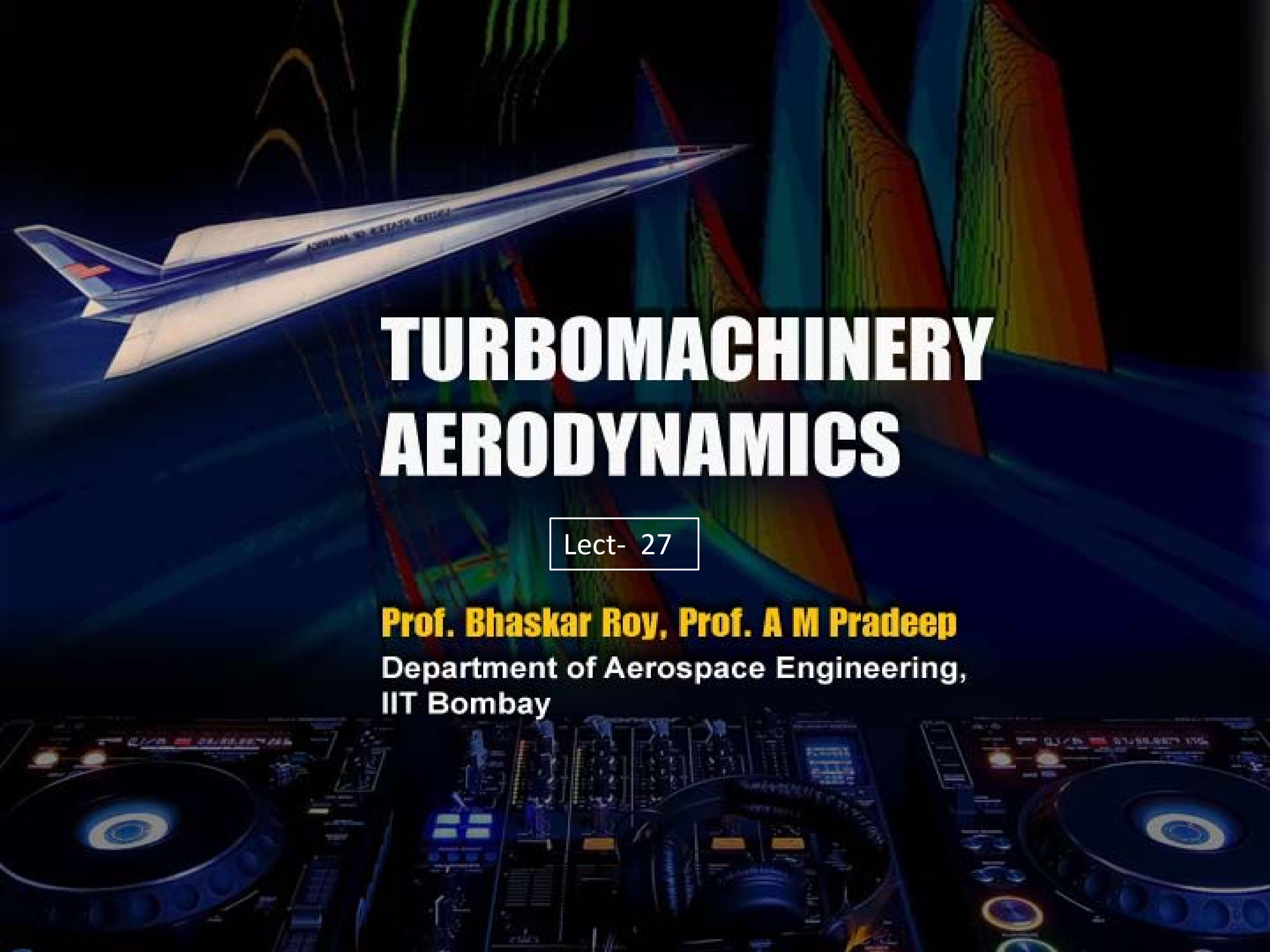


TURBOMACHINERY AERODYNAMICS

Lect- 27

Prof. Bhaskar Roy, Prof. A M Pradeep

Department of Aerospace Engineering,
IIT Bombay

In this lecture...

