- Recap: Lecture 17, 29th September 2015, 1530-1655 hrs.
  - Turbine cascade fundamentals
    - Nomenclature
    - Inviscid analysis through a cascade
    - Viscous analysis through a cascade
  - Degree of reaction
  - Turbine efficiency
    - Total-to-static and total-to-total efficiency

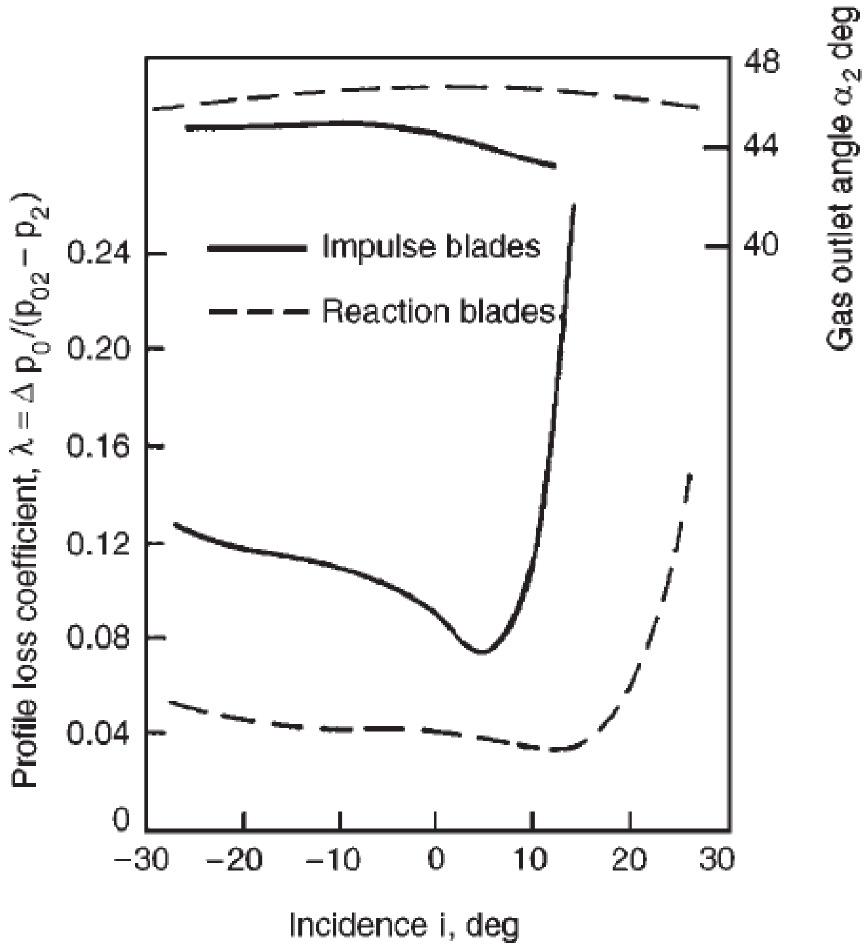
Losses in a turbine

- 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.

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

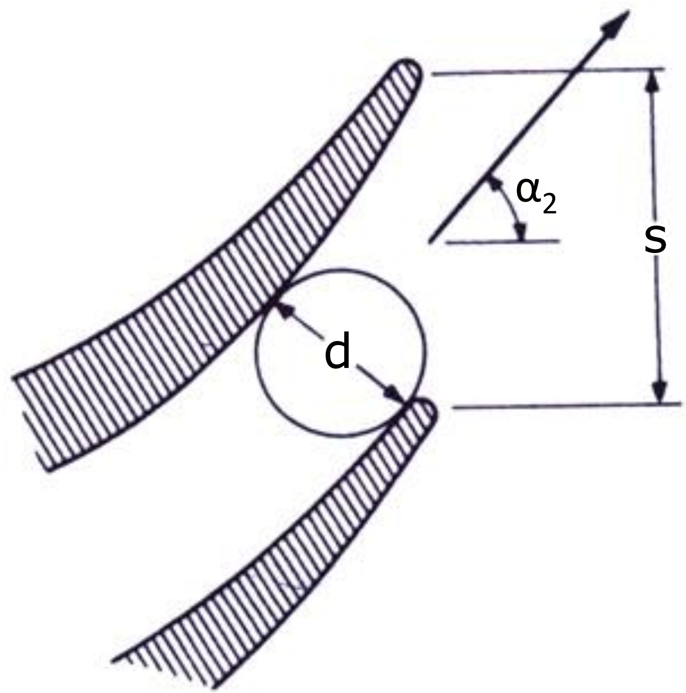
ω_E : Endwall losses

Deviation

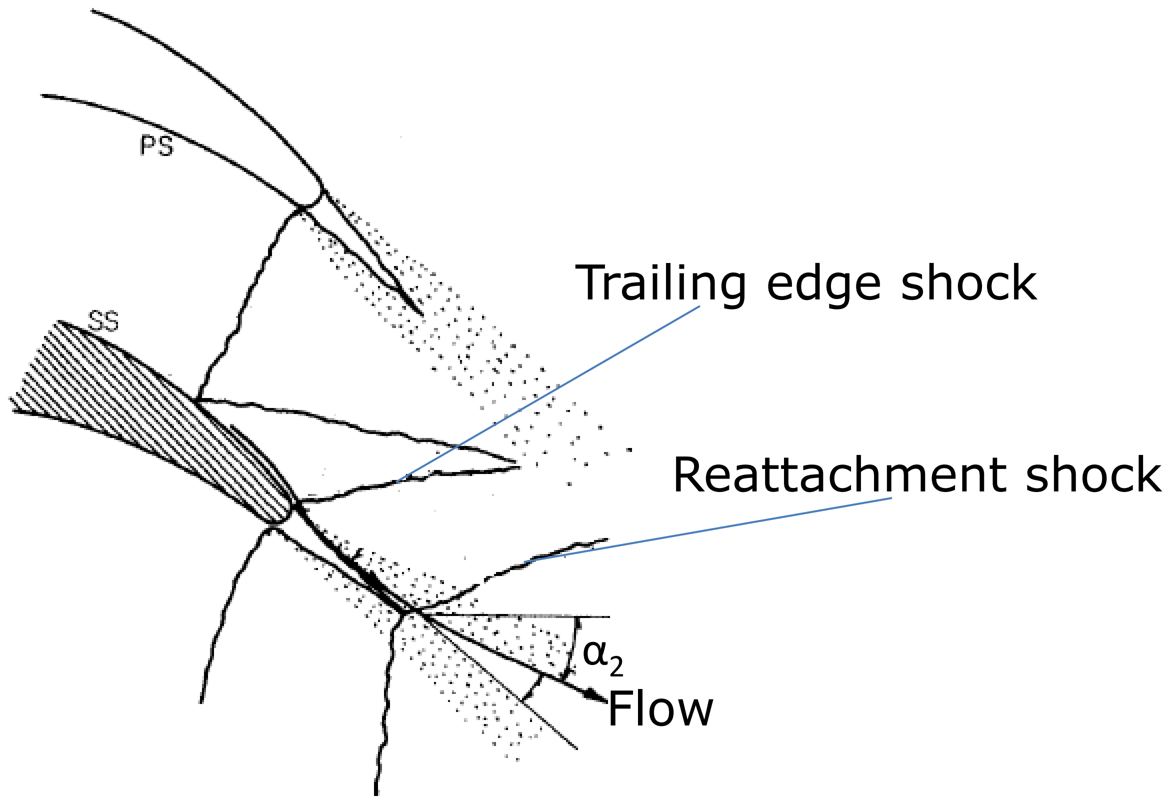
- Flow at the exit of the rotor does not leave at exactly the blade exit angle.
- It has been found from experience that the actual exit angle at the design pressure ratio is well approximated by

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

- 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
(un-choked condition)



Flow at the nozzle exit in the presence of shocks

Axial turbine performance

- We have seen that for an axial compressor,

$$P_{02}, \eta_C = f(\dot{m}, P_{01}, T_{01}, \Omega, \gamma, R, \nu, \text{design}, D)$$

In terms of non-dimensionless parameters,

$$\frac{P_{02}}{P_{01}}, \eta_C = f\left(\frac{\dot{m}\sqrt{\gamma R T_{01}}}{P_{01}D^2}, \frac{\Omega D}{\sqrt{\gamma R T_{01}}}, \frac{\Omega D^2}{\nu}, \gamma, \text{design}\right)$$

For a given design, we can assume that γ and ν do not affect the performance significantly. Also, D and R are fixed. Therefore the above reduces to

$$\frac{P_{02}}{P_{01}}, \eta_C = f\left(\frac{\dot{m}\sqrt{T_{01}}}{P_{01}}, \frac{N}{\sqrt{T_{01}}}\right)$$

