ME 3304 Heat & Mass Transfer

Lecture Note (1) - Introduction

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What is Heat?

Heat is the form of energy that is transferred between systems or objects with different temperatures

- Heat [J], [cal], [BTU] ~ Work = [N] [m] = [J]

- What is Energy? The capacity for doing work

  references
  - Enthalpy: unit of energy per unit of mass [J/kg] or [BTU/lb]
  - Entropy: unit of energy per unit of mass-temperature [J/kg·K] or [BTU/lb·°R]

- Power = [J]/[s] = [W]; work or heat transfer rate

Transfer of Heat

Observation → Concept/Simplification → Theory (equations)
(assumption/modeling)

Modeling

$q'' \sim \Delta T \qquad where\ q'' = \frac{q}{A}$, heat flux

Equation

$q'' = \text{coefficient} \times \Delta T$

Heat Transfer Mechanism

I.	Diffusion process	(1) Conduction
		(2) Convection
II.	Electromagnetic wave	(3) Radiation

Heat Transfer Modes

- Conduction $q'' = -k \times \frac{\Delta T}{L} \rightarrow -k \times \frac{dT}{dx}$

  "Fourier's Law"

  where, k: thermal conductivity

- Convection $q'' = h \times \Delta T \rightarrow h \times \left(T_{high} - T_{low}\right)$

  where, h: convection heat transfer coefficient

- Radiation $q'' \sim T^4$

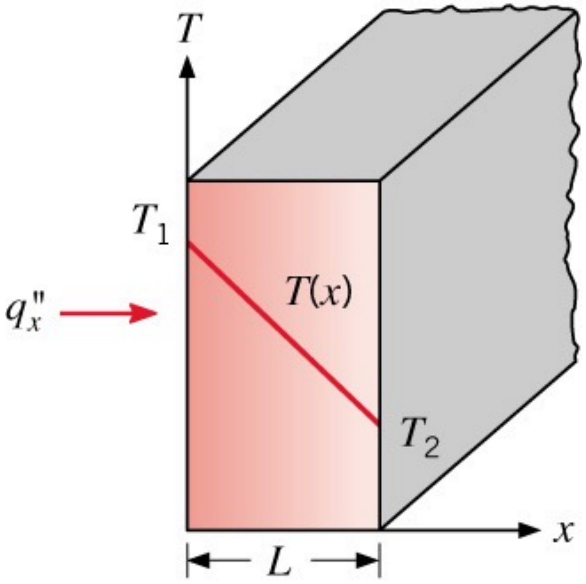
$$q''_{radiation} = q''_{emission} - q''_{absorption}$$

$$= \varepsilon \times \sigma \times \left(T^4_{surface} - T^4_{surrounding}\right)$$

where, ε = emissivity and σ = Stefan–Boltzmann constant

Conduction

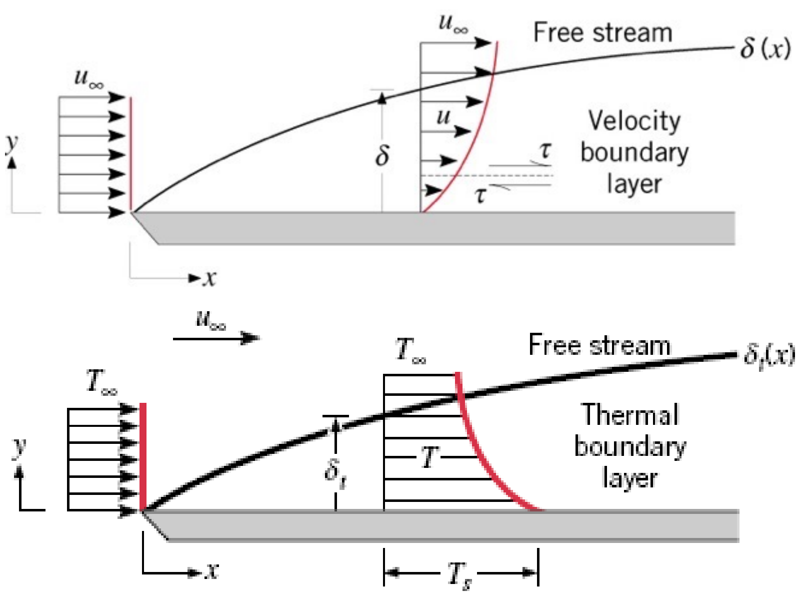
$$q'' = \frac{q_x}{A_x} = -k_x \times \frac{dT_x}{dx}$$



