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

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:

\[ \text{Nu}_x = \frac{h(x) L}{k} = \frac{L}{T_e - T_w} \left( \frac{\partial T}{\partial y} \right)_w \]

\[ \text{Nu}_x \] 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:

\[
\frac{\partial (u\phi)}{\partial x} + \frac{\partial (v\phi)}{\partial y} = \alpha \frac{\partial^2 \phi}{\partial y^2}
\]

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

The boundary conditions being:

\( y = 0, \phi = v = 0 \) and \( y \to \infty, \phi = u = \theta = 1 \)

- 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.

\[ \text{Nu}_x = 0.332 (\text{Re}_x)^{1/2} (\text{PR})^{1/3} = \frac{C_f}{2} (\text{PR})^{1/3} \text{Re}_x \]

- Heat transfer is a function of \((\text{Re}_x)^{1/2}\) and \(\text{PR}^{1/3}\) 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, \( \varepsilon_t \) 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

\[
\frac{q_t}{\tau_t} = - \frac{c_p \frac{\partial T}{\partial y}}{PR_t \frac{\partial u}{\partial y}}
\]

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

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

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:

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

A general equation for both laminar and turbulent flow analysis can be written as

$$\text{Nu}_x = A \text{Re}_x^m \text{PR}^n$$

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