Axial turbine performance

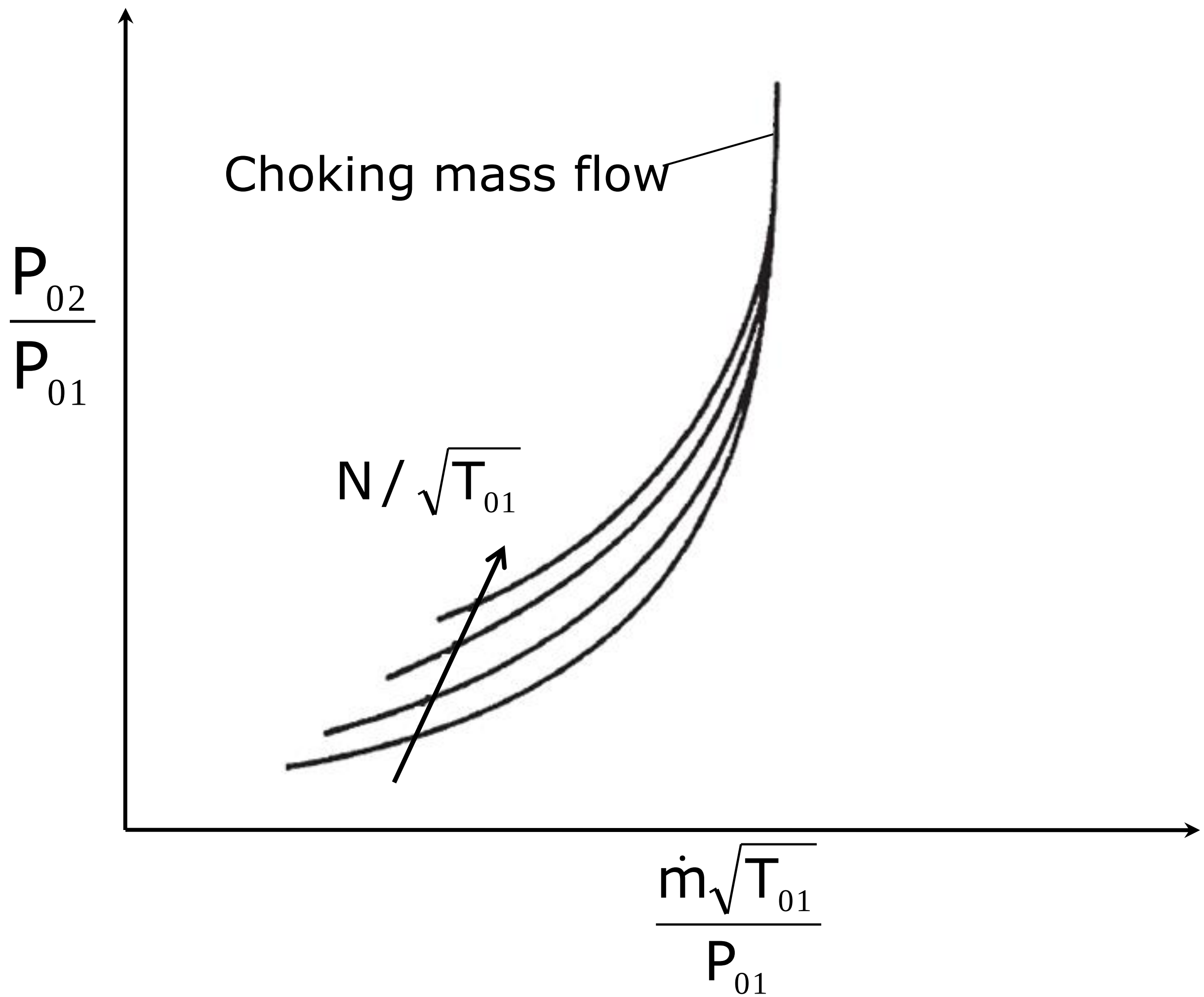
In a similar manner, we can define performance characteristics for a turbine as well.

Therefore, for a given turbine operating with a given fluid at a sufficiently high Reynolds number,

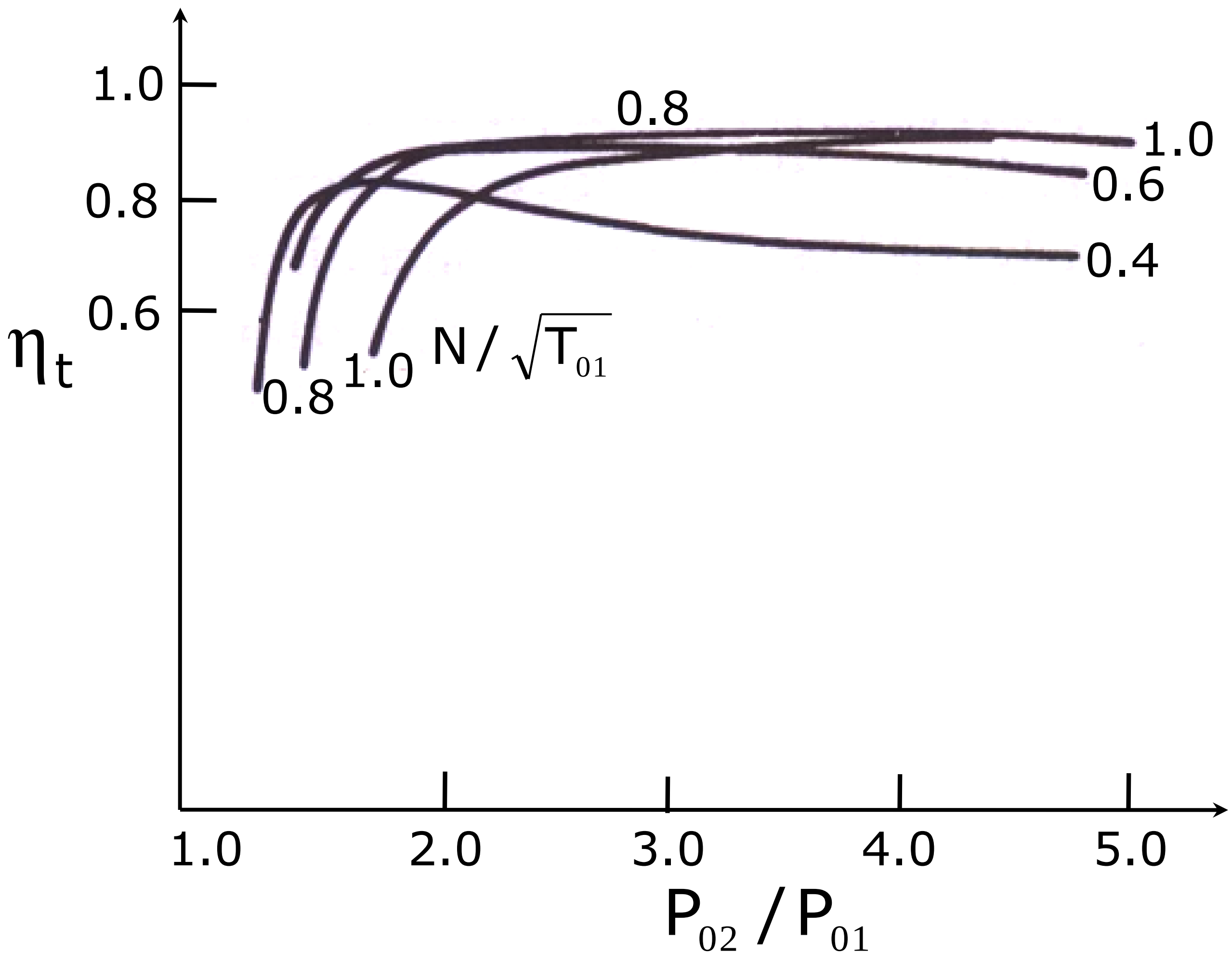
$$\frac{P_{02}}{P_{01}}, \eta_C = f\left(\frac{\dot{m}\sqrt{T_{01}}}{P_{01}}, \frac{N}{\sqrt{T_{01}}}\right)$$

Where, subscripts 01 and 02 denote the inlet and exit of the turbine, respectively.

