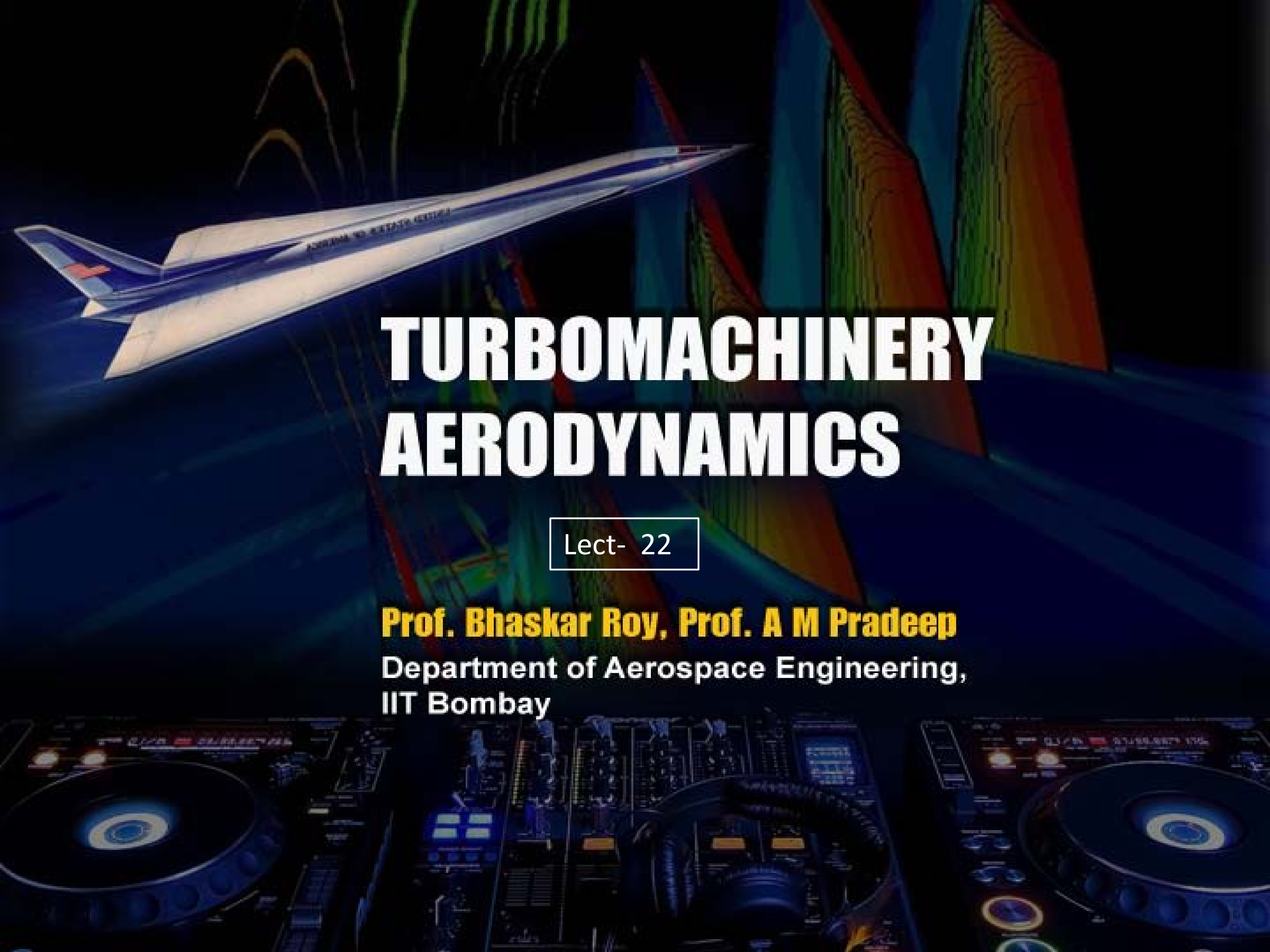

TURBOMACHINERY AERODYNAMICS

Lect- 22

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In this lecture...

