TURBOMACHINERY AERODYNAMICS

Lect- 21

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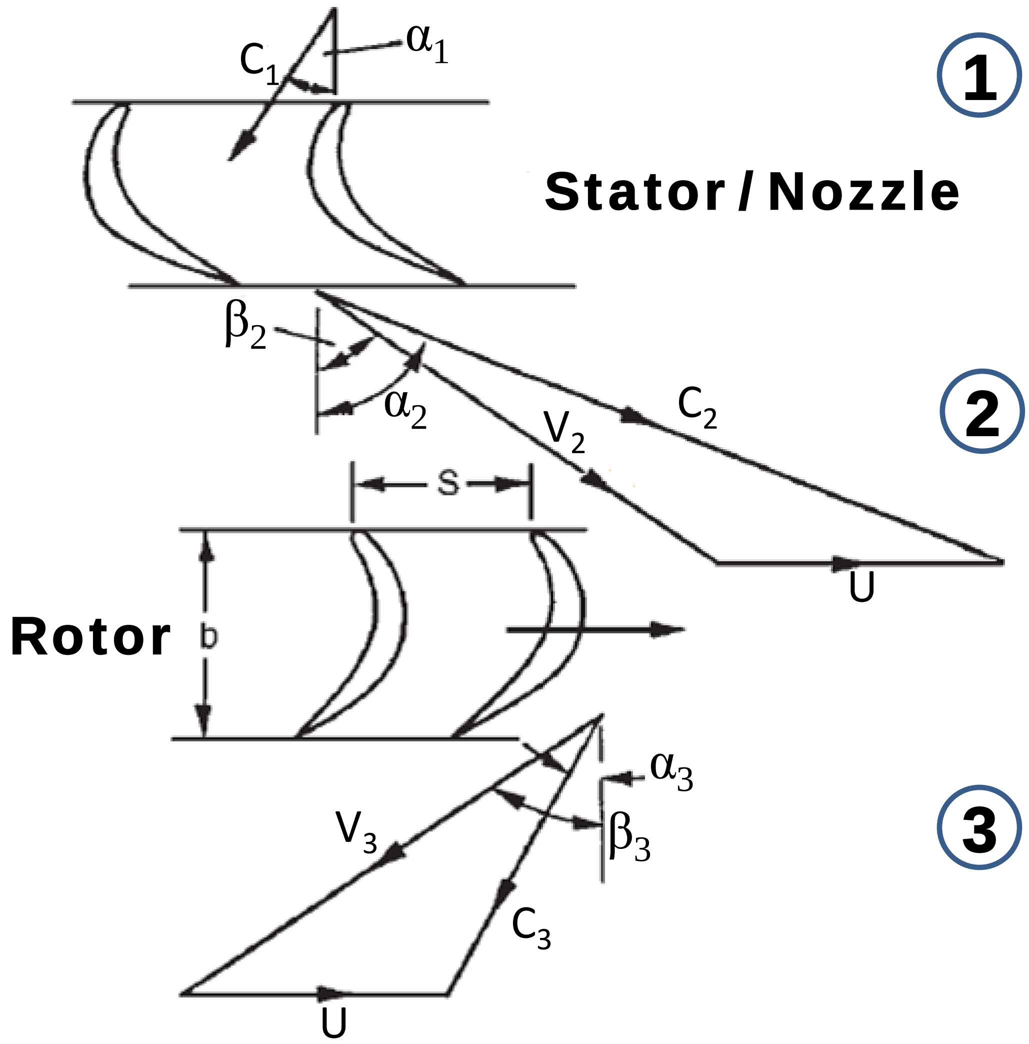
In this lecture...

- Axial flow turbine
  - Degree of Reaction, Losses and Efficiency

Degree of reaction

- Acceleration takes place in both rotor and the stator.
- Enthalpy drop 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 enthalpy drop in the stage.