Axial turbine performance



Axial turbine performance



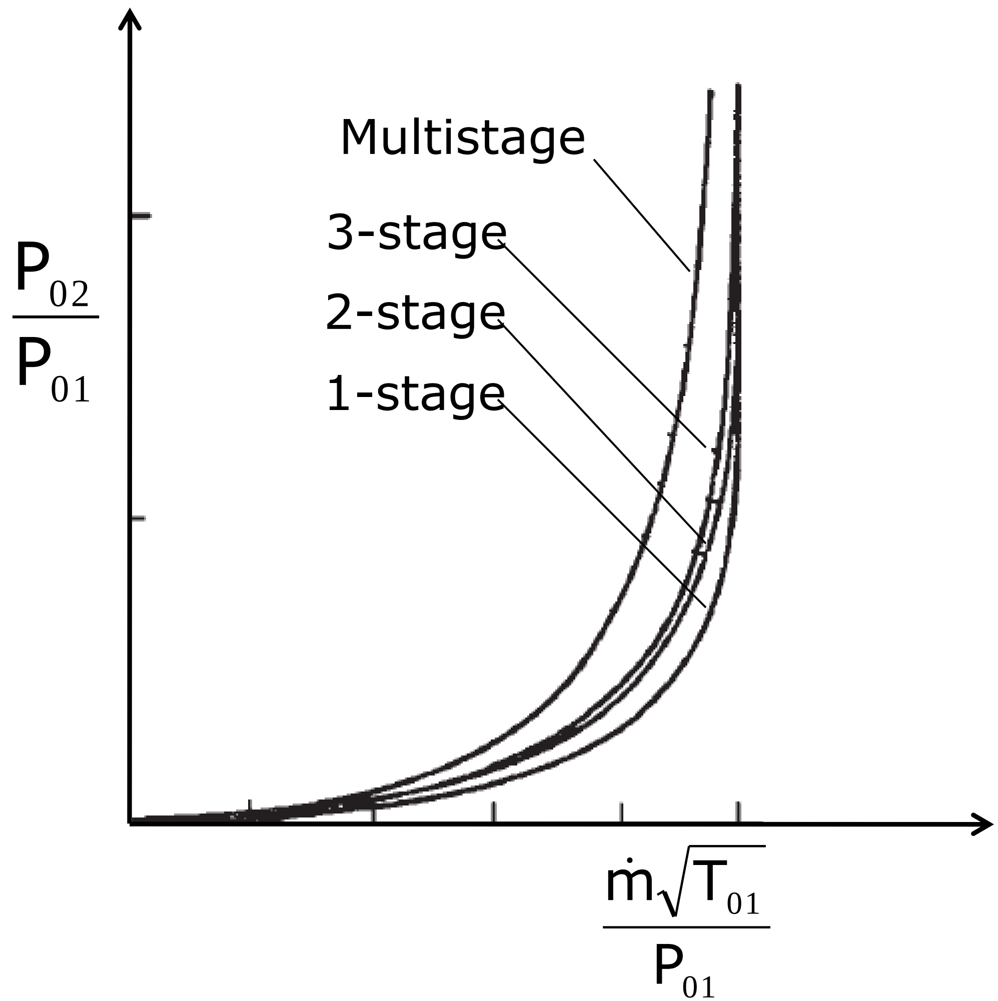
Axial turbine performance

- The efficiency plot shows that it is constant over a wide range of rotational speeds and pressure ratios.
- This is because the accelerating nature of the flow permits turbine blades to operate with a wide range of incidence.
- Maximum mass flow is limited by choking of the turbine.
- The mass flow characteristics tend to merge into a single curve independent of speed, for larger number of stages.

Axial turbine performance

- When the turbine operates close to its design point (low incidence), the performance curves can be reduced to a single curve.
- As the number of stages are increased, there is a noticeable tendency for the characteristic to become ellipsoidal.
- With increase in the number of stages, the choking mass flow also reduces.
- Stodola (1945) formulated the “ellipse law”, which has been used extensively by designers.

Axial turbine performance



Axial turbine performance

- The performance of turbines is limited by three factors:
  - Compressibility
  - Stress
  - Inlet temperature
- Compressibility limits the mass flow that can pass through a turbine.
- Stress limits the rotational speed.
- It is also known that the performance also strongly depends upon temperature.
- Temperature in turn affects the stress.
- Hence, in a design exercise, there must be a compromise between the maximum temperature and the maximum rotor speed.

Axial turbine performance

- For a given pressure ratio and adiabatic efficiency, the turbine work per unit mass is proportional to the inlet stagnation temperature.
- Therefore typically a 1% increase in the turbine inlet temperature can produce 2-3% increase in the engine output.
- Therefore there are elaborate methods used for cooling the turbine nozzle and rotor blades.
- Turbine blades with cooling can withstand temperatures higher than that permissible by the blade materials.

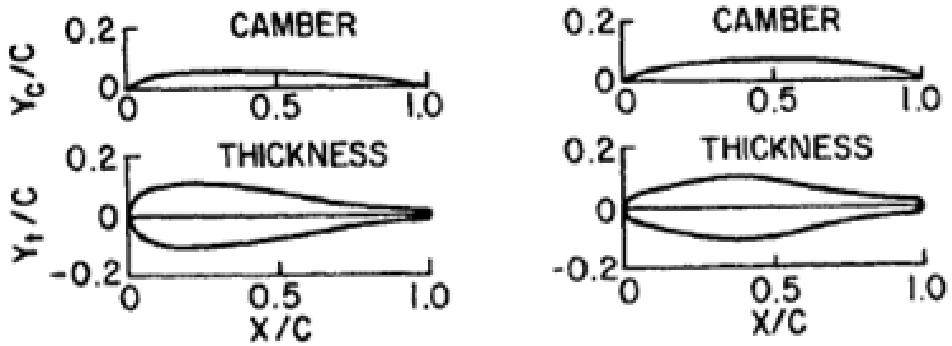
Axial turbine blades

- Blade shapes used in turbines are quite different from that used in compressors.
- The design of these blades depend upon the passage Mach number, stress levels and various other parameters.
- The thickness distributions, suction surface curvature and trailing edge shape are varied for particular applications.
- Turbine blades could be designed specifically for subsonic, transonic or supersonic Mach numbers.

Axial turbine blades

- Profiles can be generally classified as:
  - Profiles derived from various agencies like NACA, AGARD etc.
  - Profiles with circular arc and parabolic arc camber.
  - Profiles derived graphically or empirically from a specified pressure or Mach number distribution.
  - Each industry has developed their own proprietary profiles to meet their requirements.
  - Recent trend towards custom-designed or custom-tailored airfoils.

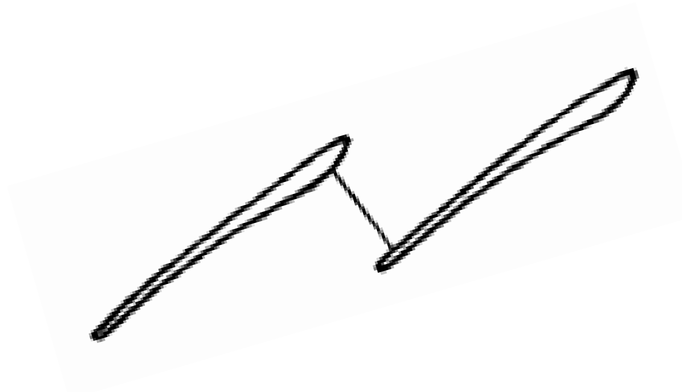
Axial turbine blades



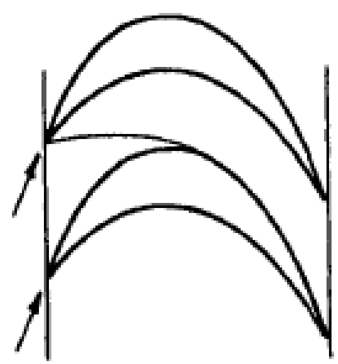
NACA basic turbine profiles

Profile for subsonic inlet and supersonic outlet

Axial turbine blades

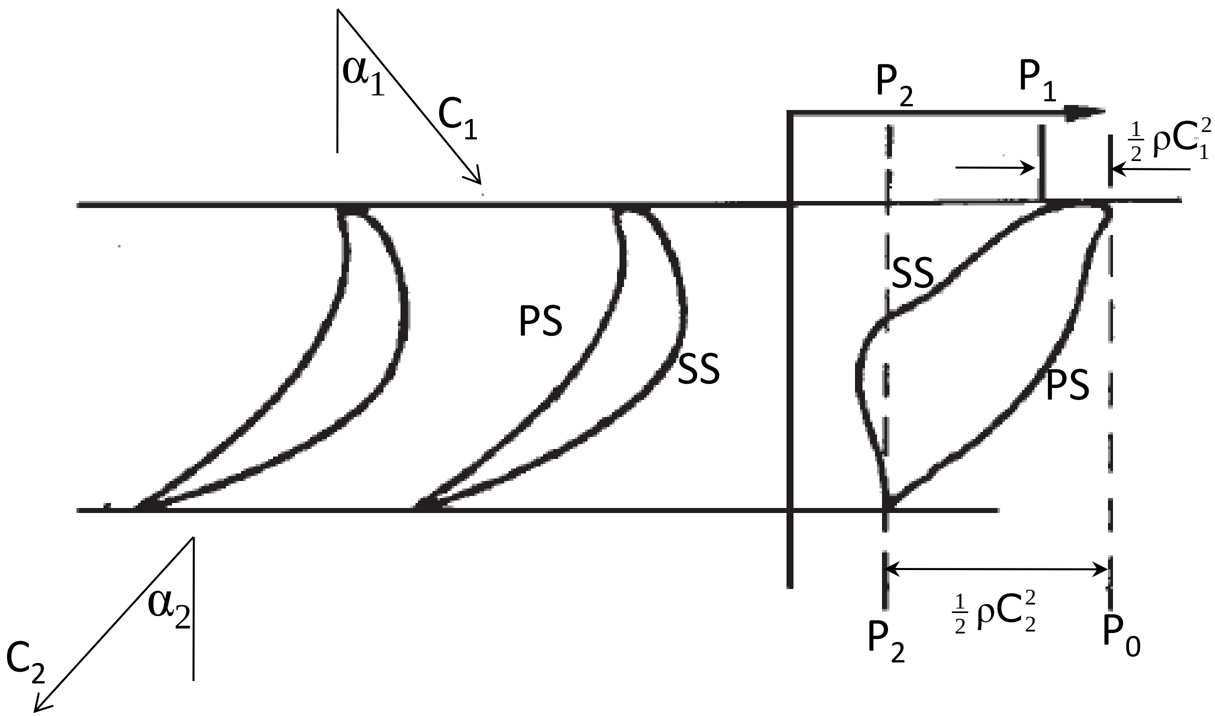


Typical steam turbine tip section airfoils



Profile for supersonic inlet and supersonic outlet

Axial turbine blades



Pressure distribution around a typical turbine blade

Axial turbine blades

- Spacing between blades is a critical parameter in turbomachine performance.
- Closer spacing means lower loading per blade, but more number of blades, increased weight and frictional losses.
- Larger spacing means higher blade loading and lower weight, losses etc.
- Optimum number of blades usually empirical.