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

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

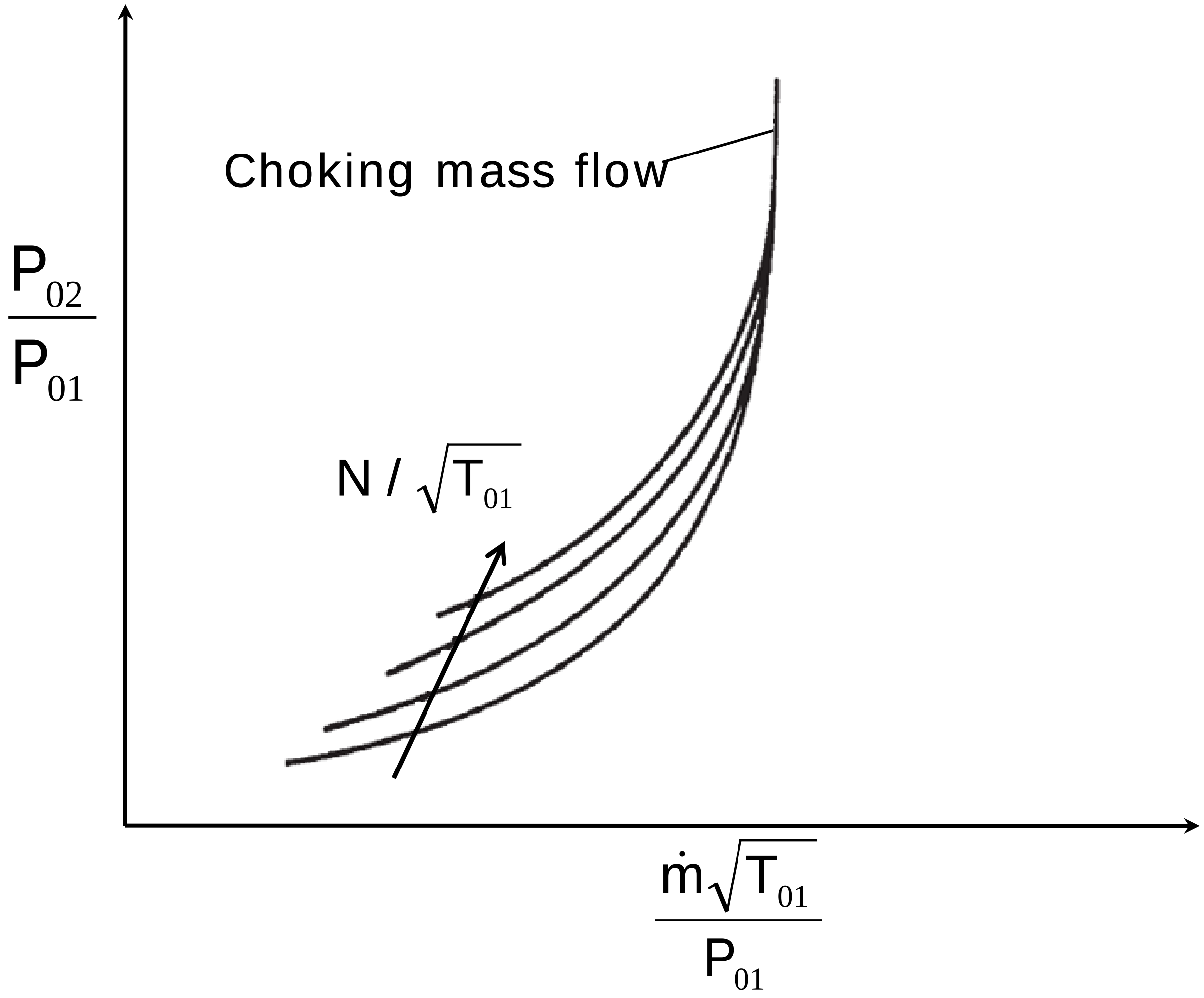
In a similar manner, we can define performance characteristics for a turbine as well.

