TURBOMACHINERY AERODYNAMICS

Lect- 3

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In this lecture...

- Design parameters
- Two dimensional analysis: Cascade aerodynamics

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.

Degree of reaction

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

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

For a nearly incompressible flow,

$$h_2 - h_1 \cong \frac{1}{\rho}\left(P_2 - P_1\right) \text{ for the rotor}$$

$$\text{and for the stage, } h_{03} - h_{01} \cong \frac{1}{\rho}\left(P_{03} - P_{01}\right)$$

$$\therefore R_x = \frac{h_2 - h_1}{h_{02} - h_{01}} \cong \frac{P_2 - P_1}{P_{02} - P_{01}}$$

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

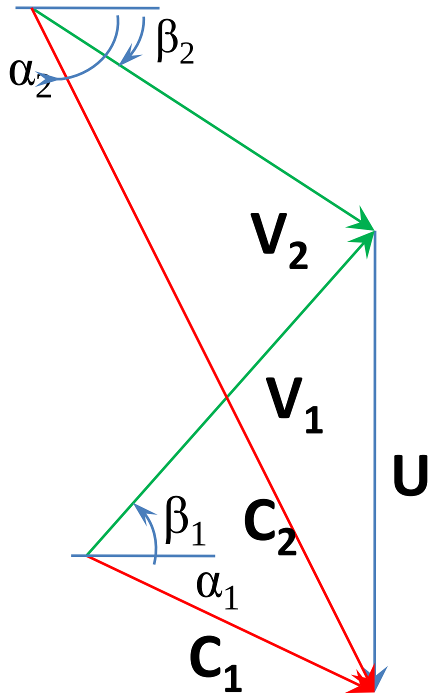
On simplification, $R_x = \frac{1}{2} - \frac{C_a}{2U}(\tan\alpha_1 - \tan\beta_2)$

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

Degree of reaction

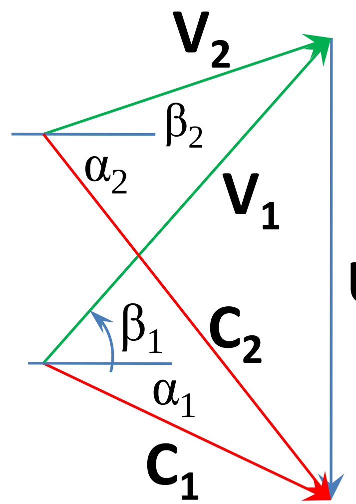
- Special cases of R_x
  - $R_x=0, \beta_2 = -\beta_1$, There is no pressure rise in the rotor, the entire pressure rise is due to the stator, the rotor merely deflects the incoming flow: impulse blading
  - $R_x=0.5$, gives $\alpha_1 = \beta_2$ and $\alpha_2 = \beta_1$, the velocity triangles are symmetric,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