- Turbine Blade Cooling
    - Blade cooling requirements
    - Fundamentals of heat transfer

Turbine blade cooling

- 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 cause 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.

Turbine blade cooling

- Thrust of a jet engine is a direct function of the turbine inlet temperature.
- Brayton cycle analysis, effect of maximum cycle temperature on work output and efficiency.
- Materials that are presently available cannot withstand a temperature in excess of 1300 K.
- However, the turbine inlet temperature can be raised to temperatures higher than this by employing blade cooling techniques.
- Associated with the gain in performance is the mechanical, aerodynamic and thermodynamic complexities involved in design and analysis of these cooling techniques.

Turbine blade cooling

- The environment in which the nozzles and rotors operate are very extreme.
- In addition to high temperatures, turbine stages are also subjected to significant variations in temperature.
- The flow is unsteady and highly turbulent resulting in random fluctuations in temperatures.
- The nozzle is subjected to the most severe operating conditions.

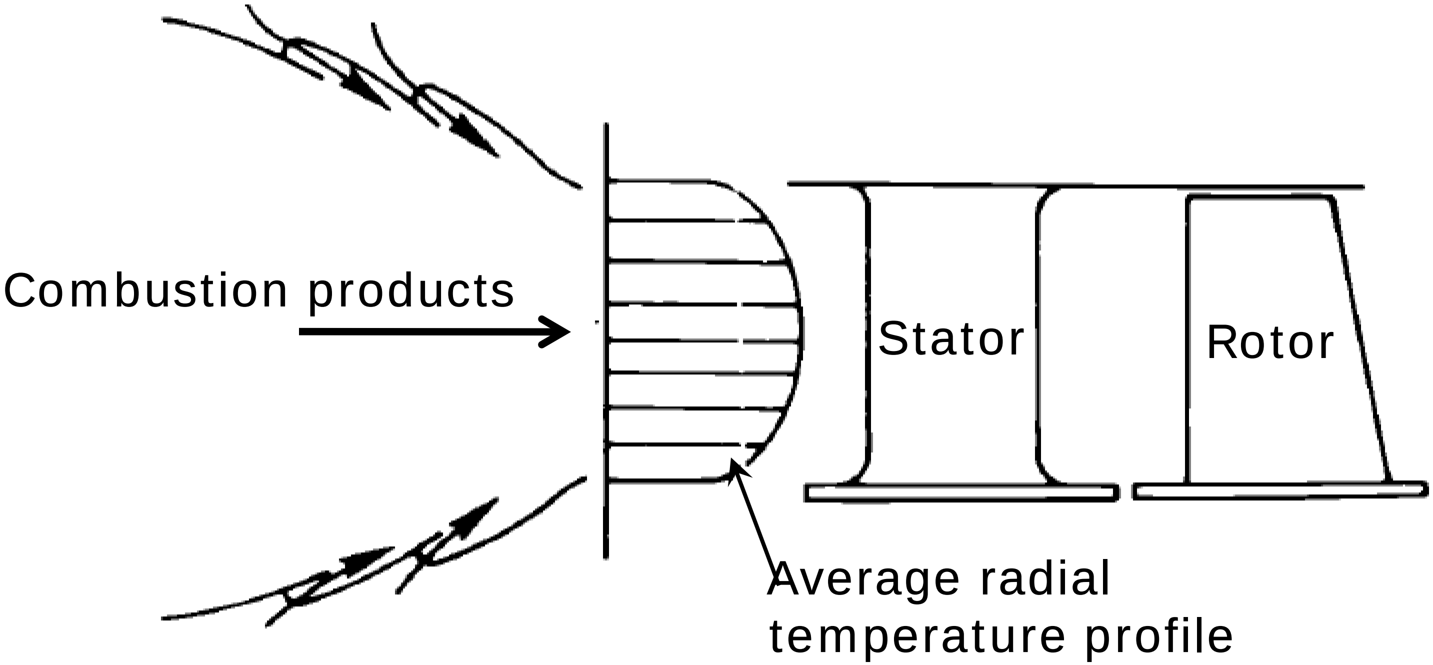
Turbine blade cooling

- Because the relative Mach number that the rotor experiences, it perceives lower stagnation temperatures (about 200-300 K) than the nozzle.
- However the rotor experience far more stresses due to the high rotational speeds.
- The highest temperatures are felt primarily by the first stage.
- Cooling problems are less complicated in later stages of the turbine.

Turbine blade cooling

- There are several modes of failure of a turbine blade.
  - Oxidation/erosion/corrosion
    - Occurs due to chemical and particulate attack from the hot gases.
  - Creep
    - Occurs as a result of prolonged exposure to high temperatures.
  - Thermal fatigue
    - As a result of repeated cycling through high thermal stresses.

Turbine blade cooling



Average temperature profile entering a turbine stage

Fundamentals of heat transfer

- Turbine blade cooling involves application of concepts of heat transfer.
- Heat transfer is a well established area and substantial knowledge base is available in the form of books, journals and other forms of literature.