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

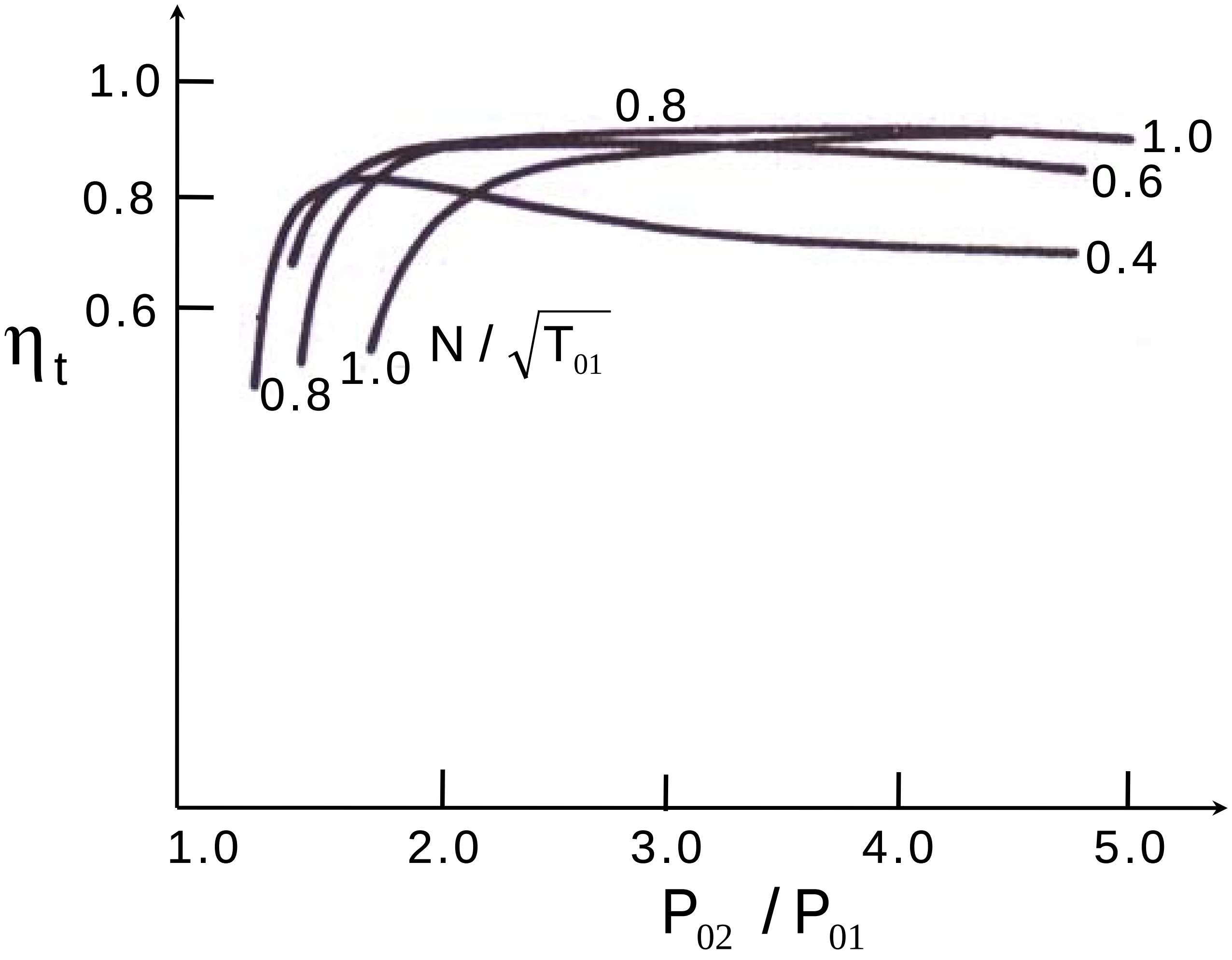
$$\frac{P_{02}}{P_{01}}, \eta_C = f\left(\frac{\dot{m}\sqrt{T_{01}}}{P_{01}}, \frac{N}{\sqrt{T_{01}}}\right)$$

