UNIT-3
AXIAL COMPRESSORS

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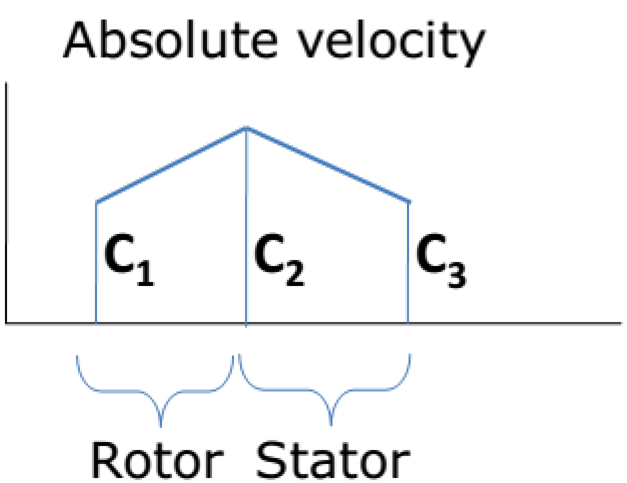
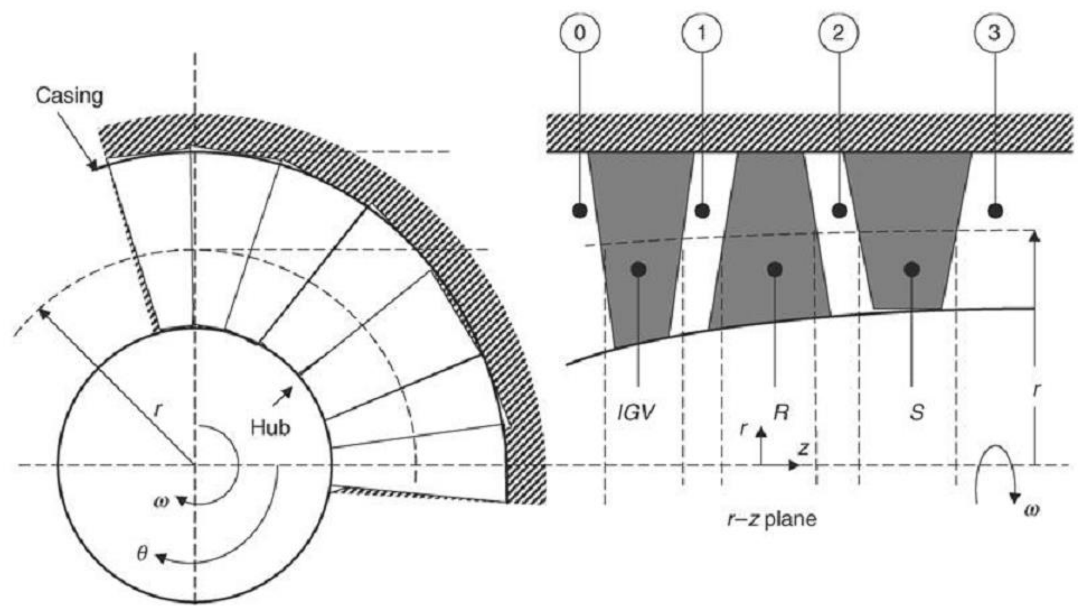
UNIT-3 SYLLABUS

- Angular momentum
- Work and compression
- Characteristic performance of a single compressor stage
- Characteristic performance of a multistage axial compressor
- Boundary layer limitation
- Compressor efficiency
- Degree of reaction
- Radial equilibrium
- Design of a subsonic axial compressor
- Transonic fan stage
- Numerical problems.