- We shall take a brief overview of the concepts of heat transfer that are required for understanding of the problems involved in turbine blade cooling.

Fundamentals of heat transfer

- There are three modes of heat transfer
  - Conduction
  - Convection
  - Radiation
- Conduction
  - Heat transfer between two bodies or two parts of the same body through molecules which are more or less stationary.
  - In liquids and gases, conduction results from transport of energy by molecular motion near the walls and in solids it takes place by a combination of lattice vibration and electron transport.

Fundamentals of heat transfer

  - Conduction involves energy transfer at a molecular level with no movement of macroscopic portions of matter relative to one another.
- Convection
  - Involves mass movement of fluids
  - When temperature difference produces a density difference – leads to mass movement – Free convection
  - Caused by external devices like a pump, blower etc. Forced convection

Fundamentals of heat transfer

- Radiation
  - Energy transfer taking place through electromagnetic waves
  - Radiation does not require a medium
- For the temperatures that are encountered in a turbine, conduction and convection are the major modes of heat transfer.
- Radiative heat transfer is usually negligible and is normally not considered in turbine heat transfer analysis.

Fundamentals of heat transfer

- Heat transfer by conduction
  - The rate of heat transfer by conduction can be written as (Fourier's conduction law)

$$\frac{Q}{A} = q = -k\frac{dT}{dy}$$

Where, Q / A is the rate of heat transfer per unit area of the surface, and dT/dy is the temperature gradient.

k is the thermal conductivity defined as the amount of heat conducted per unit time per unit area per unit negative temperature gradient.

Fundamentals of heat transfer

The generalized governing equation is a three dimensional Poisson equation

$$\frac{k}{\rho c_p}\nabla^2 T = \frac{\partial T}{\partial t}$$

This is known as the Fourier equation. The parameter $\frac{k}{\rho c_p}$ is called thermal diffusivity and is a property of the conducting material.

Simplified forms of this equation has been used extensively over the years by several researchers.