Degree of reaction



$$\beta_2 = -\beta_1$$

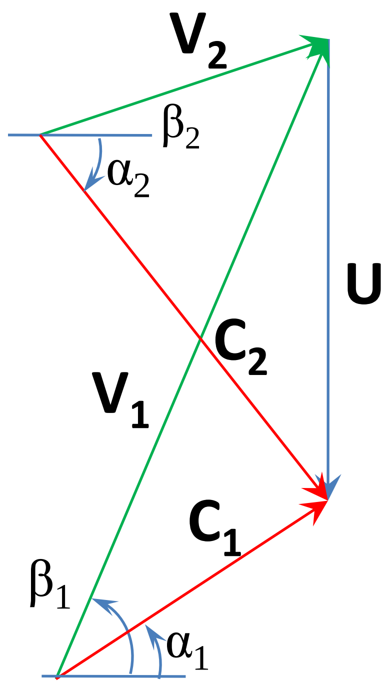
$R_x = 0.0$



$$\alpha_1 = \beta_2 \text{ and } \alpha_2 = \beta_1$$

$R_x = 0.5$

$$\alpha_2 = -\alpha_1$$



$R_x = 1.0$

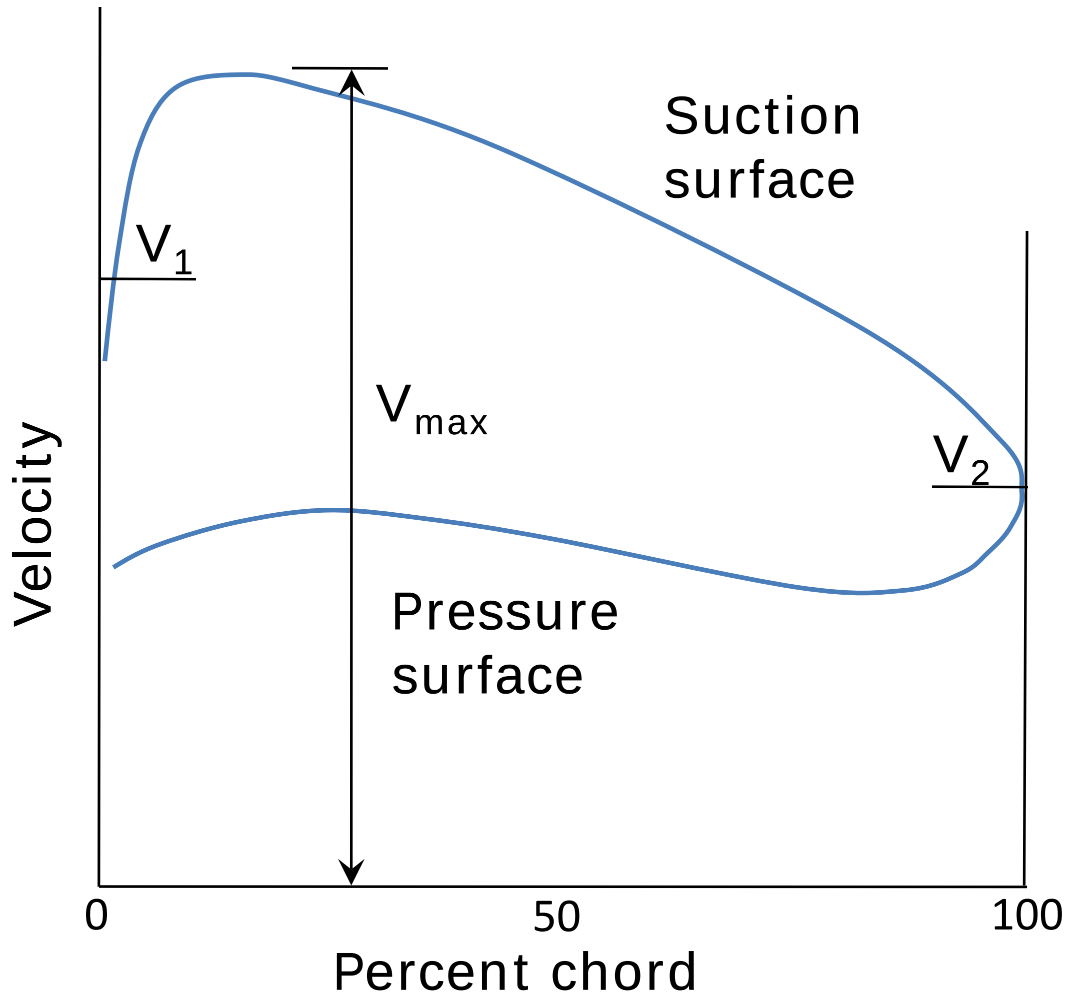
Diffusion factor

- 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

$$D^* = \frac{V_{max} - V_2}{V_1}$$

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



Diffusion factor

- Lieblein (1953) proposed an empirical parameter for diffusion factor.
  - It is expressed entirely in terms of known or measured quantities.
  - It depends strongly upon solidity (C/s).
  - It has been proven to be a dependable indicator of approach to separation for a variety of blade shapes.
  - D^* is usually kept around 0.5.

$$D^* = 1 - \frac{V_2}{V_1} + \frac{V_{w1} - V_{w2}}{2\left(\frac{C}{s}\right)V_1}$$

Where, C is the chord of the blade and s is the spacing between the blades.