Basic operation of axial compressors

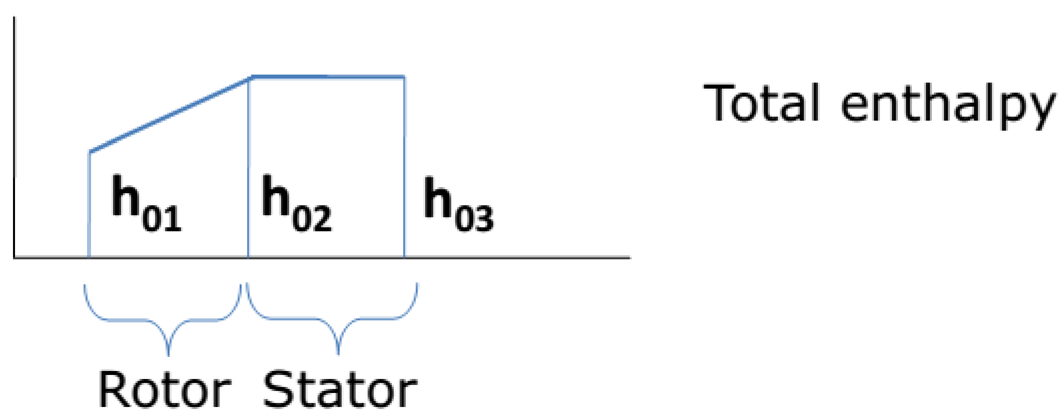
- Axial flow compressors usually consists of a series of stages.
- Each stage comprises of a row of rotor blades followed by a row of stator blades.
- The working fluid is initially accelerated by the rotor blades and then decelerated in the stator passages.
- In the stator, the kinetic energy transferred in the rotor is converted to static pressure.
- This process is repeated in several stages to yield the necessary overall pressure ratio.





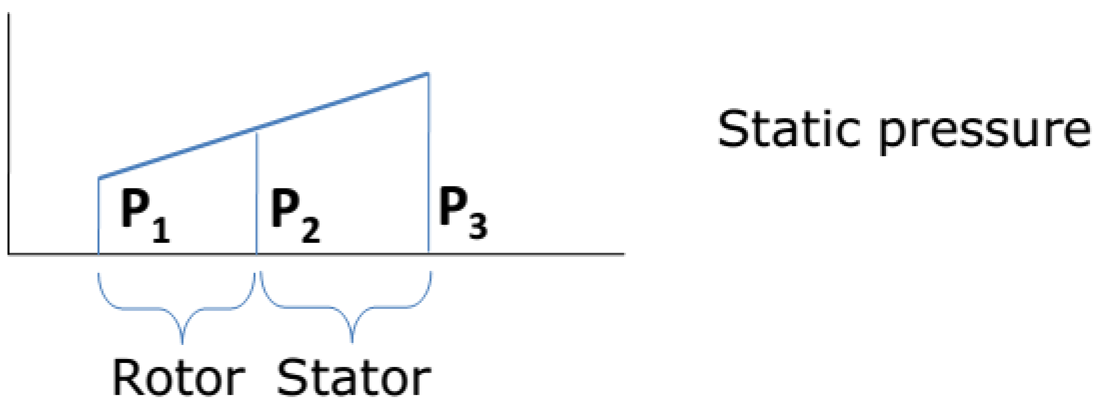
Basic operation of axial compressors

• The compression process consists of a series of diffusions.
• This occurs both in the rotor as well as the stator.
• Due to motion of the rotor blades→ two distinct velocity components: absolute and relative velocities in the rotor.
• The absolute velocity of the fluid is increased in the rotor, whereas the relative velocity is decreased, leading to diffusion.
• Per stage pressure ratio is limited because a compressor operates in an adverse pressure gradient environment.