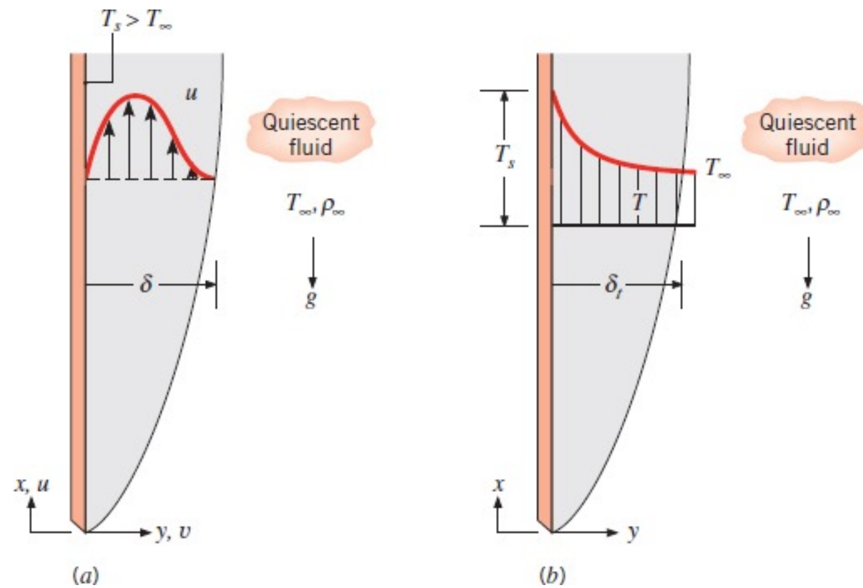
unit: $[W/m^2]$

Convection

Forced Convection

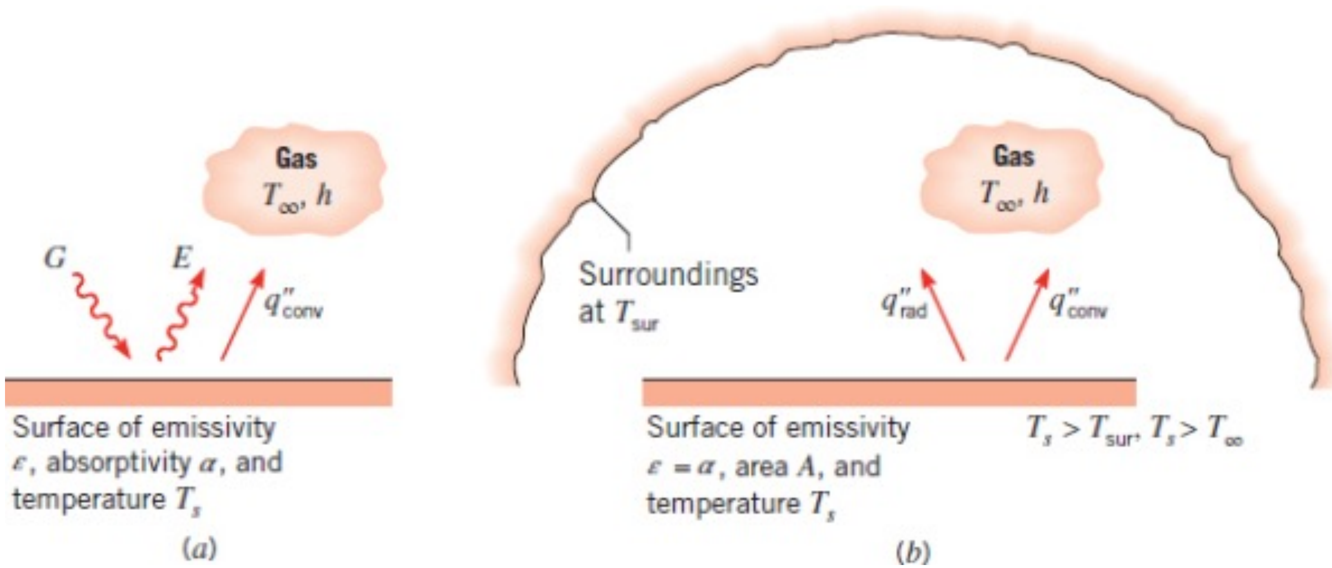


Free (Natural) Convection



$$q_s'' = h\left(T_{high} - T_{low}\right) = h\left(T_{s,surface} - T_{\infty,fluid}\right)$$