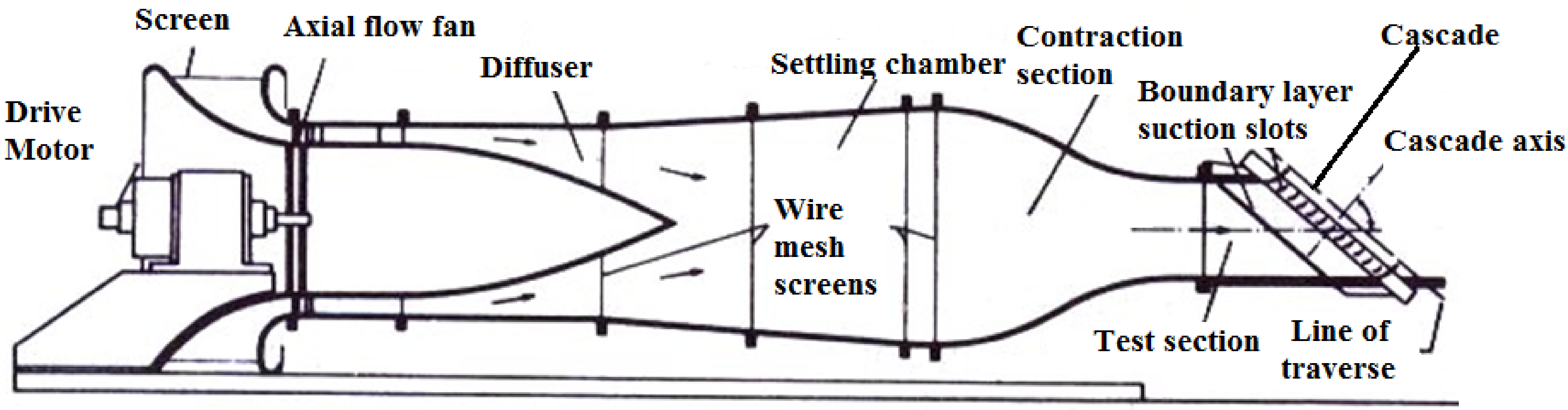
Cascade aerodynamics

- A cascade is a stationary array of blades.
- Cascade is constructed for measurement of performance similar to that used in axial compressors.
- Cascade usually has porous end-walls to remove boundary layer for a two-dimensional flow.
- Radial variations in the velocity field can therefore be excluded.
- Cascade analysis relates the fluid turning angles to blading geometry and measure losses in the stagnation pressure.

Cascade aerodynamics

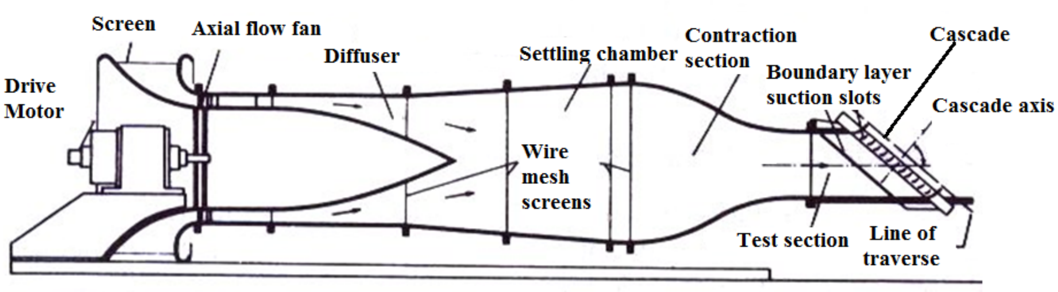
- The cascade is mounted on a turntable so that its angular direction relative to the inlet can be set at different incidence angles.
- Measurement usually consist of pressures, velocities and flow angles downstream of the cascade.
- Probe traverse at the trailing edge of the blades for measurement.
- Blade surface static pressure using static pressure taps: c_p distribution.

