(\tan\alpha_2 - \tan\alpha_1)$$

Or

$$= V_b V_f(\tan\beta_2 - \tan\beta_1)$$

Thus

$$WD/Kg = V_b V_f(\tan\beta_2 - \tan\beta_1) = Cp\ (T_{o2} - T_{o1})$$

Degree of Reaction

It is defined as the pressure rise in the rotor to the pressure rise in the stage

Total Pressure rise in stage = Work Input/stage

$$= V_b (V_{w2} - V_{w1})$$

Where $V_{w2} = V_b - V_f \tan\beta_2$

$V_{w1} = V_b - V_f \tan\beta_1$

Thus

Total Pressure rise in stage $= V_b V_f (\tan \beta_1 - \tan \beta_2)$

Degree of Reaction

Similarly

Pressure rise in the blade=(V_{r1}^2-V_{r2}^2)/2

Where as,

$V_{r1}^2 = V_f^2 + (V_f \tan \beta_1)^2$

$V_{r2}^2 = V_f^2 + (V_f \tan \beta_2)^2$

Pressure rise in the blade= $\dfrac{Vf^2}{2}(\tan^2\beta_1 - \tan^2\beta_2)$

Thus Degree of Reaction $R = \dfrac{V_f}{V_b}(\tan\beta_1 + \tan\beta_2)$

Normally, the axial flow compressor is designed for 50%reaction bladding

$$R = 0.5 = \frac{1}{2}\frac{V_f}{V_b}(\tan\beta_1 + \tan\beta_2)$$

Thus

$$\frac{V_f}{V_b} = \tan\beta_1 + \tan\beta_2$$

But

$$\frac{V_b}{V_{f1}} = \tan\alpha_1 + \tan\beta_1$$

$$\frac{V_b}{V_{f2}} = \tan\alpha_2 + \tan\beta_2$$

Hence

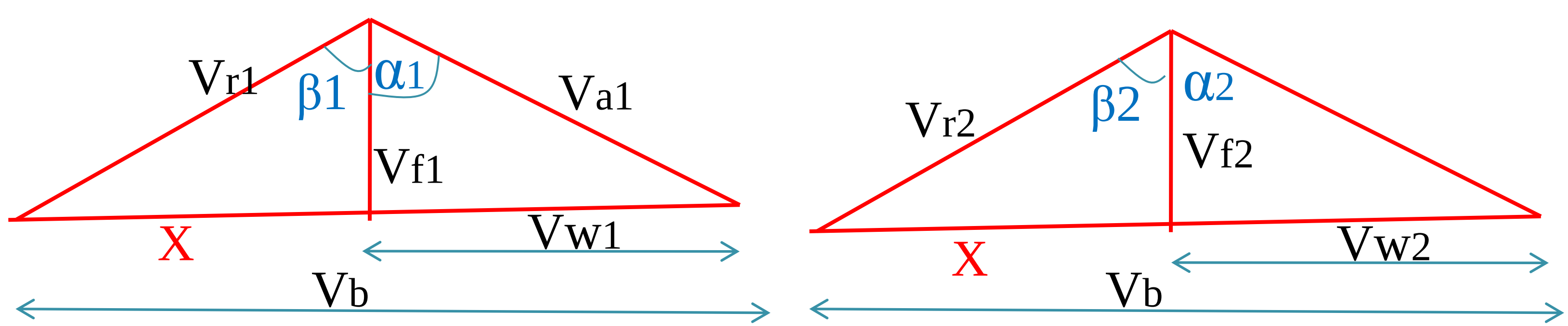
$\alpha 1=\beta 2$ and

$\alpha 2=\beta 1$

Numerical-1

An axial flow compressor with pressure ratio of 5 draws air at 20 degree and delivers it at 55 degree centigrade. Determine the velocity of flow if the blade velocity is 100 m/s and number of stages. Assume 50% degree of reaction and work done factor of 0.87.

Take α1= 10 and β1=40. Cp of air =1 Kj/Kg K

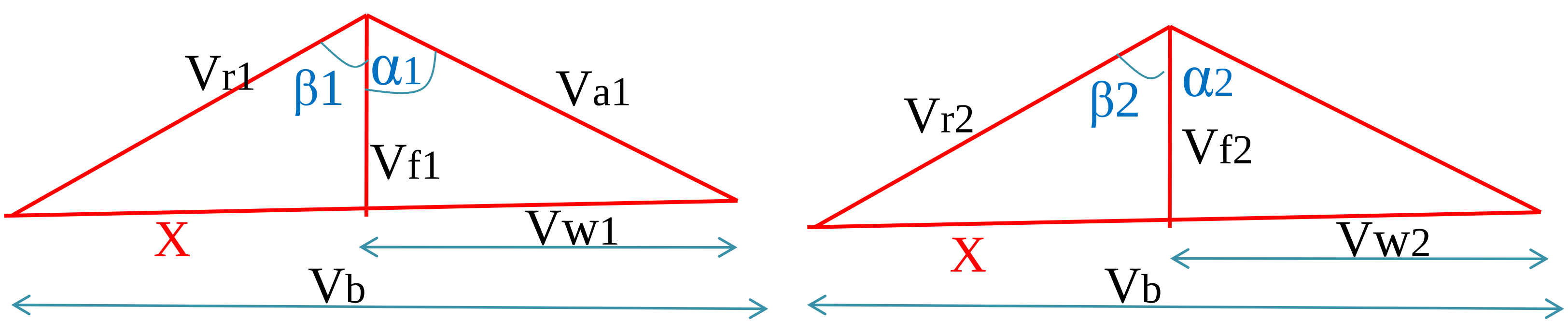


Numerical-2

The following data refers to a test on an axial flow compressor. Atmospheric pressure and the temperature at inlet are 1 bar and 18 degree centigrade. Total head pressure and temperature in the delivery pipe are 3.5 bar and 165 degree centigrade. Static pressure in delivery pipe is 3 bar. Determine

a) Total head isentropic efficiency

b) Air velocity in delivery pipe



Thanking You