Radiation



$$q_{radiation} = q_{emission} - q_{absorbption}$$

$$= \varepsilon\sigma \times \left(T_{surface}^4 - T_{surrounding}^4\right)$$

Thermodynamic Laws

The Zeroth Law (1931)

If two objects (A & B) are both in thermal equilibrium with a third object (C), then A and B will be in thermal equilibrium.

The First Law (1850)

$\oint \delta Q \; \propto \; \int \delta W$ *for all closed systems*

- No limit on the inter-conversion.
- Energy cannot appear or disappear.
- Energy accounting must be balanced.

The Second law (1824)

Although all work can be converted completely to heat, heat cannot be completely and continuously converted into work.

$$\eta_{thermal} = \frac{W}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

→ Evaluate theoretical efficiency as a function of available energy, output and work required for parasitic load

The Third Law

All perfect crystals have zero entropy at a temp of absolute zero.

Thermodynamic Laws

The First Law (1850) – Conservation of Energy (Energy Balance)

$\oint \delta Q \propto \int \delta W$ for all closed systems

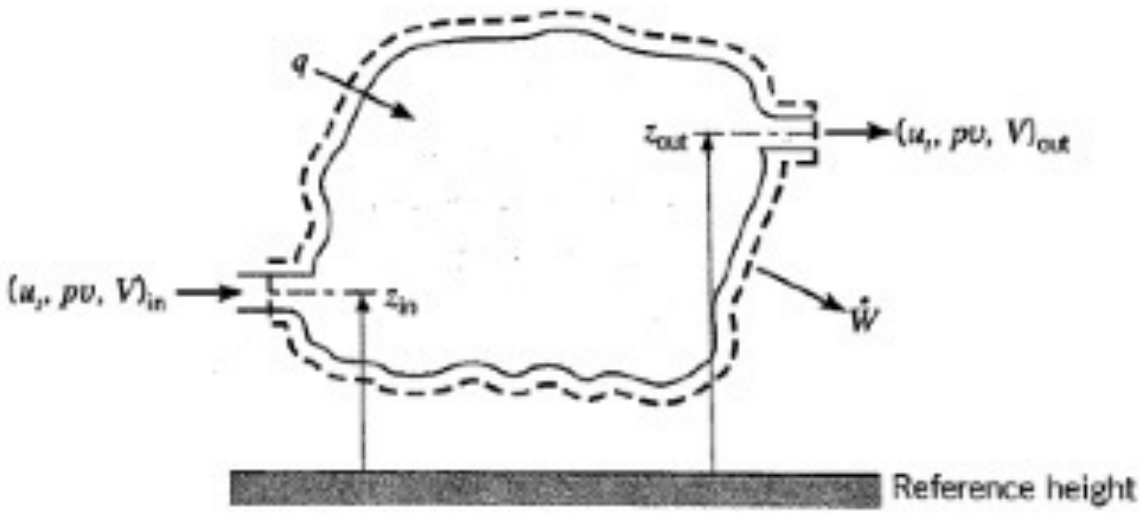
$$\Delta E_{st} = Q - W$$

$$\Delta E_{st} = E_{in} - E_{out} + E_g$$

$$\dot{E}_{st} \equiv \frac{dE_{st}}{dt} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_g$$

where $E = KE + PE + U$

Energy Conservation
1D Steady Flow Energy Equation
with no heat generation



Heat Transfer Text Book

$$\dot{m}\left(u + pv + \frac{1}{2}V^2 + gz\right)_{in} - \dot{m}\left(u + pv + \frac{1}{2}V^2 + gz\right)_{out} + q - \dot{W} = 0$$

Fluid Mechanics Text Book

$$\dot{m}\left(u + pv + \frac{1}{2}V^2 + gz\right)_{in} - \dot{m}\left(u + pv + \frac{1}{2}V^2 + gz\right)_{out} = \dot{Q}_{in,net} + \dot{W}_{shaft,in,net}$$

Symbols based on text book

heat rate	$q = q'' \times A$	[W]
heat flux	$q'' = \frac{q}{A}$	[W/m^2]
energy transfer	$Q = q \times t$	[J]
work rate	$\dot{W}$	[W]

Mass Transfer

Mass Transfer is due to random molec ular motion.