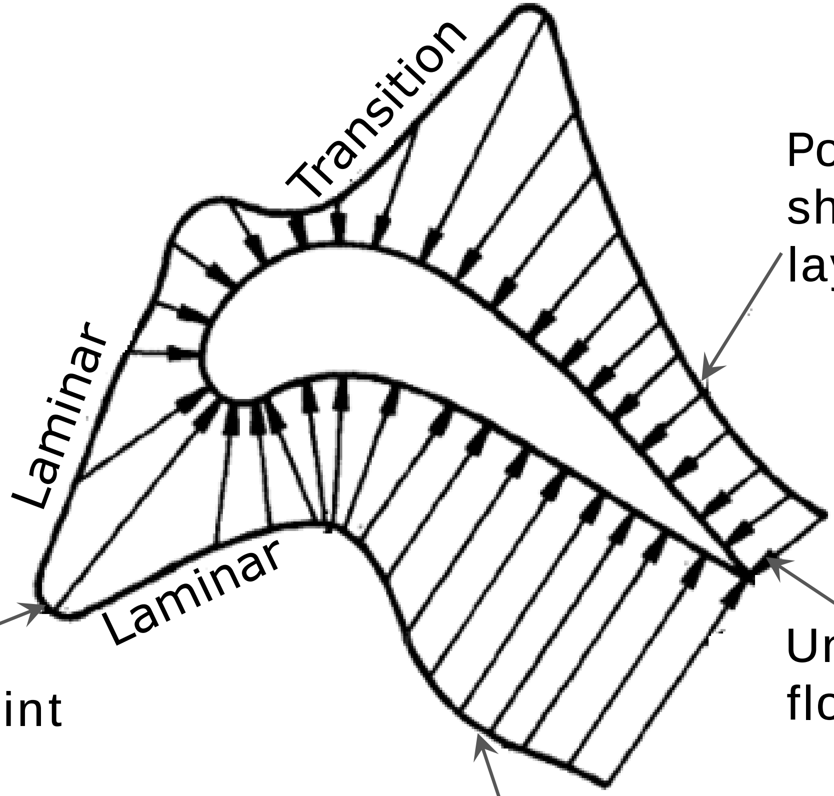
Fundamentals of heat transfer

- Heat transfer by convection
  - Unlike in a solid, heat transfer in a fluid can take place through conduction as well as convection.
  - In general, the temperature and velocity fields are coupled and have strong influence on each other.
  - In modern day turbines, velocity as well as temperature gradients are high.
  - Forced convection is the dominant phenomena in turbine flows.

Fundamentals of heat transfer

- In a typical turbine blade, the boundary layer developing on the blade surface and the freestream temperature are of interest.
- The boundary layer that acts as a buffer between the solid blade and the hot freestream, offers resistance to heat transfer.
- Heat transfer occurs in this viscous layer between the blade and the fluid through both conduction and convection.
- The nature of the boundary layer (laminar or turbulent) plays an important role in the heat transfer process.

Fundamentals of heat transfer



Possibility of shock-boundary layer interaction

Stagnation point

Unsteady wake flow

Possibility of transition followed by relaminarisation

Variation of heat transfer around a turbine blade

Fundamentals of heat transfer

- Due to close coupling between fluid mechanics and heat transfer, each of the regions around a blade require special analysis valid for that region.
- The overall heat transfer is related to the temperature difference between the fluid and the solid through the Newton's law of cooling:

$$q_w(x) = h(x)(T_r - T_w) = k\left(\frac{\partial T}{\partial y}\right)_w$$

where, $q_w(x)$ is the heat flux from the fluid to the wall,

$h(x)$ is the heat transfer coefficient.

Fundamentals of heat transfer

- The heat transfer coefficient is non-dimensionalised by the thermal conductivity and characteristic length:

$$Nu_x = \frac{h(x)L}{k} = \frac{L}{T_e - T_w}\left(\frac{\partial T}{\partial y}\right)_w$$

Nu_x is the Nusselt number.

- In addition to Nusselt number there are other important non-dimensional groups namely, Reynolds number (Re), Prandtl number (PR), Eckert's number (Ec), Grashof number (Gr) Richardson number (Ri) and Stanton number (St).
- All these numbers play a significant role in a transfer analysis depending upon the application.