$$\text{Zwifel}(1945)\ \text{criterion}: \quad Z = \frac{2F_W}{\rho V_2^2 C} \qquad F_W: \text{blade force; } C: \text{chord}$$

$$\text{This can be simplified as } Z = \frac{2F_W}{\rho V_2^2 C} = 2\cos^2\alpha_2 \frac{S}{C}\left(\tan\alpha_1 - \tan\alpha_2\right)$$

Axial turbine blades

- There are several differences between the flow through a turbine blade passage as compared with a compressor:
  - Pressure drop in a turbine is much larger than the pressure rise in a compressor.
  - The flow turning in a compressor: 20^o-35^o whereas in a turbine: as high as 160^o.
  - Turbine designer usually delays formation of shocks (to minimize losses); in a compressor shocks are one of the modes of deceleration.
  - Therefore transonic compressors usually have lower efficiency than transonic turbines.

Exit flow matching

- The operation of a turbine is affected by components upstream (compressor) and downstream (nozzle).
- The compressor and turbine performance characteristics form an important part of this performance matching.
- It was discussed earlier that turbines do not exhibit any significant variation in non-dimensional mass flow with speed.
- However the turbine operating region is severely affected by the nozzle.

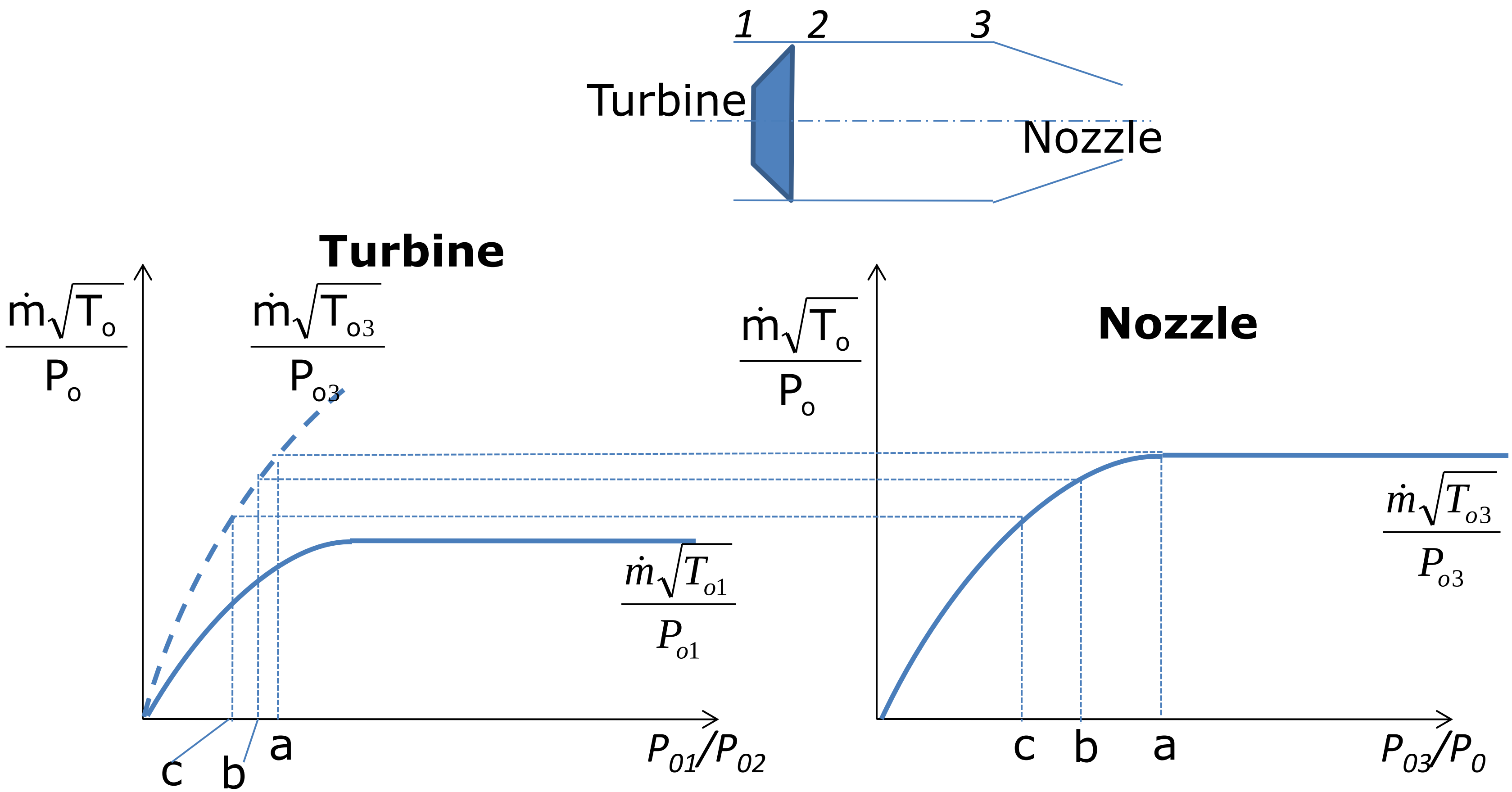
Exit flow matching

- The nozzle exit area has a significant influence on the off-design operation of a turbine and the engine in general.
- The operation of the nozzle under choked or unchoked condition also influences the matching.
- The similarity between the flow characteristic of a nozzle and a turbine is the fact that thermodynamically, both are flow expanders.
- The matching between the turbine and the nozzle is identical to that between a free-turbine / power-turbine and the main turbine.

Exit flow matching

- Once the nozzle is choked, the nozzle non-dimensional flow will reach its maximum value and will become independent of the nozzle pressure ratio and therefore the flight speed.
- This results in the turbine operating point getting fixed because of matching requirement between turbine and nozzle.
- Therefore, when the nozzle is choking, the equilibrium running line will be uniquely determined by the fixed turbine operating point and will be independent of flight speed.

Exit flow matching



Matching characteristics of turbine and nozzle

Exit flow matching

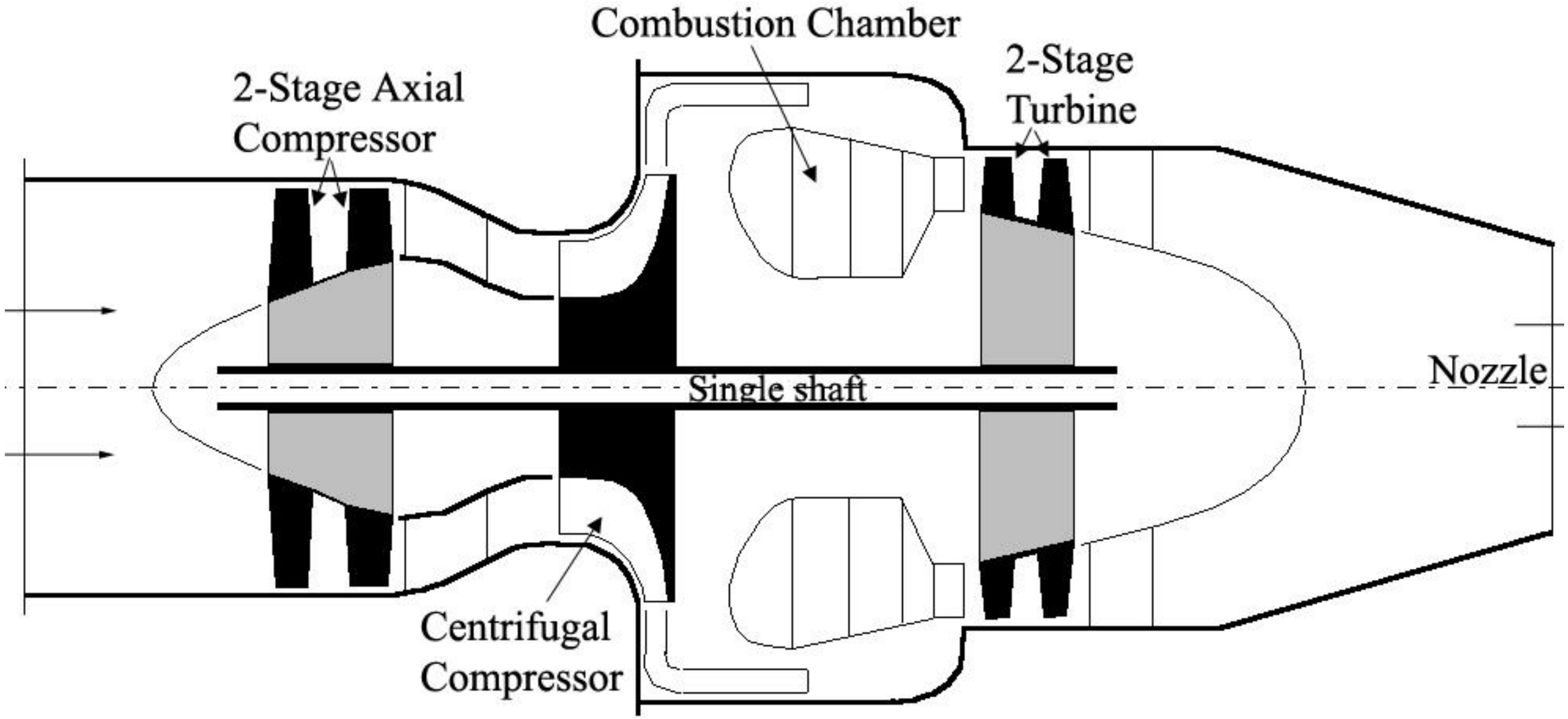
- Most of the modern engines operate with choked nozzle during majority of the operation.
- Only when the engine is operating with a low thrust say, when preparing to land or taxiing, the nozzle may be un-choked.
- Therefore at low speeds too, one must ensure that the matching is maintained as at low speeds, the operating line is closer to the surge line of the compressor.