Velocity triangles



Degree of reaction

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

$$= \frac{h_2 - h_3}{h_{01} - h_{03}}$$

Since, in a coordinate system fixed to the rotor, the apparent stagnation enthalpy is constant,

$$h_2 - h_3 = \frac{V_3^2}{2} - \frac{V_2^2}{2}$$

If the axial velocity is the same upstream and downstream of the rotor, this becomes,

$$h_2 - h_3 = \tfrac{1}{2}(V_{w3}^2 - V_{w2}^2) = \tfrac{1}{2}(V_{w3} - V_{w2})(V_{w3} + V_{w2})$$

Also, since $h_{01} - h_{03} = U(C_{w2} - C_{w3})$

Degree of reaction

$$R_x = \frac{(V_{w3} - V_{w2})(V_{w3} + V_{w2})}{2U(C_{w2} - C_{w3})}$$

Since, $(V_{w3} - V_{w2}) = (C_{w3} - C_{w2})$

Therefore, $R_x = -\frac{(V_{w3} + V_{w2})}{2U}$

We know that, $V_{w3} = C_a \tan\beta_3$

and $V_{w2} = C_a \tan\alpha_2 - U$

so that $R_x = \frac{1}{2}\left[1 - \frac{C_a}{U}(\tan\alpha_2 + \tan\beta_3)\right]$