Basic operation of axial compressors

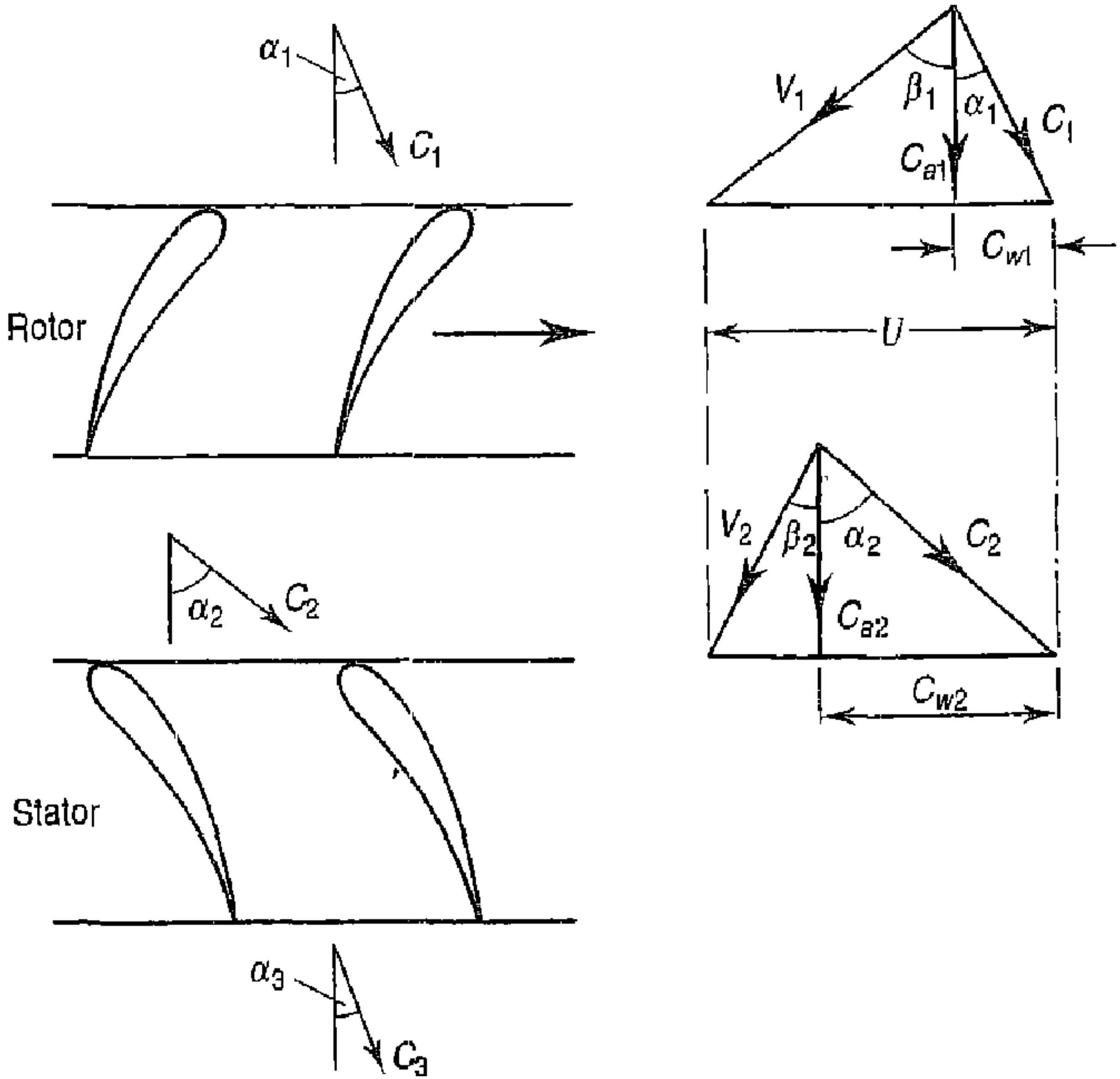
- Turbines on the other hand operate under favourable pressure gradients.
- Several stages of an axial compressor can be driven by a single turbine stage.
- Careful design of the compressor blading is essential to minimize losses as well as to ensure stable operation.
- Some compressors also have inlet Guide Vanes (IGV) that permit the flow entering the first stage to vary under off-design conditions.