Multi-staging

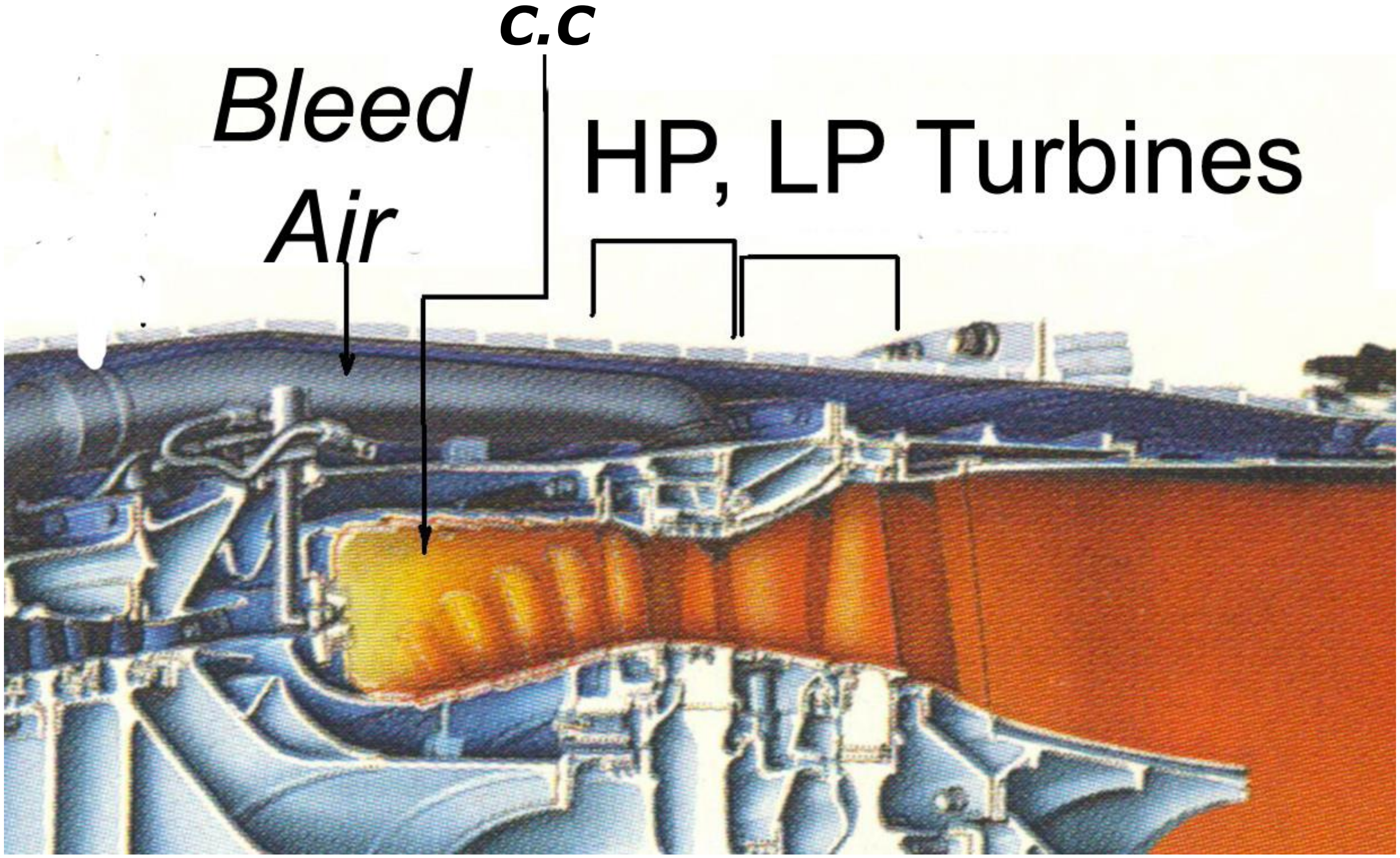
- Requirement for multi-staging of turbines comes from the aggregate of shaft work that needs to be produced.
- Typically if turbine pressure ratio requirement is more than 2.5 / 3.0 - multi-staging is required.
- As compression ratio over the years have kept on increasing, multi-staging has become inevitable in all aero-engines.
- Number of integer stages to be decided by the state of art of turbine design

Multi-spooling of Turbines

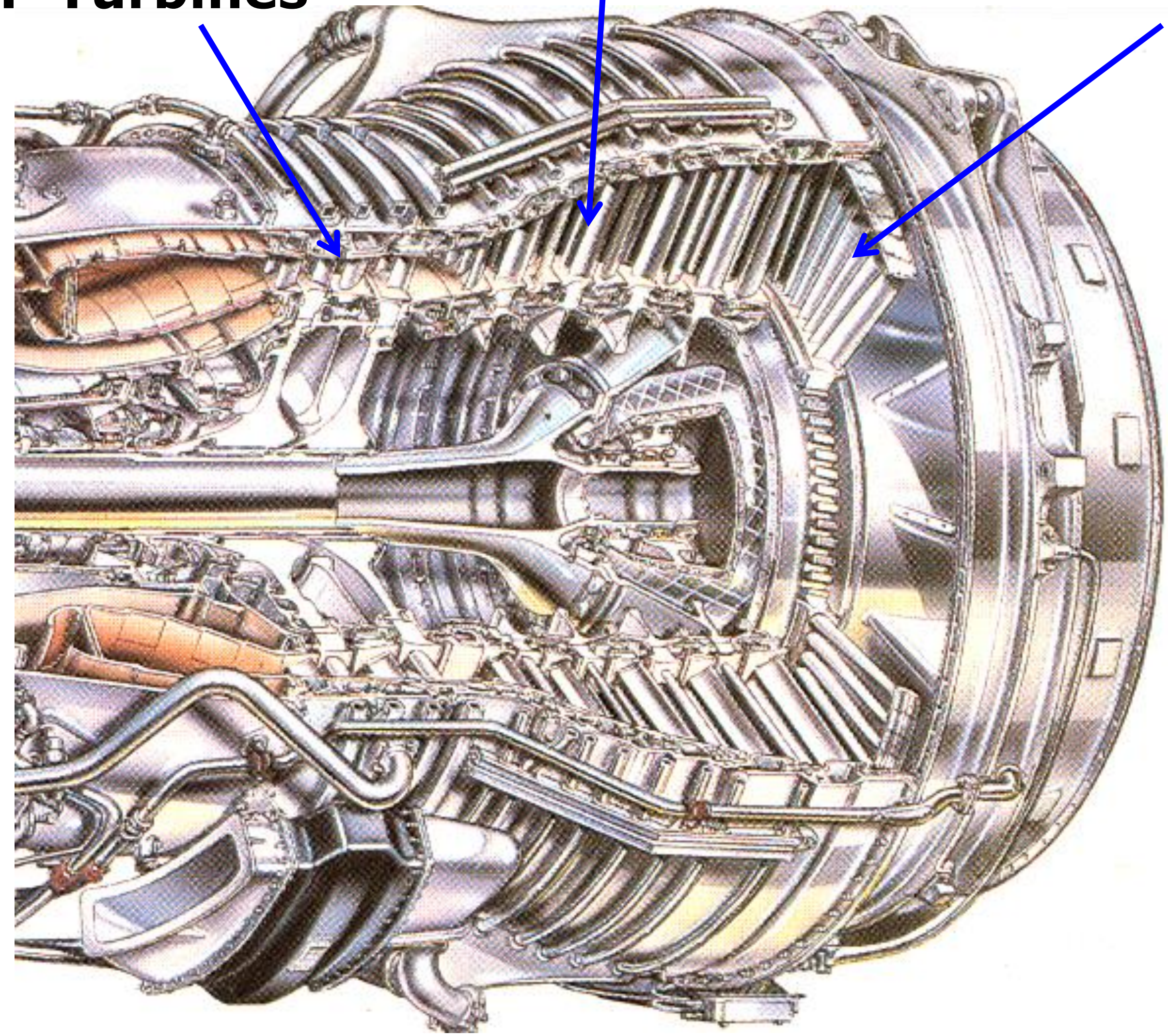
- Multi-spooling of turbines is necessary if the compressors have been split in more than one spool
- Multi-spooling is necessary in a turbo-prop engine if the propeller is needed to be run separately (with a gear box)
- Most modern aero-engines are 2-spool engines and there are a few with 3-spool arrangements