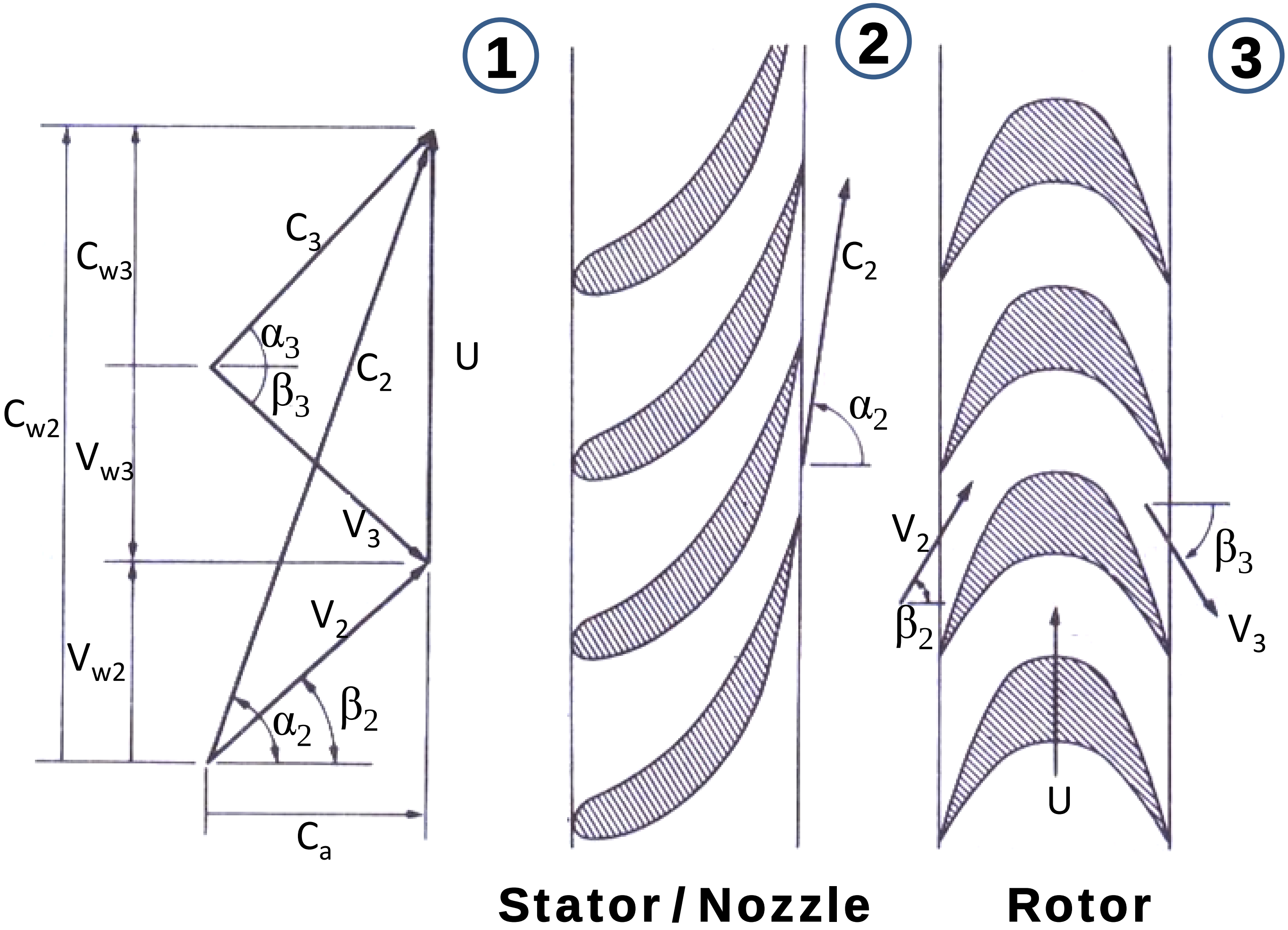
Degree of reaction

It can be seen that for a special case of symmetrical triangles, $\alpha_2 = -\beta_3$, $R_X = 0.5$.

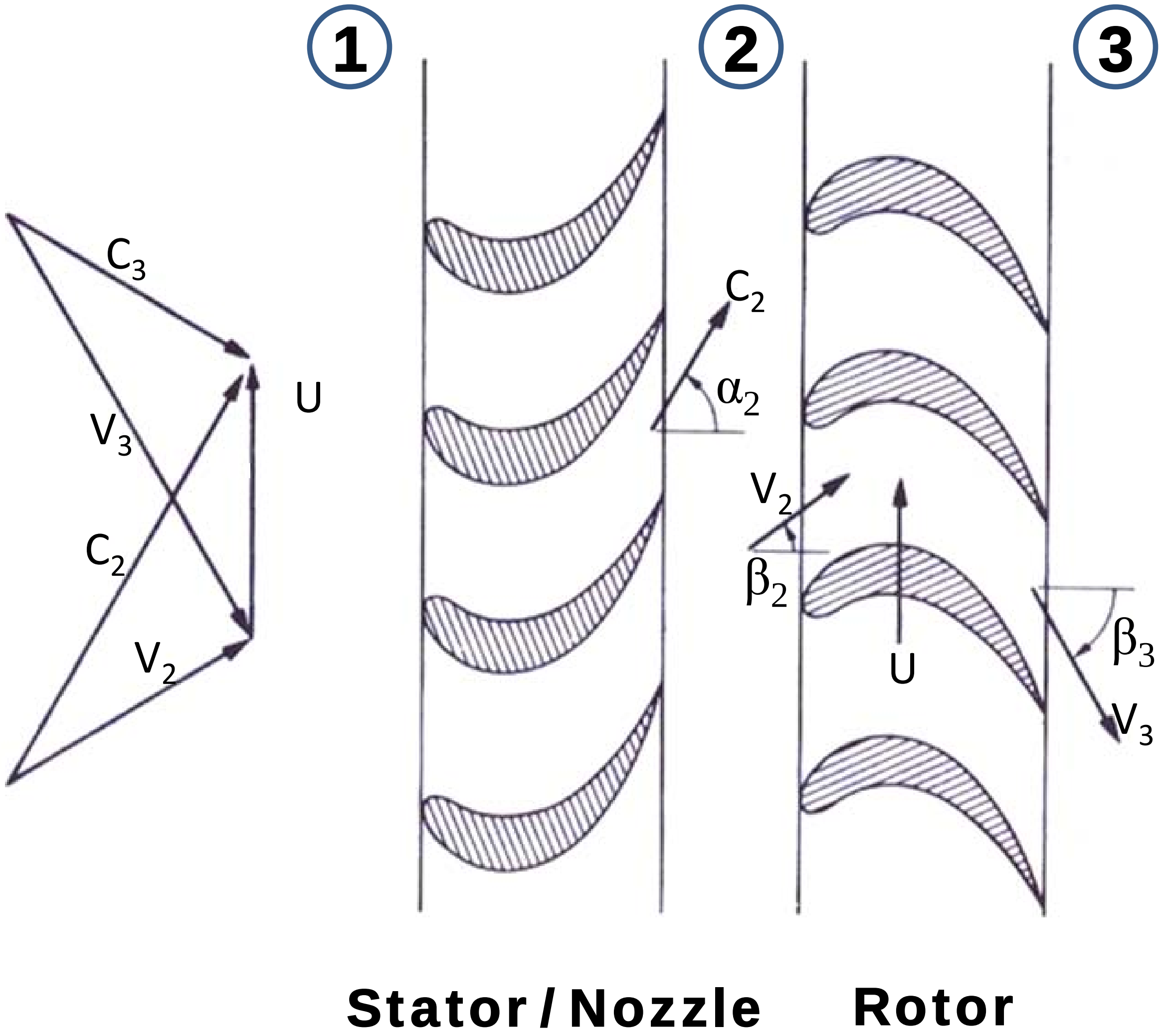
When, $V_{w3} = -V_{w2}$, $R_X = 0 \rightarrow$ Impulse turbine