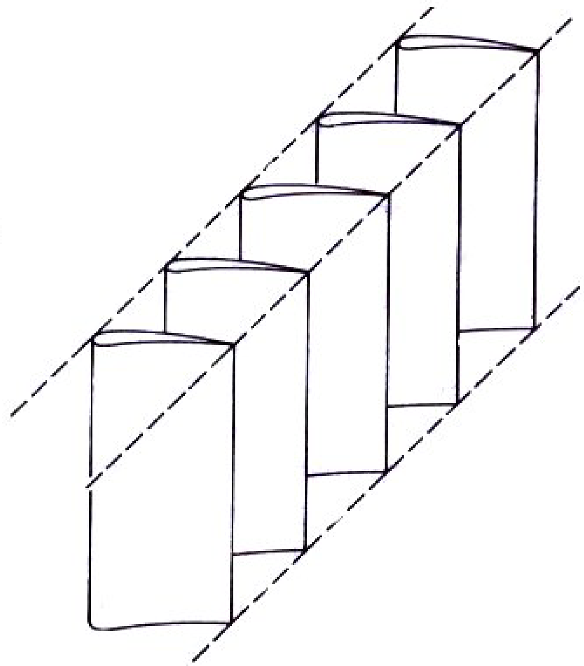
Cascade wind tunnel



Linear open circuit cascade wind tunnel

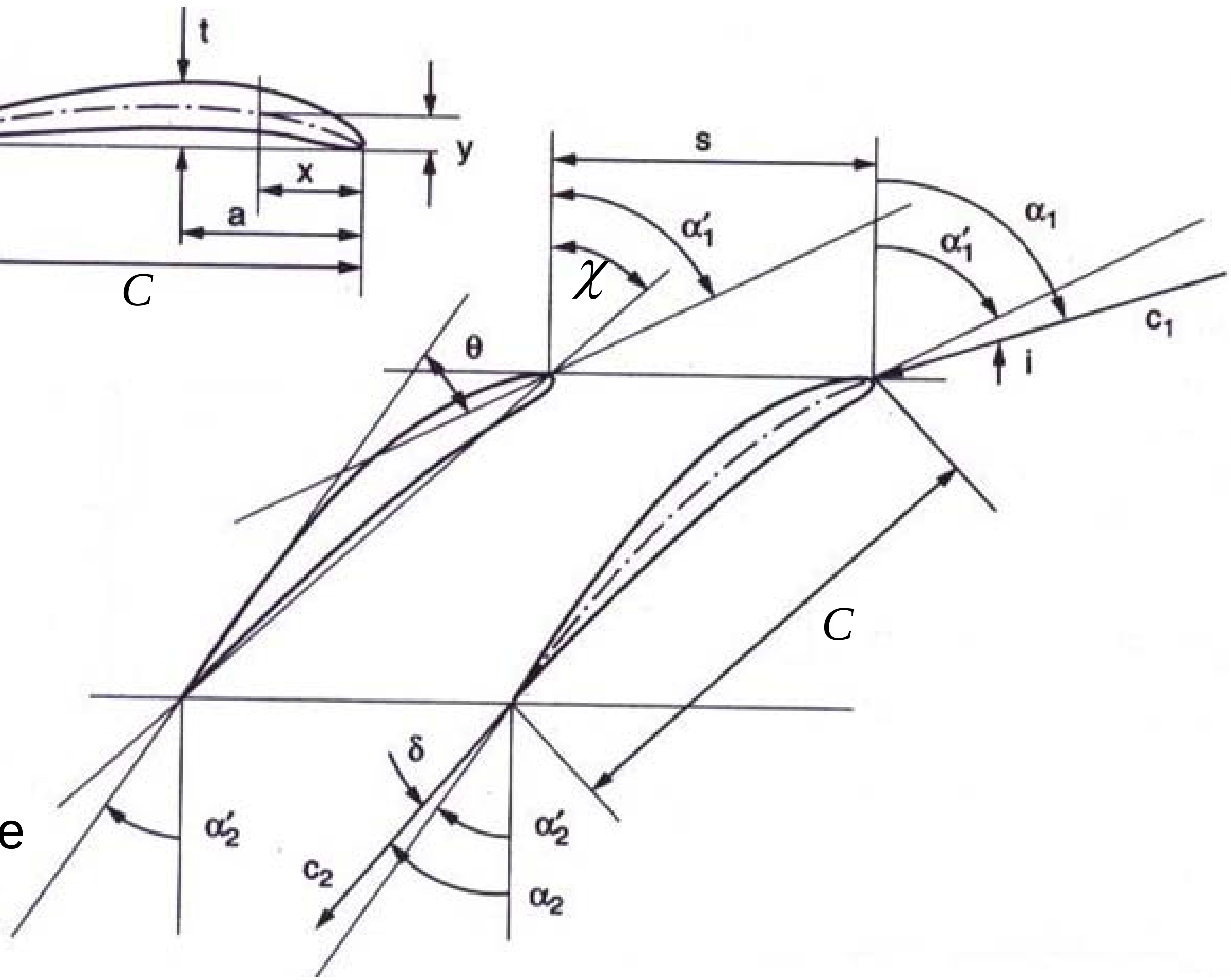
Cascade wind tunnel





Linear open circuit cascade wind tunnel

Cascade nomenclature



C = Chord

s = spacing / pitch

t = thickness

θ = camber

χ = stagger

i = incidence angle

δ = deflection angle

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Cascade aerodynamics

- The cascade is mounted on a turntable so that its angular direction relative to the inlet can be set at different incidence angles.
- Measurement usually consist of pressures, velocities and flow angles downstream of the cascade.
- Special nulling type probes (cylindrical, claw or cobra type) are used in the measurements.

Performance parameters

- Measurements from cascade: velocities, pressures, flow angles …
- Loss in total pressure expressed as total pressure loss coefficient

$$\overline{W}_{PLC} = \frac{P_{01} - P_{02}}{\frac{1}{2}\rho V_1^2}$$

- Total pressure loss is very sensitive to changes in the incidence angle.
- At very high incidences, flow is likely to separate from the blade surfaces, eventually leading to stalling of the blade.