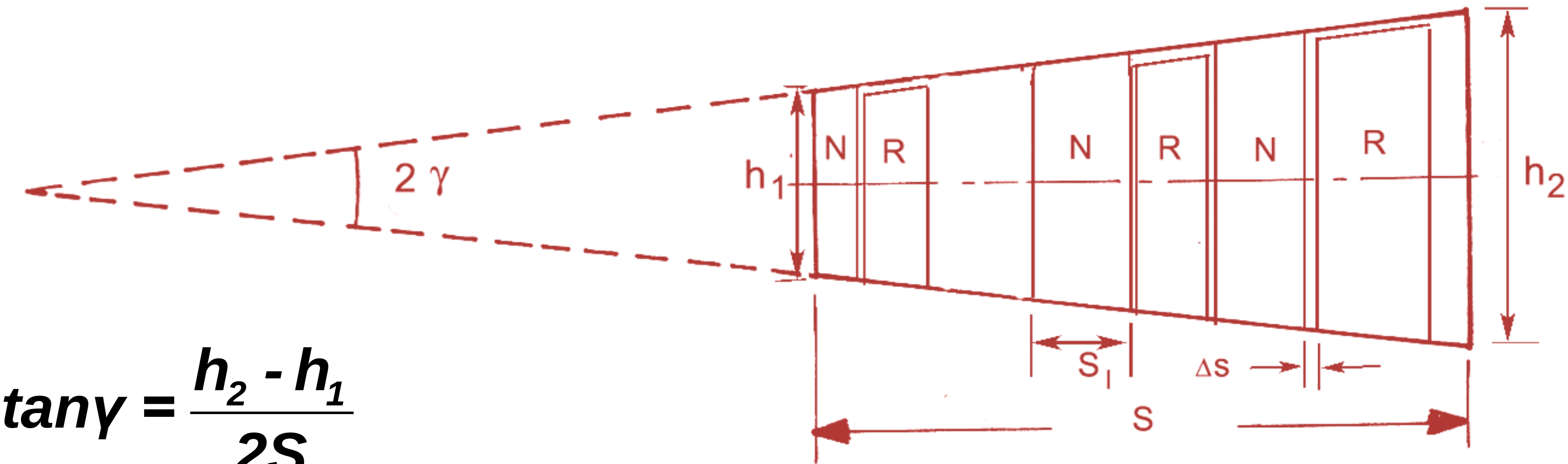
A single spool engine with multi-staged turbine



Multi-stage HP + LP turbine layout: Military Engine



3-spool Civil aircraft engine



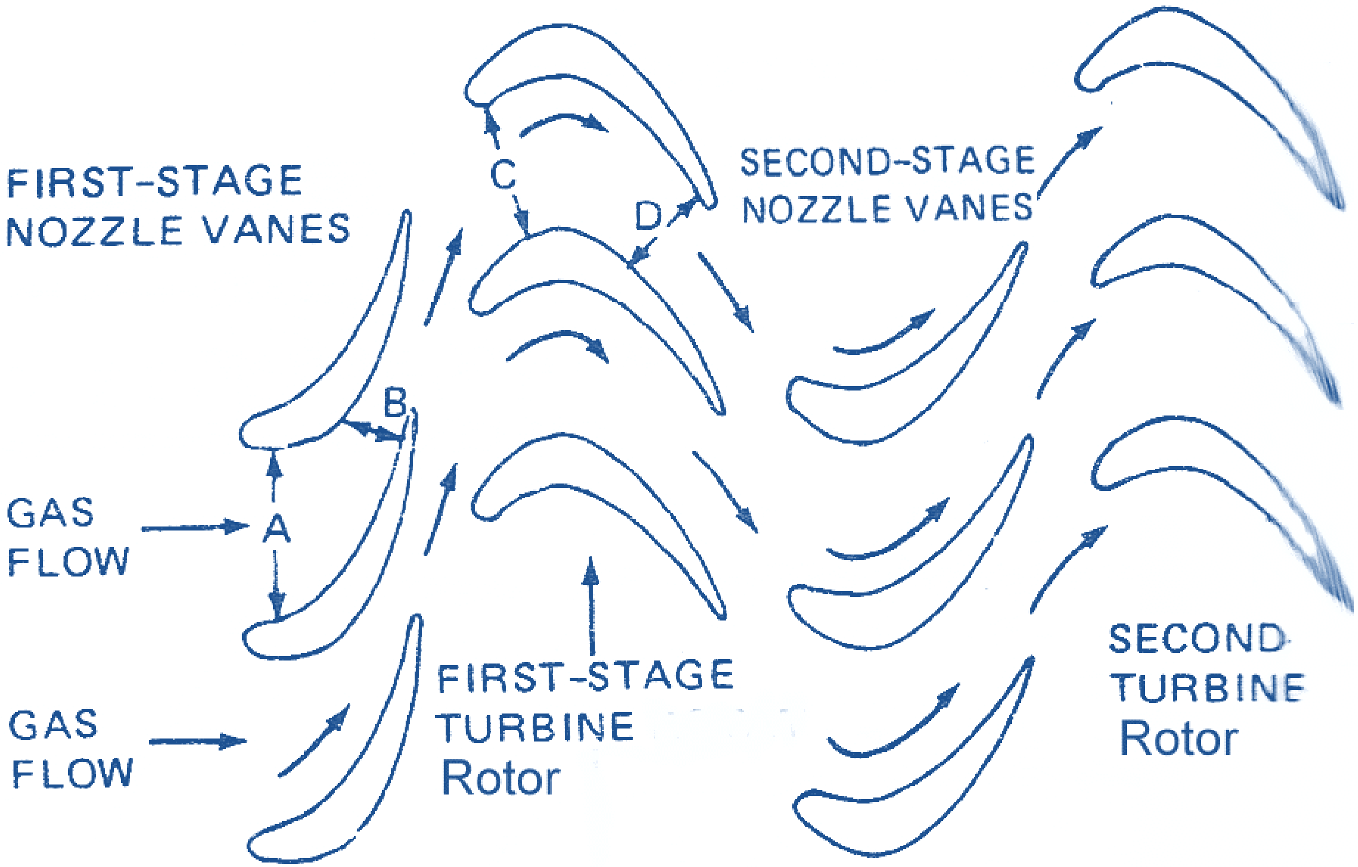
$$\tan\gamma = \frac{h_2 - h_1}{2S}$$

$$S = \Sigma\Delta S + \Sigma S_i = \Delta S.Z_p + S_i.Z$$

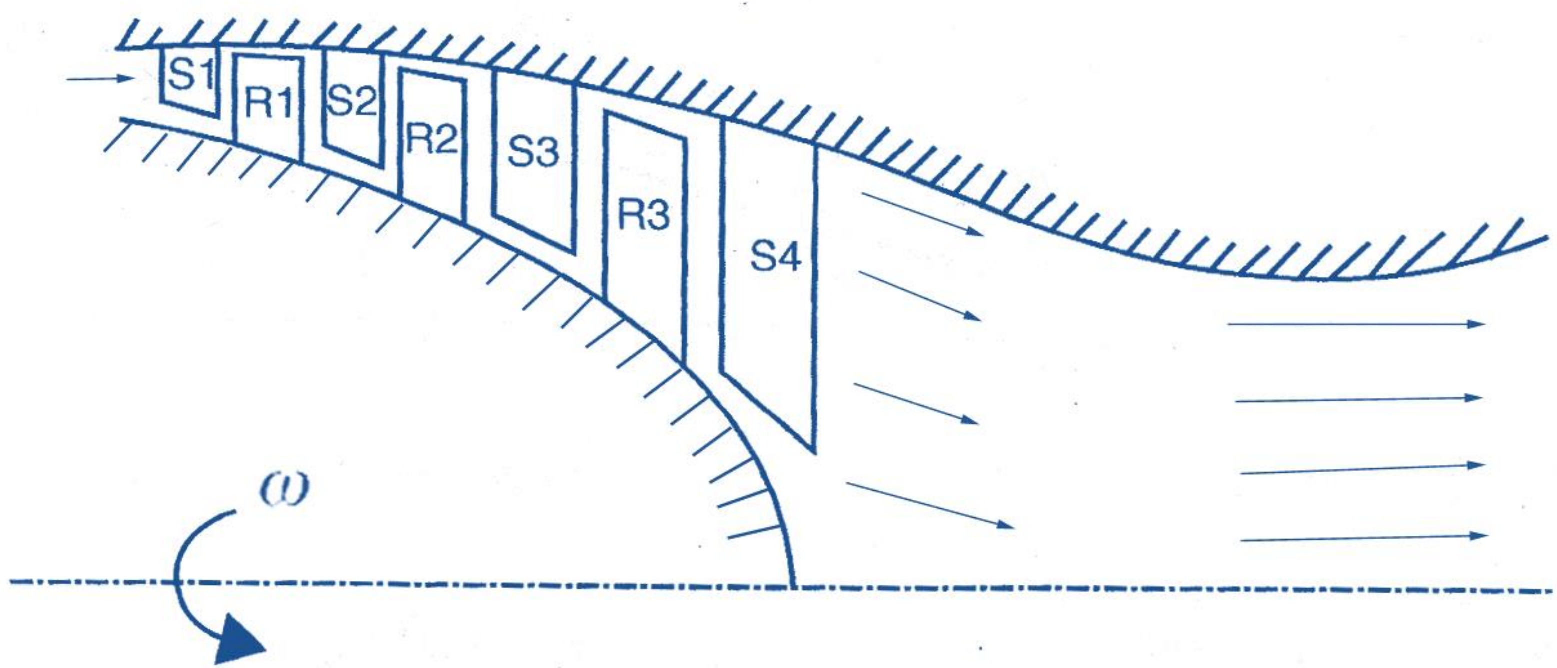
where Z is the number of stages, and $Z_p = 2.Z-1$