For a given stator outlet angle, the impulse turbine stage requires a much higher axial velocity ratio than does the 50% reaction stage. In the impulse turbine stage, all the flow velocities are higher and that is one of the reason why its efficiency is lower than that of a 50% reaction stage.

Impulse turbine stage



50 % Reaction turbine stage



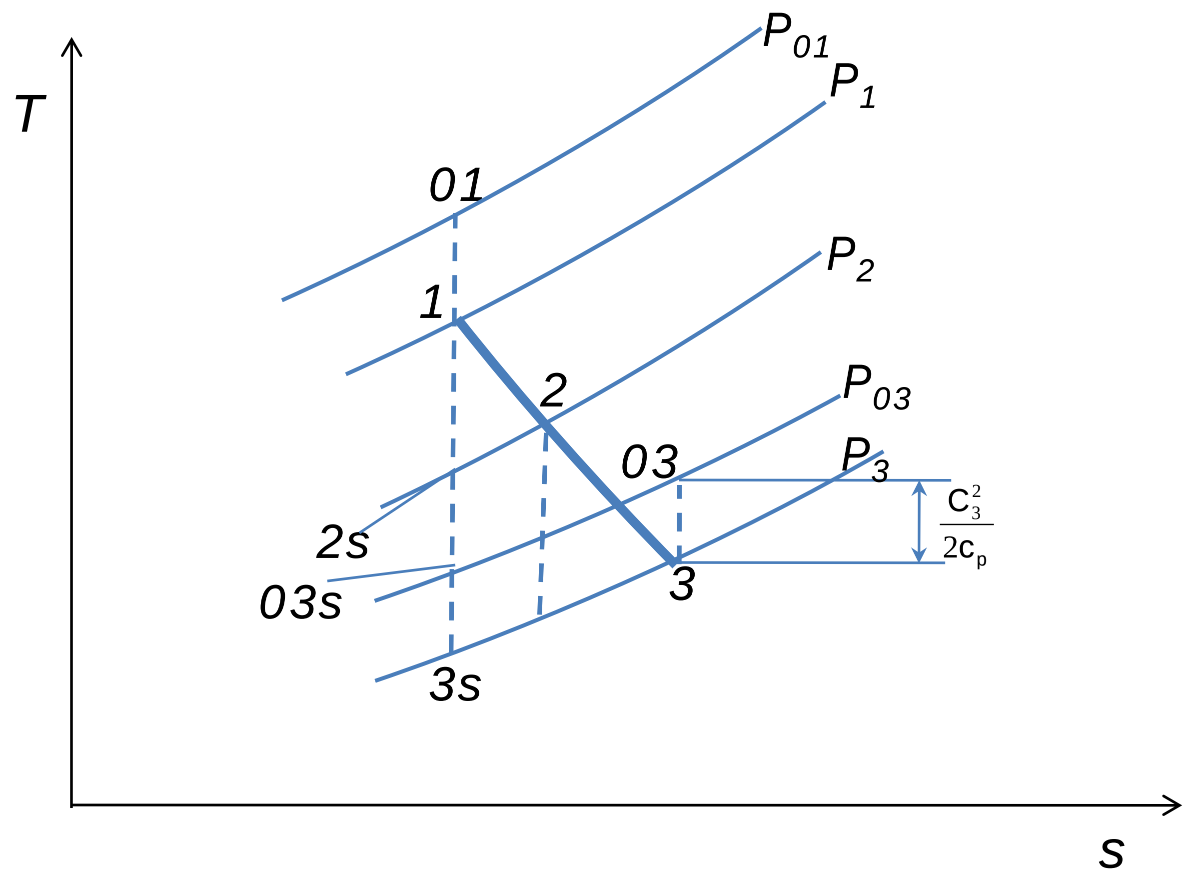
Efficiency

- We noted that the aerodynamic losses in the turbine differ with the stage configuration, or the degree of reaction.
- Improved efficiency is associated with higher reaction, which implies less work per stage and therefore a higher number of stages for a given overall pressure ratio.
- The understanding of losses is important to design, not only in the choice of the configuration, but also on methods to control these losses.

Efficiency

- There are two commonly used turbine efficiency definitions.
  - Total-to-static efficiency
  - Total-to-total efficiency
- The usage of the efficiency definition depends upon the application.
- In land-based power plants, the useful turbine output is in the form of shaft power and exhaust KE is a loss.
- In this case the ideal turbine process would be isentropic such that there is no exhaust KE.

Efficiency



Expansion process in a turbine stage

Efficiency

The ideal turbine work with no exhaust KE would be

$$W_{T,\,ideal} = c_P(T_{01} - T_{3s})$$

The total - to - static efficiency is defined as

$$\eta_{ts} = \frac{T_{01} - T_{03}}{T_{01} - T_{3s}}$$

$$= \frac{T_{01} - T_{03}}{T_{01}\left[1 - (P_3 / P_{01})^{(\gamma-1)/\gamma}\right]} = \frac{1 - (T_{03} / T_{01})}{\left[1 - (P_3 / P_{01})^{(\gamma-1)/\gamma}\right]}$$

Efficiency

In many applications (turbojets), the exhaust KE is not considered a loss as this is converted to thrust in such machines.

The ideal turbine work in such cases would be

$$W_{T,\,ideal} = c_P(T_{01} - T_{03s})$$

The total - to - total efficiency is defined as

$$\eta_{ts} = \frac{T_{01} - T_{03}}{T_{01} - T_{03s}}$$

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

Efficiency

We can compare the two definitions of efficiency by making an approximation :

$$T_{03s} - T_{3s} \cong T_{03s} - T_{3} = C_3^2 / 2c_p$$

Therefore, $\eta_{tt} = \dfrac{\eta_{ts}}{1 - C_3^2\left[2c_p(T_{01} - T_{3s})\right]}$

We can see that, $\eta_{tt} > \eta_{ts}$

The efficiency definitions can also be related to the specific work done in the following way :

$$w_t = \eta_{tt} c_p T_{01}\left[1 - \left(\frac{P_{03}}{P_{01}}\right)^{(\gamma-1)/\gamma}\right] \text{ and } w_t = \eta_{ts} c_p T_{01}\left[1 - \left(\frac{P_{3}}{P_{01}}\right)^{(\gamma-1)/\gamma}\right]$$