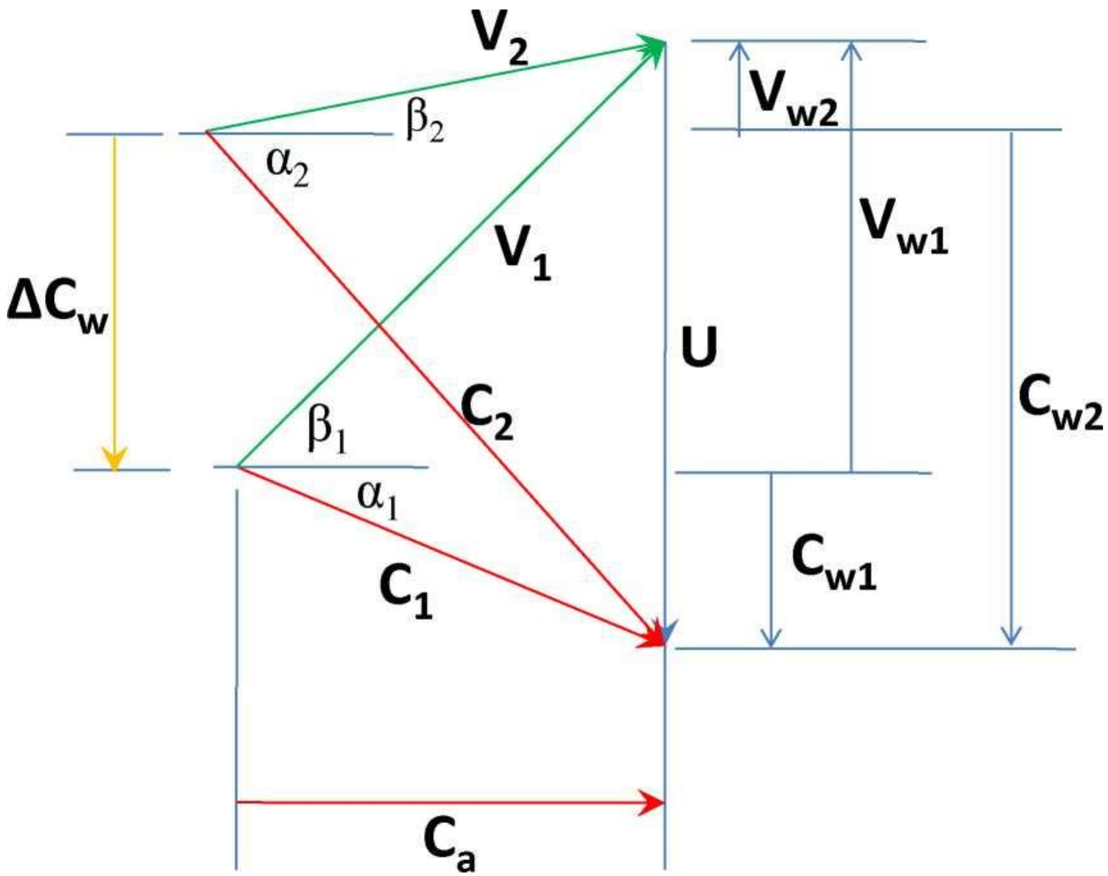
Velocity triangles-Blade Elementary Theory

- Elementary analysis of axial compressors begins with velocity triangles.
- The analysis will be carried out at the mean height of the blade, where the peripheral velocity or the blade speed is, U.
- The absolute component of velocity will be denoted by, C and the relative component by, V.
- The axial velocity (absolute) will be denoted by Ca and the tangential components will be denoted by subscript w (for eg, Cw or Vw)
- α denotes the angle between the absolute velocity with the axial direction
- β denotes the angle between the absolute velocity with relative velocity.

Velocity triangles-Blade Elementary Theory



Velocity triangles-Blade Elementary Theory



Work and compression

- **Assuming** $C_a = C_{a1} = C_{a2}$**, from the velocity triangles, we can see that**

$$\frac{U}{C_a} = \tan\alpha_1 + \tan\beta_1 \quad \text{and} \quad \frac{U}{C_a} = \tan\alpha_2 + \tan\beta_2$$

- **By considering the change in angular momentum of the air passing through the rotor, work done per unit mass flow is**

$$w = U(C_{w2} - C_{w1}),$$

where C_{w1} and C_{w2} are the tangential components of the fluid velocity before and after the rotor, respectively.