Laminar boundary layer (forced convection)

Consider an incompressible laminar flow over a flat plate. We can write the transport equation for such a case as :

$$\frac{\partial(u\varphi)}{\partial x} + \frac{\partial(v\varphi)}{\partial y} = \alpha \frac{\partial^2 \varphi}{\partial y^2}$$

where, $\varphi = u$ or θ, $\alpha = \mu / \rho$ or $k / \rho c_p$ and $\theta = (T - T_w) / (T_e - T_w)$

The boundary conditions being :

$y = 0,\ \varphi = v = 0$ and $y \to \infty,\ \varphi = u = \theta = 1$

- The transport equations for velocity and temperature are similar and therefore the coupling is obvious.

Laminar boundary layer (forced convection)

- It can be shown that the heat transfer is related to the Reynolds number and Prandtl number through the Nusselt number.

$$\mathrm{Nu}_x = 0.332(\mathrm{Re}_x)^{1/2}(\mathrm{PR})^{1/3} = \frac{C_f}{2}(\mathrm{PR})^{1/3}\mathrm{Re}_x$$

- Heat transfer is a function of $(\mathrm{Re}_x)^{1/2}$ and $\mathrm{PR}^{1/3}$ and C_f.
- A thin boundary layer has a larger heat transfer.
- Therefore maximum heat transfer in a turbine blade occurs near the stagnation point and the leading edge.

Turbulent boundary layer (forced convection)

- The heat transfer due to turbulent fluctuations is written as:

$$q_t = \rho c_p \overline{v'T'} = -c_p \varepsilon_t \frac{\partial T}{\partial y}$$ where, ε_t is the eddy diffusivity.

- There is a close coupling between the momentum transfer and heat transfer, which in turn translates to coupling between heat flux and shear stress.
- We can therefore define the turbulent Prandtl number as

$$PR_t = \frac{\mu_t}{\varepsilon_t}$$

Turbulent boundary layer (forced convection)

Hence the ratio of heat flux and momentum flux is given by

$$\frac{q_t}{\tau_t} = -\frac{c_p(\partial T / \partial y)}{PR_t(\partial u / \partial y)}$$

The total rate of heat transfer due to both molecular and turbulent motions is

$$q = q_{molecular} + q_{turbulent} = -c_p\left(\frac{\mu}{PR} + \frac{\mu_t}{PR_t}\right)\frac{\partial T}{\partial y}$$

There is a clear difference between PR and PR_t. The Prandtl number (PR) is a physical property of the fluid, whereas the Turbulent Prandlt number (PR_t) is a property of the flowfield.

Turbulent boundary layer (forced convection)

For a flat plate with a turbulent boundary layer, the following equation is commonly used :

$$\mathrm{Nu}_x = 0.029(\mathrm{Re}_x)^{4/5}\mathrm{PR}^{1/3}$$

A general equation for both laminar and turbulent flow analysis can be written as $\mathrm{Nu}_x = A\mathrm{Re}_x^m \mathrm{PR}^n$

where, A, m and n are constants for a particular flow. This is called the Nusselt's equation.

Fundamentals of heat transfer

- Based on our discussion on laminar and turbulent flows:
  - Heat transfer is higher for a thin boundary layer than a thick boundary layer as the temperature gradient is higher for a thin boundary layer.
  - Heat transfer for a turbulent boundary layer is higher than a laminar boundary layer.
  - Heat transfer in thin viscous regions like stagnation point or leading edge, is very high. The velocity and temperature gradients are extremely high in these zones.

Turbine blade cooling

- In order to decide the cooling methodology to be used in a turbine blade, a very strong understanding of the heat transfer mechanisms are essential.
- Turbine blade cooling requires significant amount of compressor air (as high as 20%).
- The cooling air also mixes with the turbine flow leading to losses.
- Due to the above, vigorous analysis is carried out to minimize the amount of cooling as well as the negative aerodynamic effects of cooling.

In this lecture...

- Turbine Blade Cooling
  - Blade cooling requirements
  - Fundamentals of heat transfer