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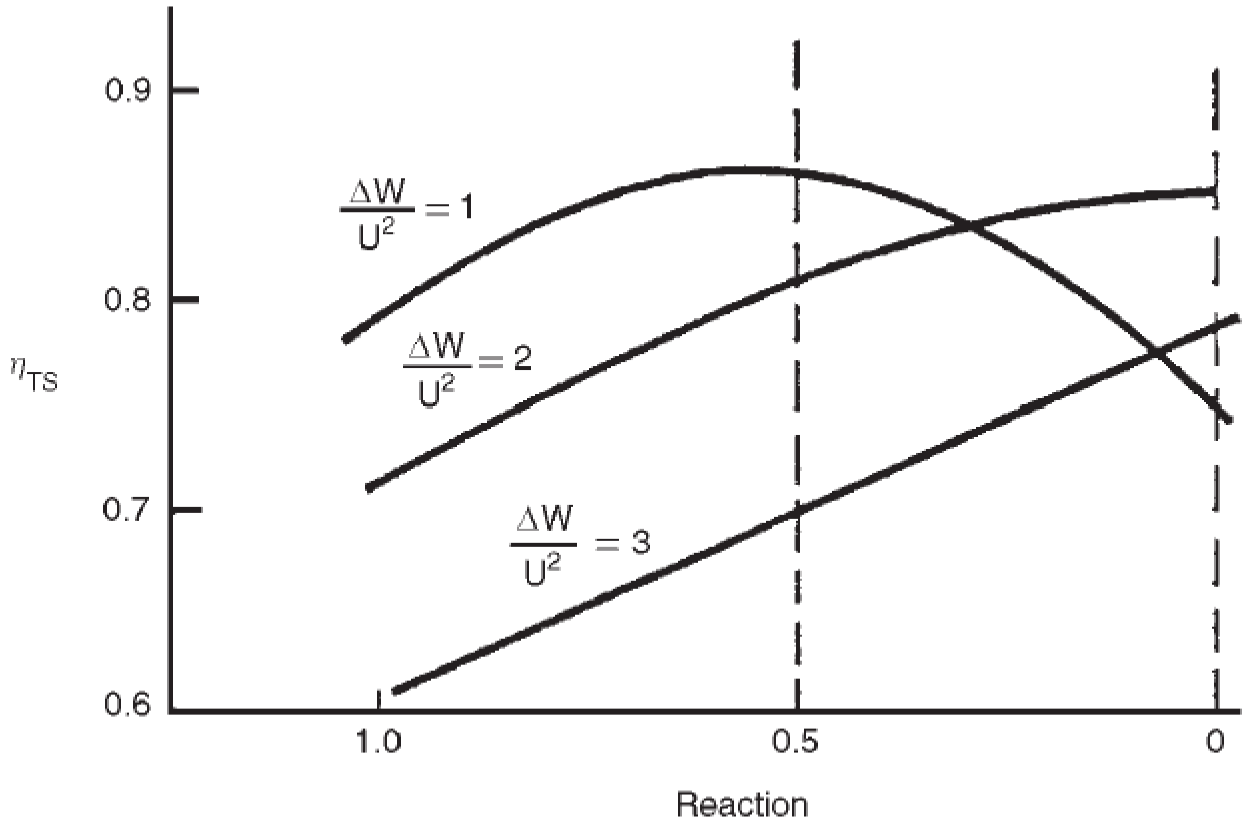
Efficiency