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

Axial turbine performance



Axial turbine performance



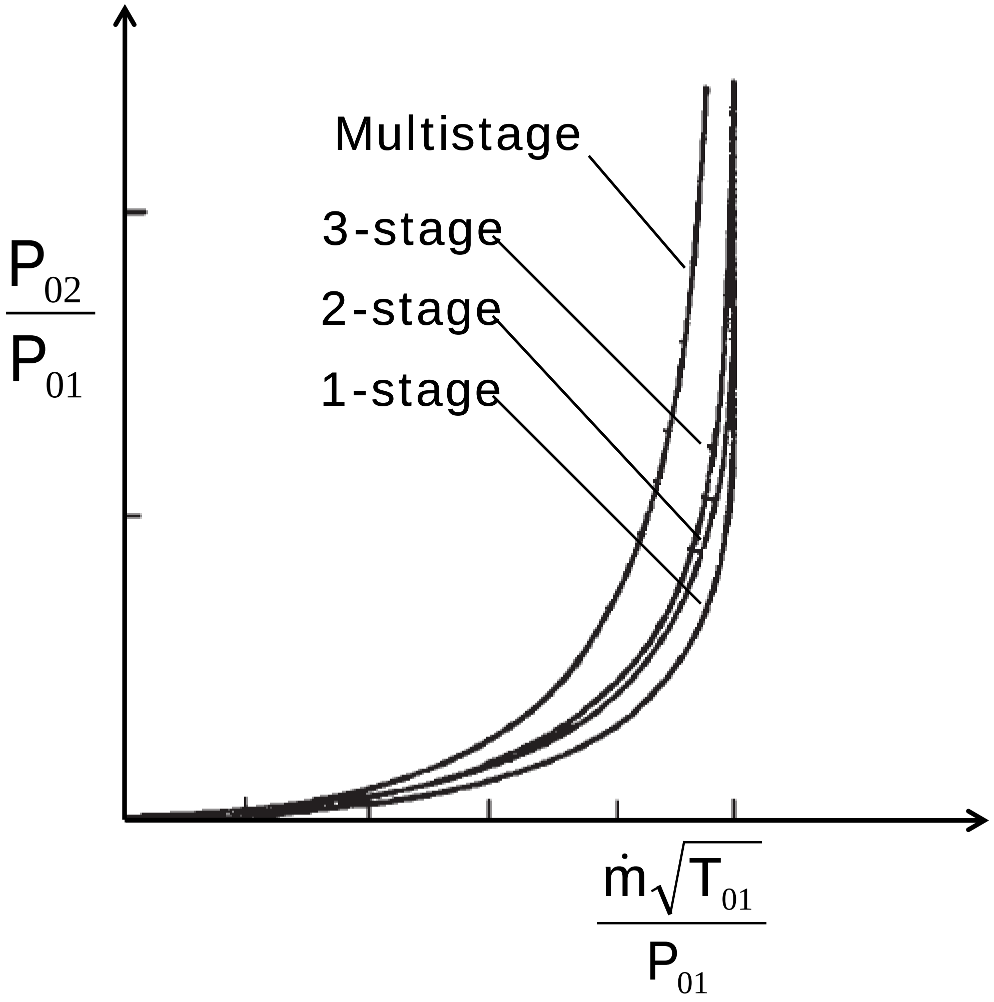
Axial turbine performance

- 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 two 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.

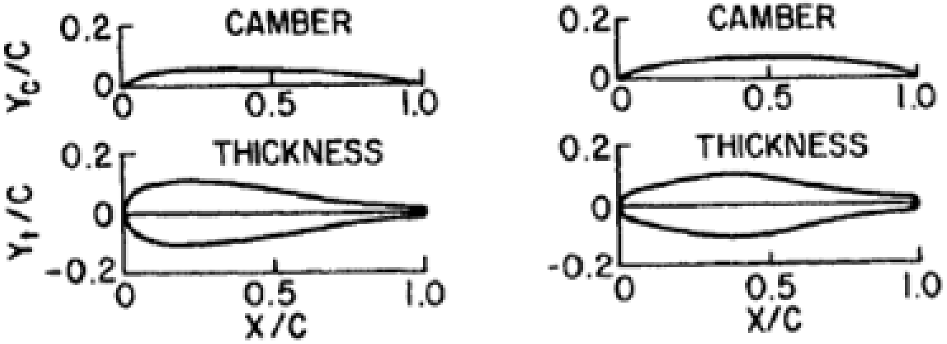
Axial turbine blades

- 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.