Performance parameters

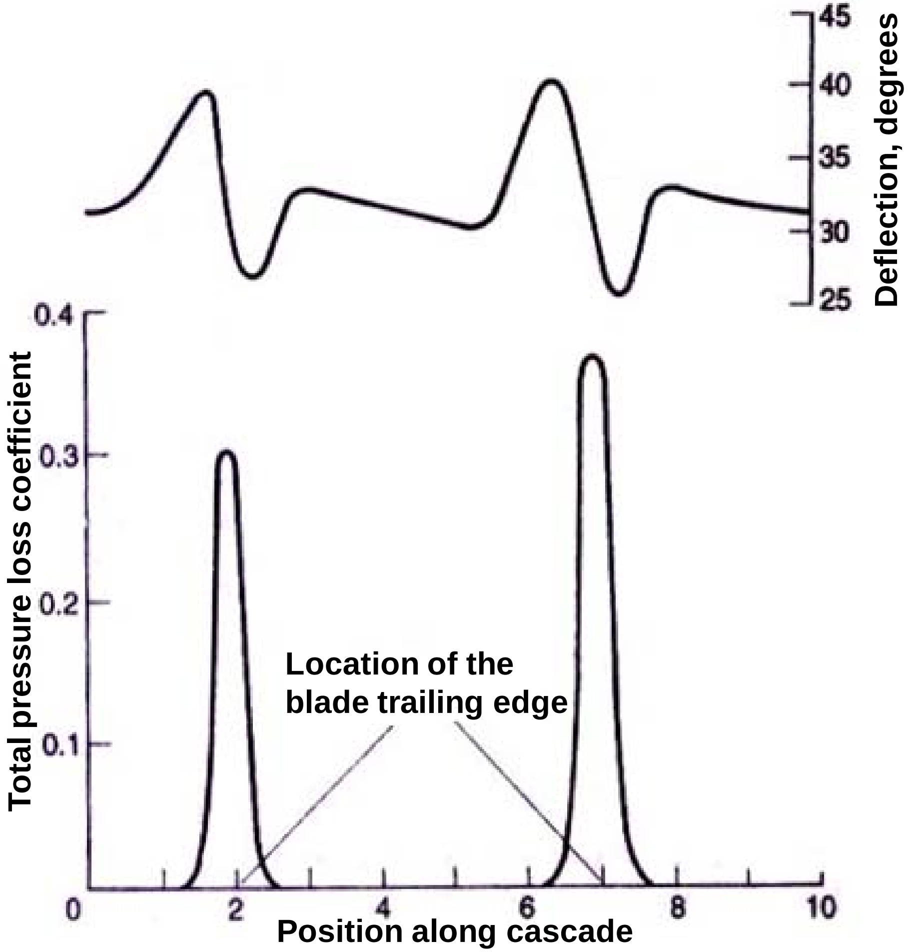
- Blade performance/loading can be assessed using static pressure coefficient:

$$C_P = \frac{P_{local} - P_{ref}}{\frac{1}{2}\rho V_1^2}$$

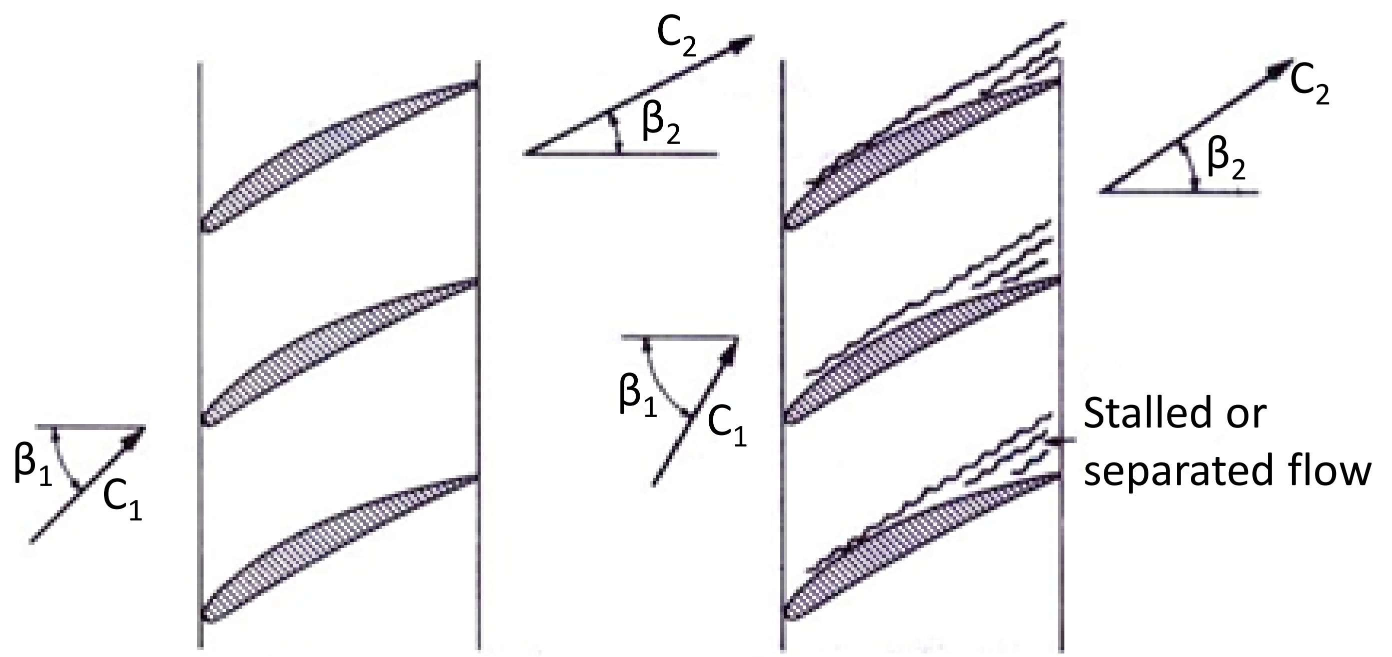
Where, P_{local} is the blade surface static pressure and P_{ref} is the reference static pressure (usually measured at the cascade inlet)