Work and compression

The above equation can also be written as,

$$w = UC_a(\tan\alpha_2 - \tan\alpha_1)$$

Since, $(\tan\alpha_2 - \tan\alpha_1) = (\tan\beta_1 - \tan\beta_2)$

$$\therefore w = UC_a(\tan\beta_1 - \tan\beta_2)$$

In other words, $w = U\Delta C_w$

- **The input energy will reveal itself in the form of rise in stagnation temperature of the air.**
- **The work done per unit mass flow as given above will also be equal to the change in stagnation enthalpy across the stage.**

Work and compression

$$h_{02} - h_{01} = U\Delta C_w$$

$$T_{02} - T_{01} = \frac{U\Delta C_w}{c_p} \Rightarrow \frac{\Delta T_0}{T_{01}} = \frac{U\Delta C_w}{c_p T_{01}}$$

Since the flow is adiabatic and no work is done as the fluid passes through the stator, $T_{03} = T_{02}$

Let us define stage efficiency, η_{st}, as

$$\eta_{\text{st}} = \frac{h_{03s} - h_{01}}{h_{03} - h_{01}}$$

This can be expressed as

$$\frac{T_{03s}}{T_{01}} = 1 + \eta_{\text{st}} \frac{\Delta T_0}{T_{01}}$$

Work and compression

In the above equation, $\Delta T_0 = T_{03} - T_{01}$

In terms of pressure ratio,

$$\frac{P_{03}}{P_{01}} = \left[1 + \eta_{st}\frac{\Delta T_0}{T_{01}}\right]^{\gamma/(\gamma-1)}$$

This can be combined with the earlier equation to give,

$$\frac{P_{03}}{P_{01}} = \left[1 + \eta_{st}\frac{U\Delta C_w}{c_p T_{01}}\right]^{\gamma/(\gamma-1)}$$

Design parameters

- The following design parameters are often used in the parametric study of axial compressors:
  - Flow coefficient,

    $$\phi = C_a / U$$
  - Stage loading,

    $$\psi = \Delta h_0 / U^2 = \Delta C_w / U$$
  - Degree of reaction, R_x
  - Diffusion factor, D^*

Degree of reaction

- Diffusion takes place in both rotor and the stator.
- Static pressure rises in the rotor as well as the stator.
- Degree of reaction provides a measure of the extent to which the rotor contributes to the overall pressure rise in the stage.

$$R_x = \frac{\text{Static enthalpy rise in the rotor}}{\text{Stagnation enthalpy rise in the stage}}$$

$$= \frac{h_2 - h_1}{h_{03} - h_{01}} \approx \frac{h_2 - h_1}{h_{02} - h_{01}}$$

Degree of reaction

From the steady flow energy equation,

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

$$\therefore R_x = \frac{h_2 - h_1}{h_{03} - h_{01}} = \frac{V_1^2 - V_2^2}{2U(C_{w2} - C_{w1})}$$

For constant axial velocity, $V_1^2 - V_2^2 = V_{w1}^2 - V_{w2}^2$

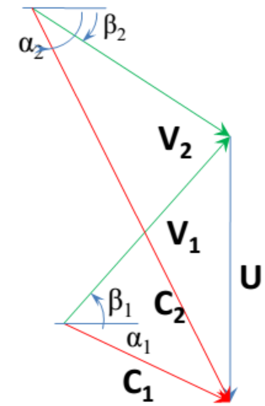
And, $V_{w1} - V_{w2} = C_{w1} - C_{w2}$

On simplification, $R_x = \frac{1}{2} - \frac{C_a}{2U}(\tan\alpha_1 - \tan\beta_2)$

or, $R_x = \frac{C_a}{2U}(\tan\beta_1 + \tan\beta_2)$

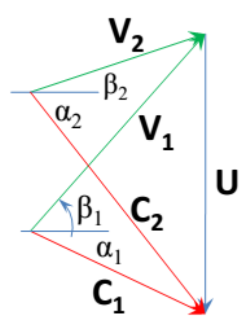
Degree of reaction

- Special cases of R_x
  - R_x=0,$\beta_2 = -\beta_1$, There is no pressure rise in the rotor, the entire pressure rise is due to the stator, the rotor merely deflects the incoming flow: impulse blading
  - R_x=0.5, gives $\alpha_1 = \beta_2$ and $\alpha_2 = \beta_1$, the velocity triangles are symmetric, equal pressure rise in the rotor and the stator
  - R_x=1.0,$\alpha_2 = -\alpha_1$, entire pressure rise takes place in the rotor while the stator has no contribution.