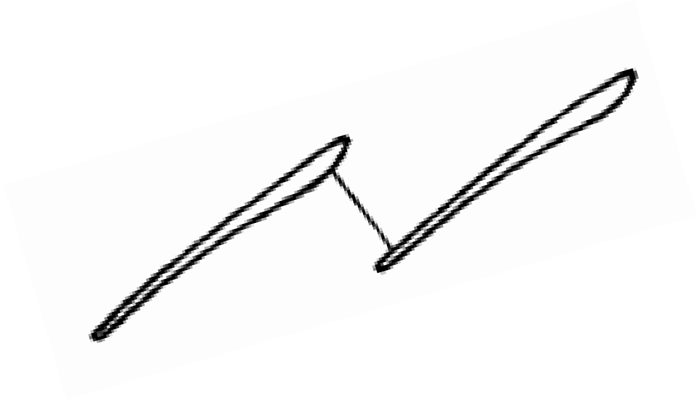
Axial turbine blades



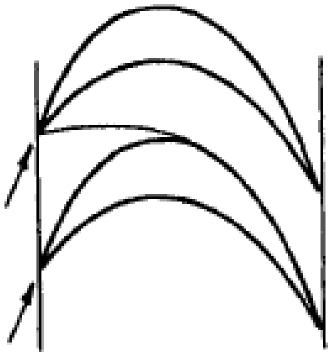
NACA basic turbine profiles

Profile for subsonic inlet and supersonic outlet

Axial turbine blades

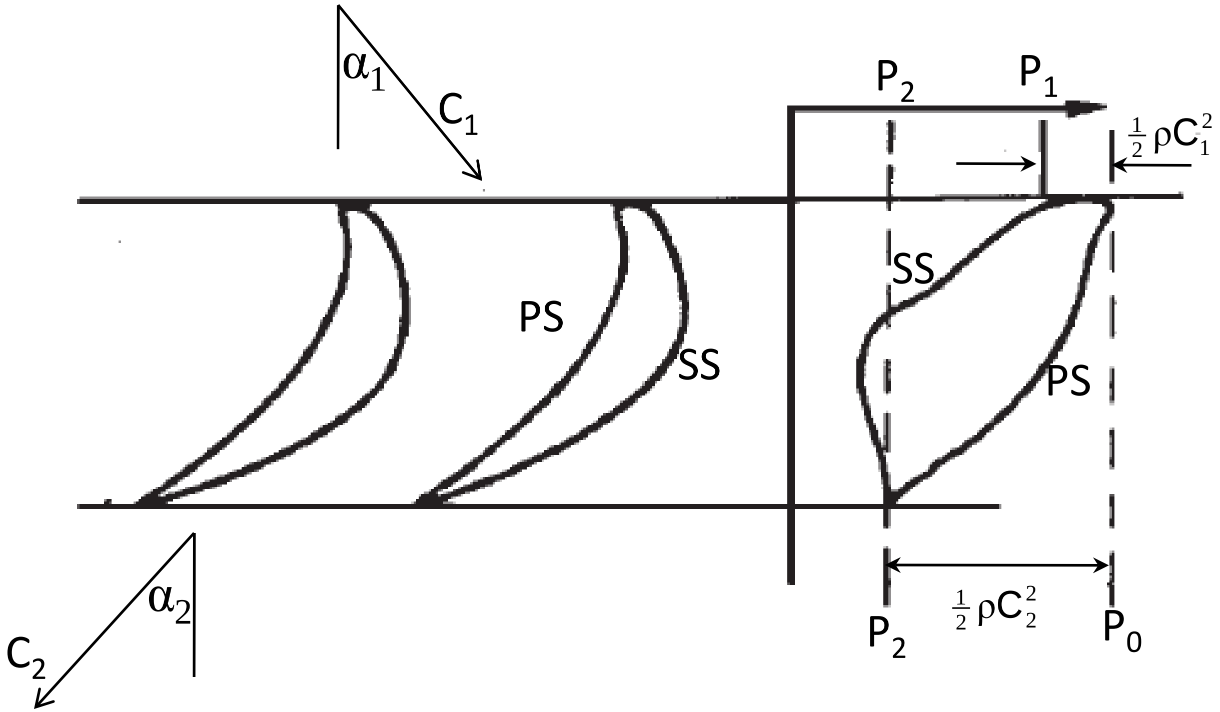


Typical steam turbine tip section airfoils



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.