- The C_P distribution (usually plotted as C_P *vs. x/C*) gives an idea about the chordwise load distribution.

Performance parameters

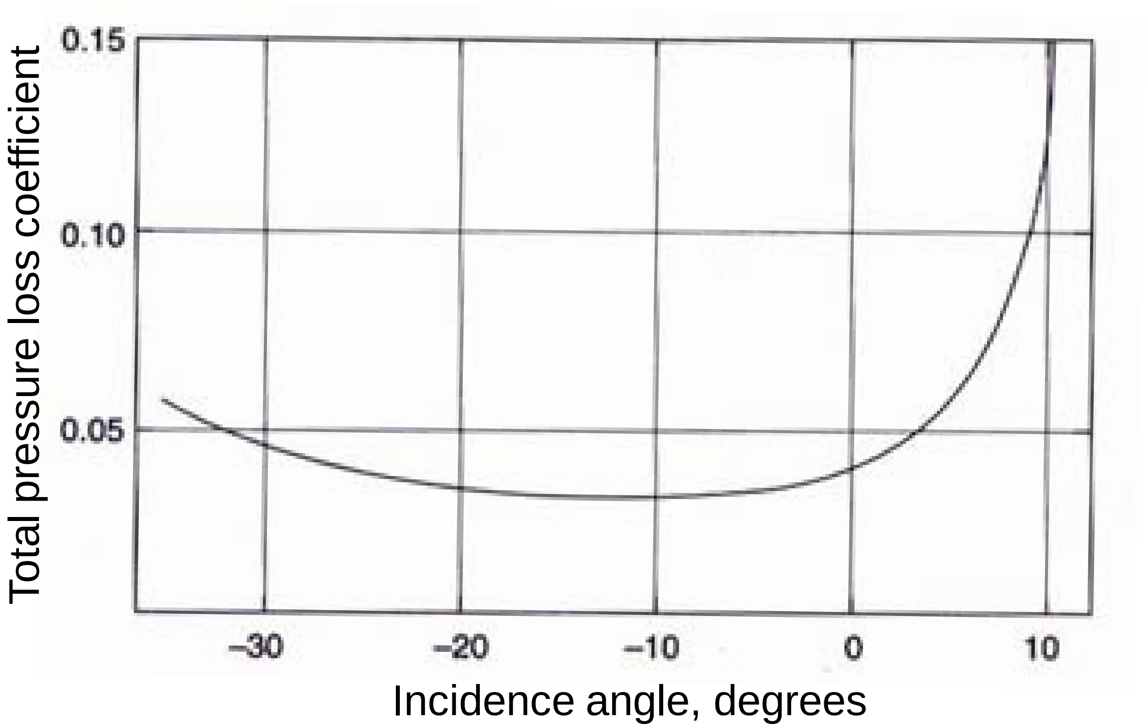


Performance parameters



(a) Normal operation (b) Stalled operation

Performance parameters



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In the next lecture...

- 2-D losses in axial compressor stage – primary losses

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