$$\tan\gamma = \frac{h_2 - h_1}{2Z_p\left(S_i + \Delta S\right)} = \frac{S_i\left(\overline{h_2} - \overline{h_1}\right)}{2Z_p S_i\left(1 + \frac{\Delta S}{S_i}\right)} = \frac{\overline{h_2}\left(1 - \frac{\overline{h_1}}{\overline{h_2}}\right)}{2Z_p\left(1 + \frac{\Delta S}{S_i}\right)}$$

Flow through the blades is non-axial and varies from the root to the tip



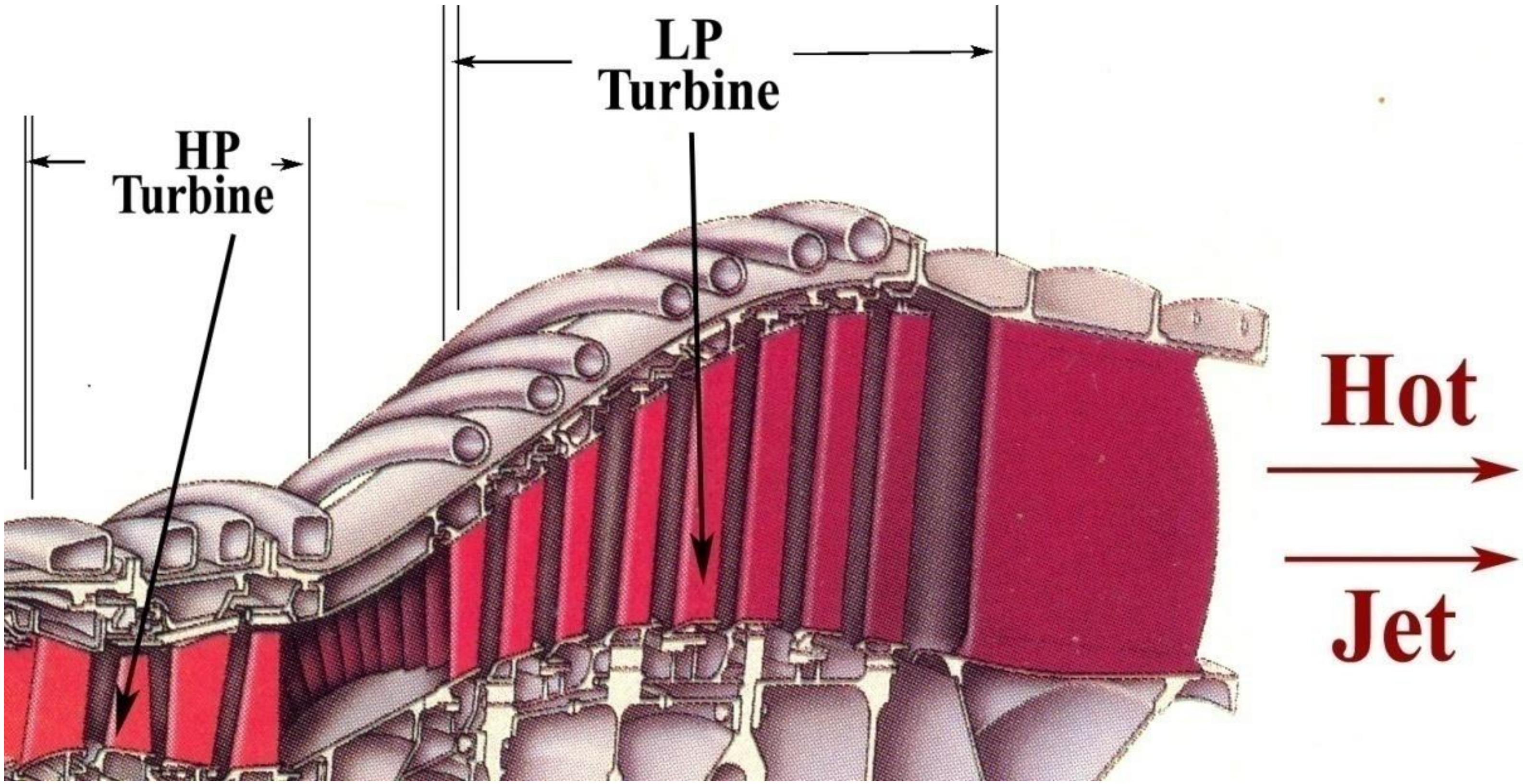
Axial Flow track in modern multi-stage turbines is often curved



Multi-stage flow analysis

- Flow track design decision comes from continuous application of continuity condition
- The track is diverging in axial direction
- Flow paths through the blades are generally in curved converging passages.
- This, thus, requires application of 3-D flow analysis to get accurate notion of the flow
- Most modern turbines are analyzed using 3-D CFD analytical techniques