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

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

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°-35° whereas in a turbine: as high as 160°.
  - 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.

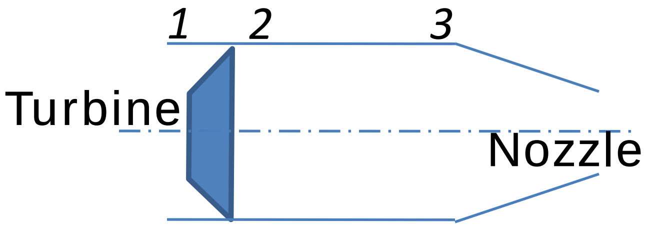
Exit flow matching

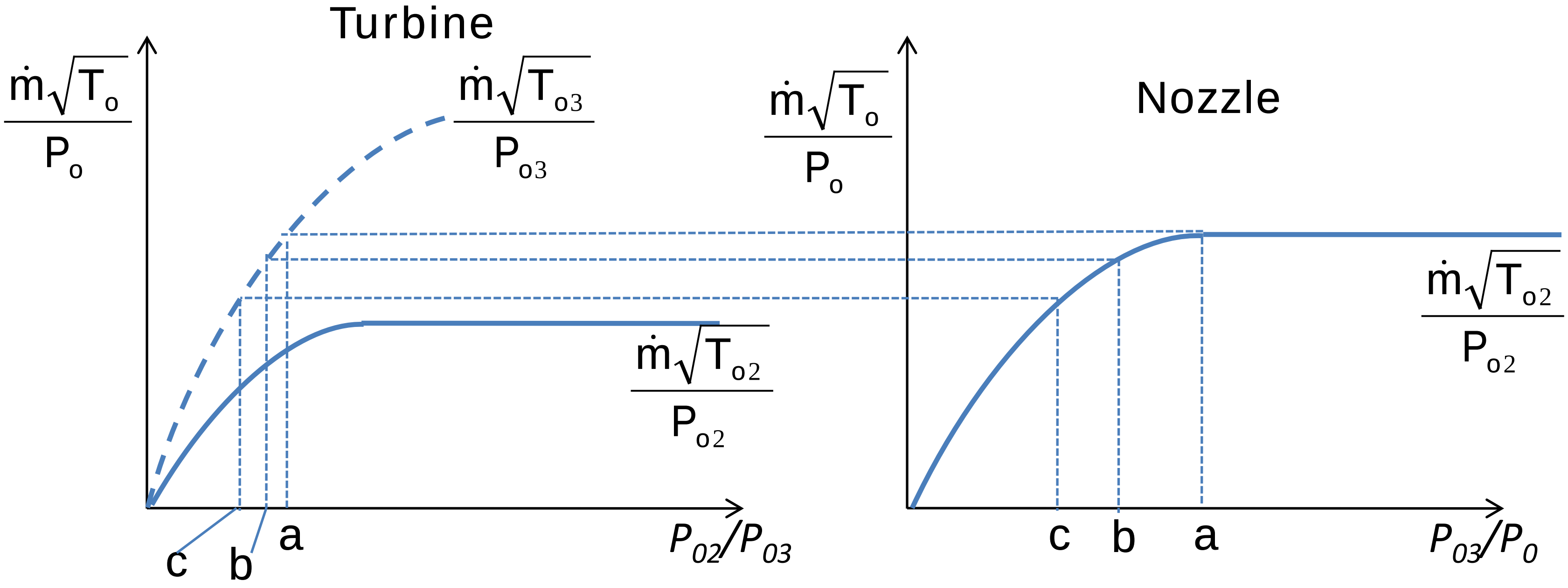
- The nozzle exit area has a significant influence on the off-design operation of a turbine and the engine in general.
- The operation of the nozzle under choked or unchoked condition also influences the matching.
- The similarity between the flow characteristic of a nozzle and a turbine is the fact 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 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.

In this lecture...

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

In the next lecture...

- Tutorial on axial flow turbines