$\beta_2 = -\beta_1$

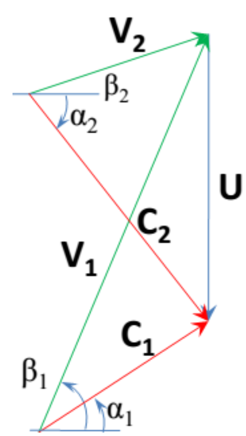
R_x=0.0



$\alpha_1 = \beta_2$ and $\alpha_2 = \beta_1$

R_x=0.5

$\alpha_2 = -\alpha_1$



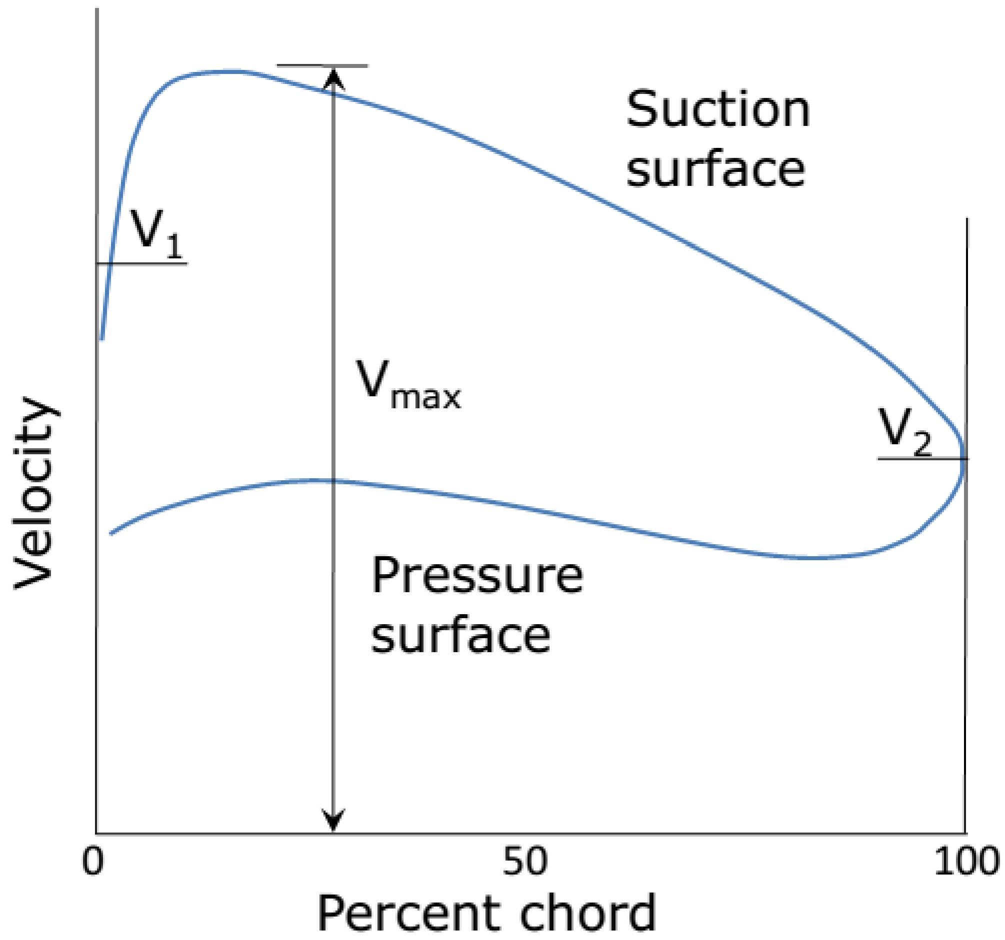
R_x=1.0

Diffusion factor

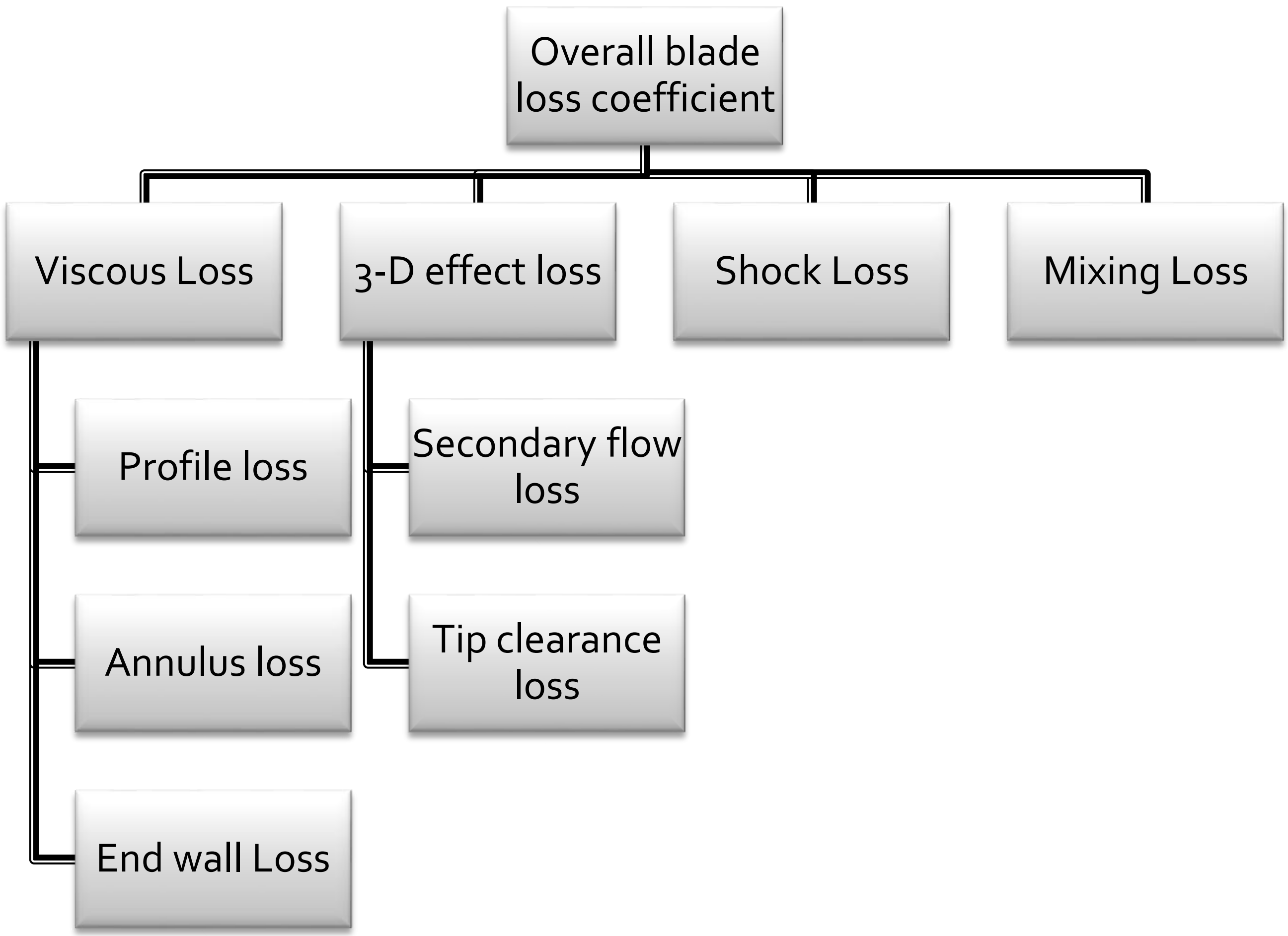
- Fluid deflection (β_2-β_1)is an important parameter that affects the stage pressure rise.
- Excessive deflection, which means high rate of diffusion, will lead to blade stall.
- Diffusion factor is a parameter that associates blade stall with deceleration on the suction surface of the airfoil section.
- Diffusion factor, D*, is defined as

$D^* = \dfrac{V_{\max} - V_2}{V_1}$ Where, $V_{\max}$ is the ideal surface velocity at the minimum pressure point and V_2 is the ideal velocity at the trailing edge and V_1 is the velocity at the leading edge.