Multi-staging of Turbine

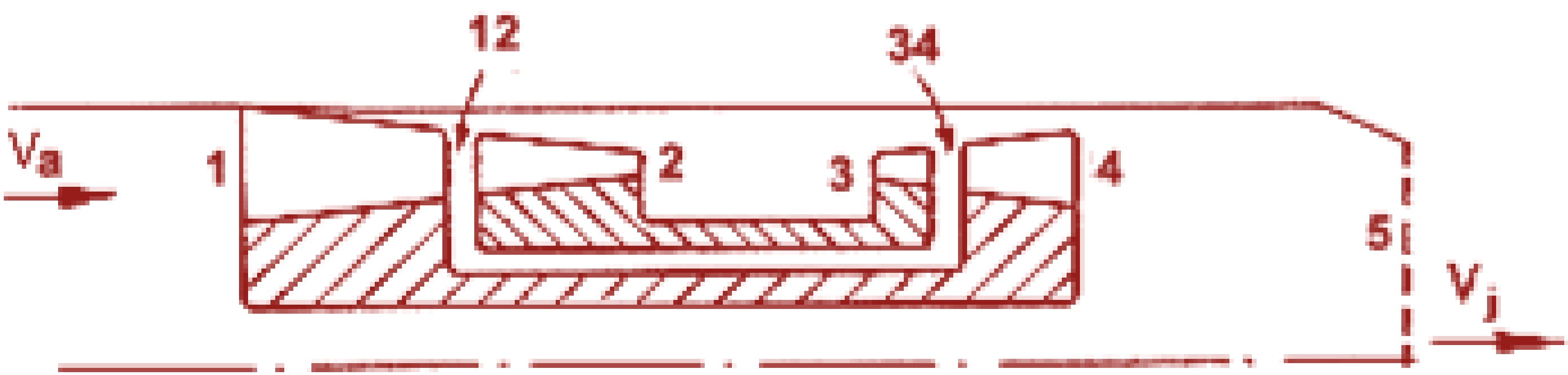


Multi-stage HP + LP turbine layout; Civil Engine

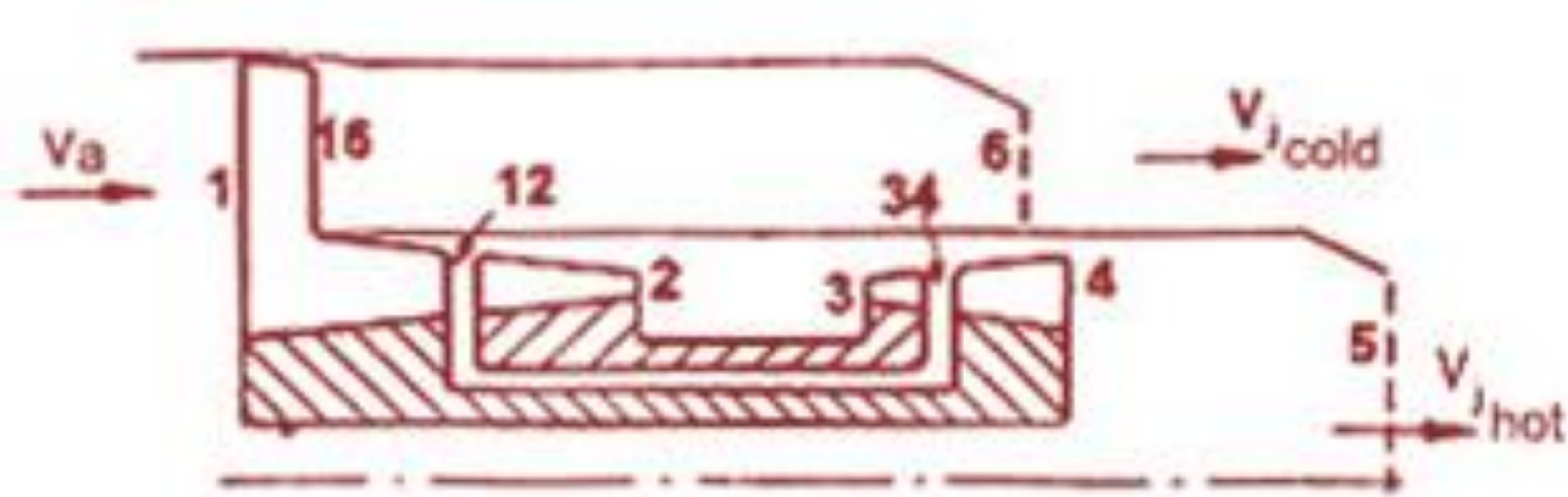
Compressor Turbine Matching

SINGLE SPOOL ENGINE

TWO-SPOOL TURBOJET



TWO-SPOOL HIGH BYPASS TURBOFAN ENGINE



Two – spool arrangement

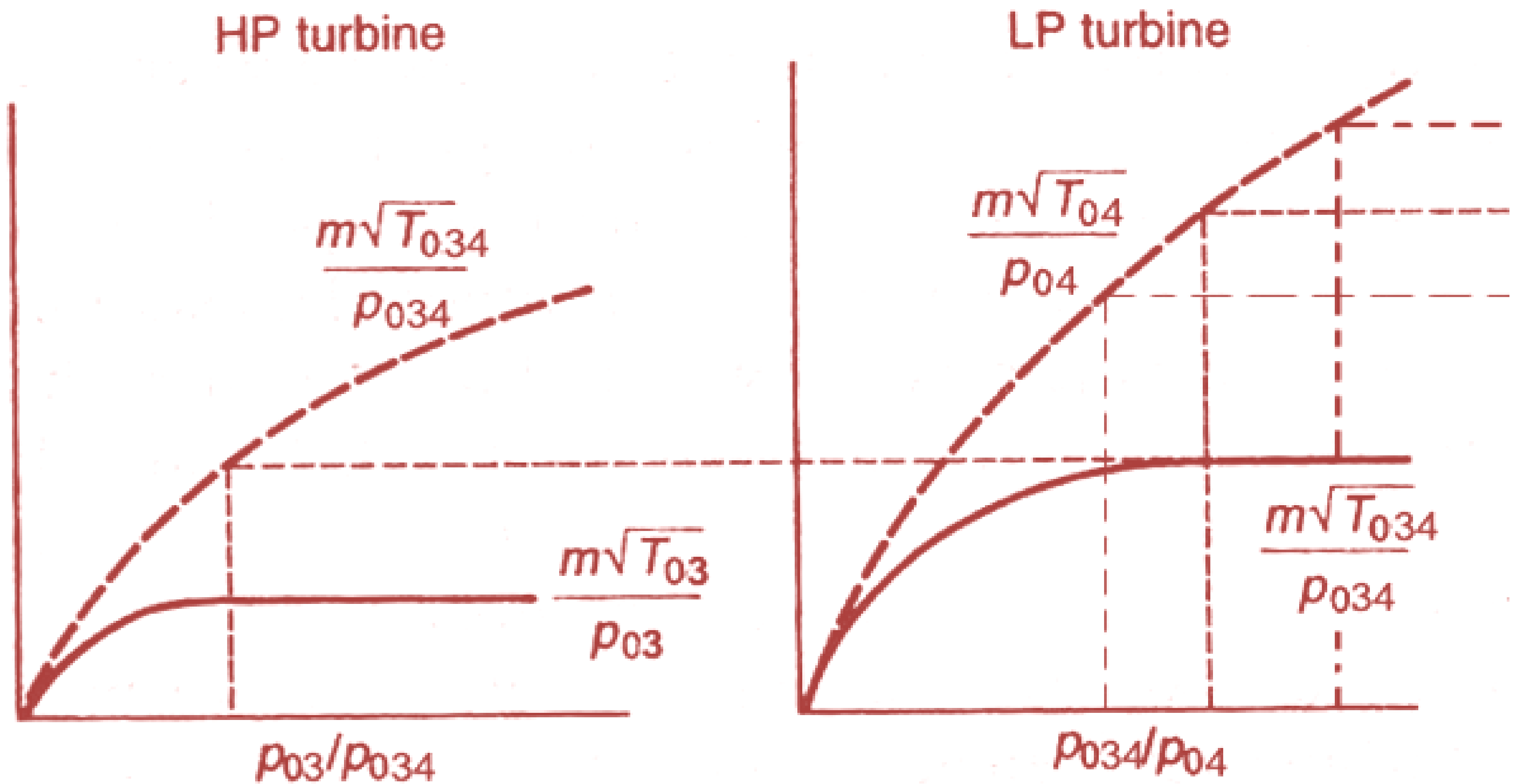
HP turbine:

$$W_{HP}/\ m = C_{pg}.(T_{03} - T_{034})$$
$$= C_{pg}.T_{03}\,(1 - T_{034}\,/\,T_{03})$$
$$= C_{pg}.k_{HP}.T_{03}$$

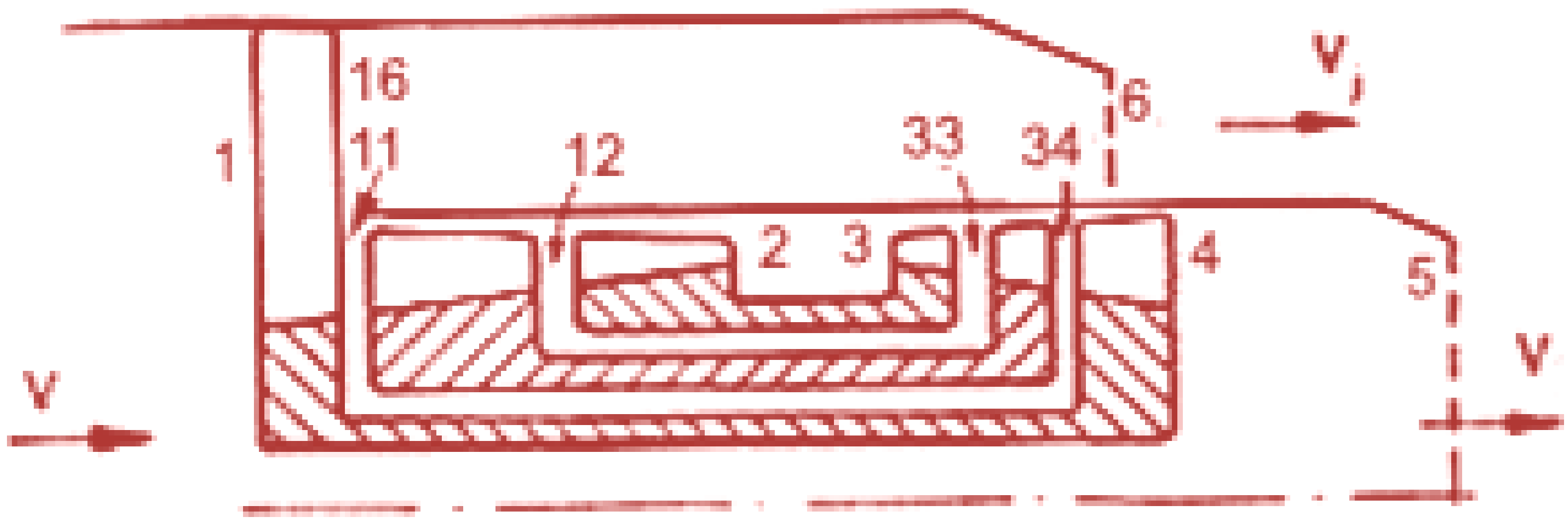
LP turbine:

$$W_{LP}/\ m = C_{pg}.(T_{034} - T_{04})$$
$$= C_{pg}.T_{034}\,(1 - T_{04}\,/\,T_{034})$$
$$= C_{pg}.k_{LP}.T_{03}$$

Turbine Spool Matching



THREE-SPOOL HIGH BYPASS TURBOFAN ENGINE



Three spool engine