Influence of loading on the total-to-static efficiency

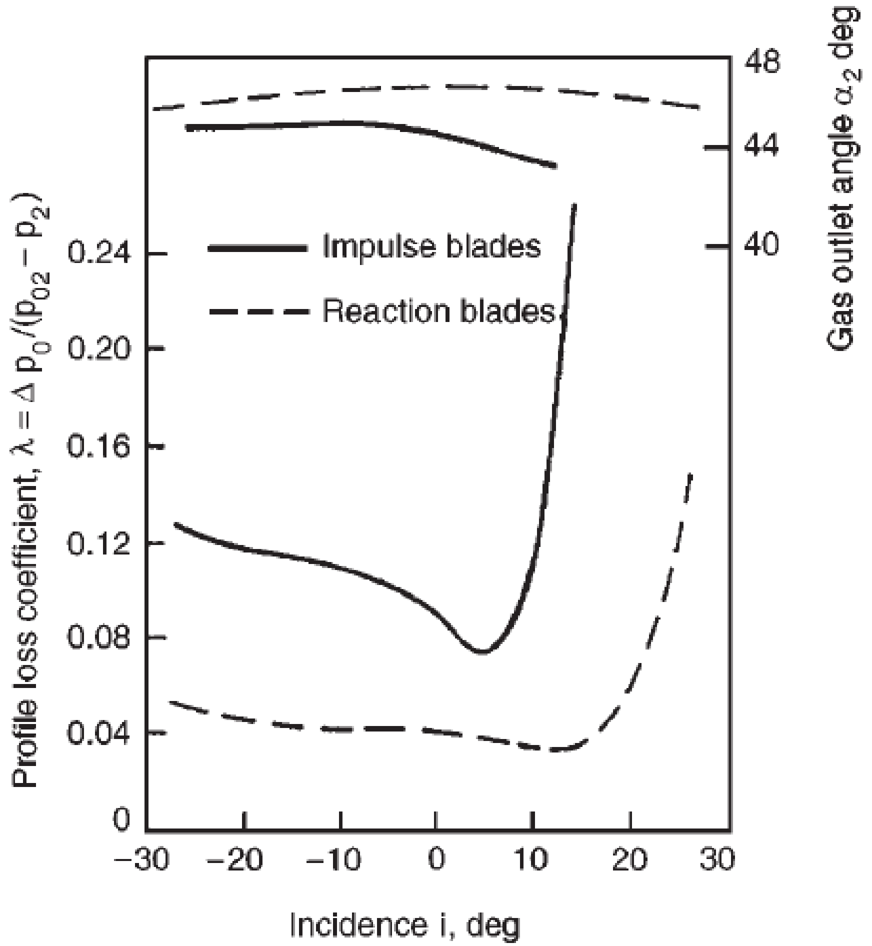
Losses in a turbine

- Nature of losses in an axial turbine
  - Viscous losses
  - 3-D effects like tip leakage flows, secondary flows etc.
  - Shock losses
  - Mixing losses
- Estimating the losses crucial designing loss control mechanisms.
- However isolating these losses not easy and often done through empirical correlations.
- Total losses in a turbine is the sum of the above losses.

Losses in a turbine

- Viscous losses
  - Profile losses: on account of the profile or nature of the airfoil cross-sections
  - Annulus losses: growth of boundary layer along the axis
  - Endwall losses: boundary layer effects in the corner (junction between the blade surface and the casing/hub)
- 3-D effects:
  - Secondary flows: flow through curved blade passages
  - Tip leakage flows: flow from pressure surface to suction surface at the blade tip
  - 3-D effects are likely to be stronger in a turbine blade as compared to compressor blade due to high camber and flow turning

Losses in a turbine



Variation of profile loss with incidence

2-D Losses in a turbine

- 2-D losses are relevant only to axial flow turbomachines.
- These are mainly associated with blade boundary layers, shock-boundary layer interactions, separated flows and wakes.
- The mixing of the wake downstream produces additional losses called mixing losses.
- The maximum losses occur near the blade surface and minimum loss occurs near the edge of the boundary layer.

2-D Losses in a turbine

- 2-D losses can be classified as:
  - Profile loss due to boundary layer, including laminar and/or turbulent separation.
  - Wake mixing losses
  - Shock losses
  - Trailing edge loss due to the blade.

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Total losses in a turbine

- The overall losses in a turbine can be summarised as:

$$\omega = \omega_P + \omega_{sh} + \omega_s + \omega_L + \omega_E$$

Where, ω_P : profile losses

ω_{sh} : shock losses

ω_s : secondary flow loss

ω_L : tip leakage loss

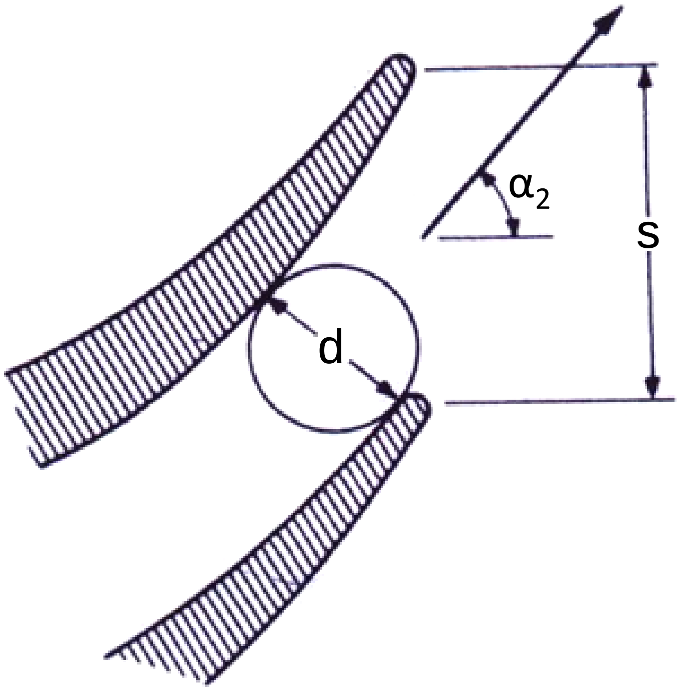
ω_E : Endwall losses

Deviation

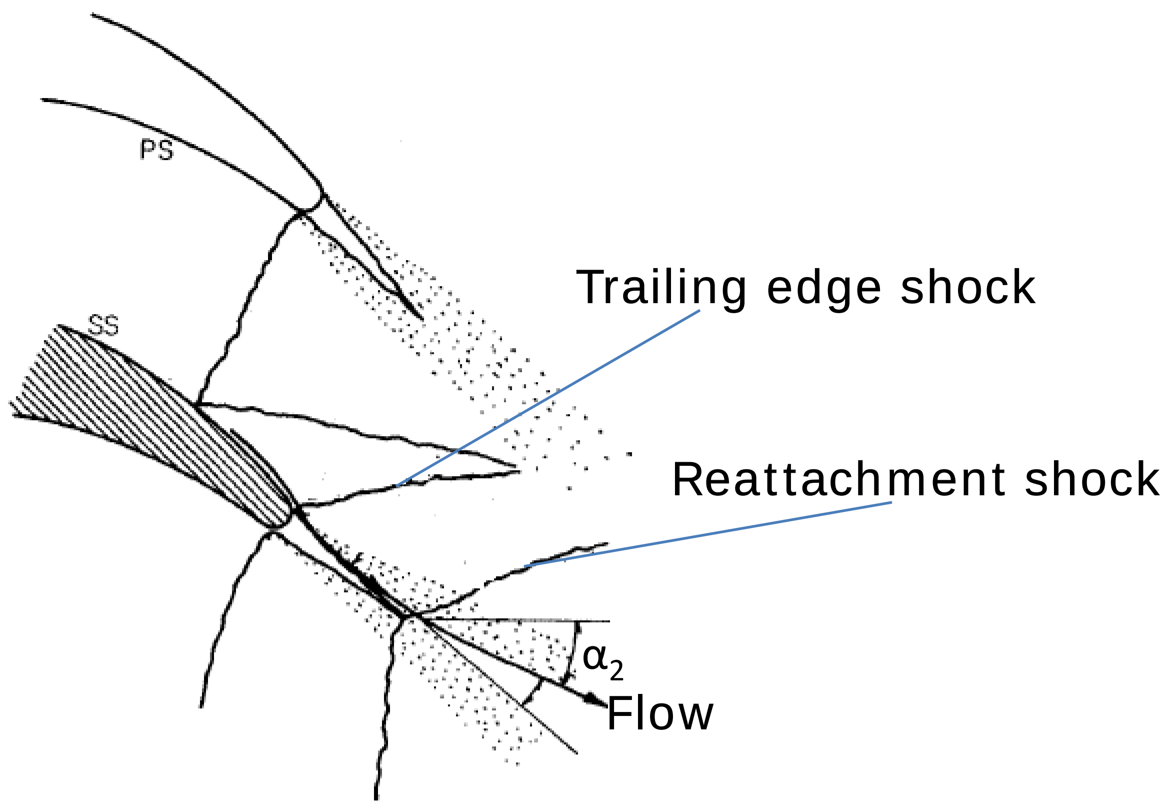
- Flow at the exit of the rotor does not leave at exactly the blade exit angle.
- It has been found from experience that the actual exit angle at the design pressure ratio is well approximated by

$$\alpha_2 = \cos^{-1}(d/s)$$

- This is true as long as the nozzle is not choked.
- Under choked condition, a supersonic expansion may alter the flow direction at the exit.



Flow at the nozzle exit



Flow at the nozzle exit in the presence of shocks

In this lecture...

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In the next lecture...

- Axial flow turbine
  - Performance characteristics
  - Exit flow matching with nozzle