Diffusion factor



Losses in Compressor Blades



$$\lambda_{\text{Total}} = \overbrace{\lambda_{\text{Profile}}}^{\text{Measured in cascade}} + \overbrace{\lambda_{\text{Annulus}} + \lambda_{\substack{\text{Secondary}\\ \text{flow loss}}}}^{\text{Grouped into one term secondary loss } \lambda_s} + \lambda_{\substack{\text{Tip clearance}\\ \text{Loss}}} + \lambda_{\textit{Shock Loss}} + \lambda_{\textit{Mixing Loss}}$$

- **Profile loss**
  - boundary layer growth over the blade profile including separation loss under adverse condition of extreme angle of incidence or high inlet Mach number.
- **Annulus loss**
  - Boundary layer growth on the inner and outer walls of the annulus
- **End wall Loss**
  - Boundary Layer effect in corner (junction between the blade surface and the casing/hub)
- **Secondary flow loss**
  - Secondary flows which are always present when a wall boundary layer is turned through an angle by an adjacent curved surface
- **Tip clearance loss**
  - Near the rotor blade tip the gas does not follow the intended path, fails to contribute its work output and interacts with the wall boundary layer

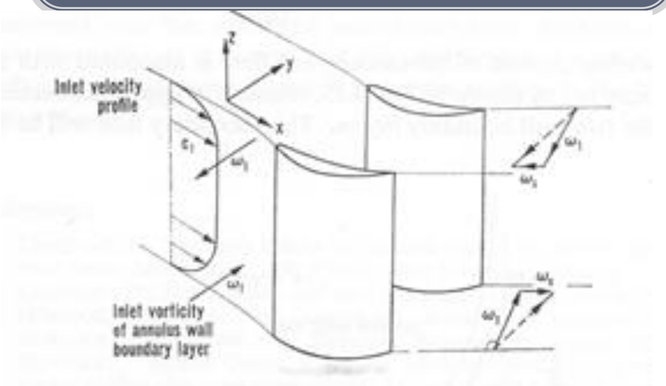
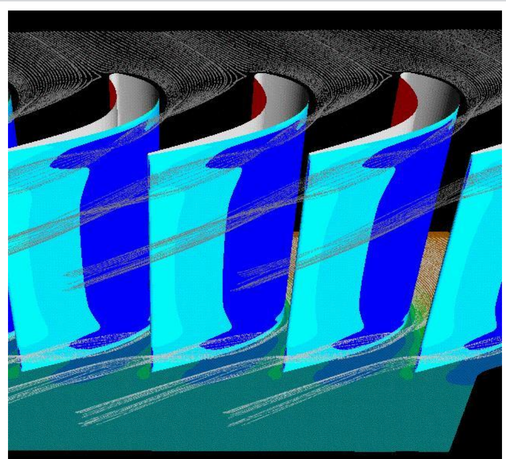
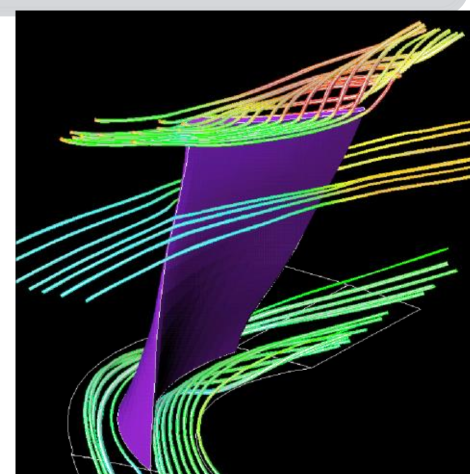


FIG. 6.14. Secondary vorticity produced by a row of guide vanes.





Losses in a compressor blade

- Shock losses
  - Due to interaction of shocks at the blade tip with the primary flow
  - Of concern in transonic rotors
- Mixing losses:
  - Interaction of the flow from the rotor with the succeeding stator, stator wakes with the succeeding rotor etc.
  - Includes the effect of wakes interaction with the blades.

Losses in a compressor blade

- The annulus-wall region accounts for up to 50 % of the total losses.
- The leakage vortex interacts with the blade boundary layer, casing boundary layer and the secondary flows.
- There is a large turbulence production due to mixing in this zone.
- The presence of a shock wave increases the complexity.
- In the hub region, there are corner stalls, which may increase the effective blockage.