Consider two species A and B at the sa me T and p, but initially separated by a partition.

- Diffusion in the direction of decrea sing concentration dictates net tran sport of A molecules to the right an d B molecules to the left.
- In time, uniform concentrations of A and B are achieved.

Mass diffusion occurs in liquids and so lids, as well as in gases.

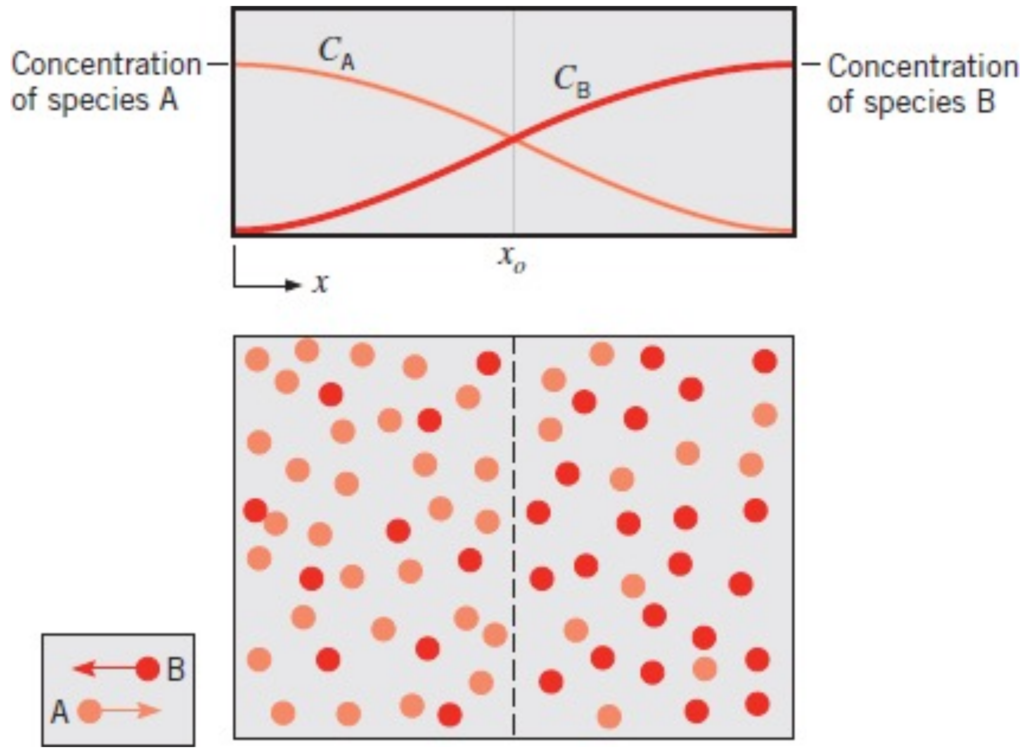


FIGURE 14.1 Mass transfer by diffusion in a binary gas mixture.

Mass Diffusion

The mass flow of a species per unit area (mass flux) is proportional to the concentration gradient. (**Fick's law**)

Mass Flux $n''_A = \frac{\dot{m}_A}{A} = -D_{AB}\frac{\partial \rho_A}{\partial x}$ **Mole Flux** $N''_A = -D_{AB}\frac{\partial C_A}{\partial x}$

$$n''_A = N''_A M_A$$

where,

$\dot{m}_A$: mass flow per unit time, [kg/s]
A: area, [m]
D: diffusion coefficient, [m^2/s]
ρ_A: density of species A, [kg/m^3]
C_A: molar concentration of species A per unit volume, [$kmol/m^3$]
M_A: molecular weight of species A, [kg/kmol]

The diffusivities for energy, species and momentum all have the same unit [m^2/s]

Summary

Heat is transferred if there is a temperature difference in a medium.

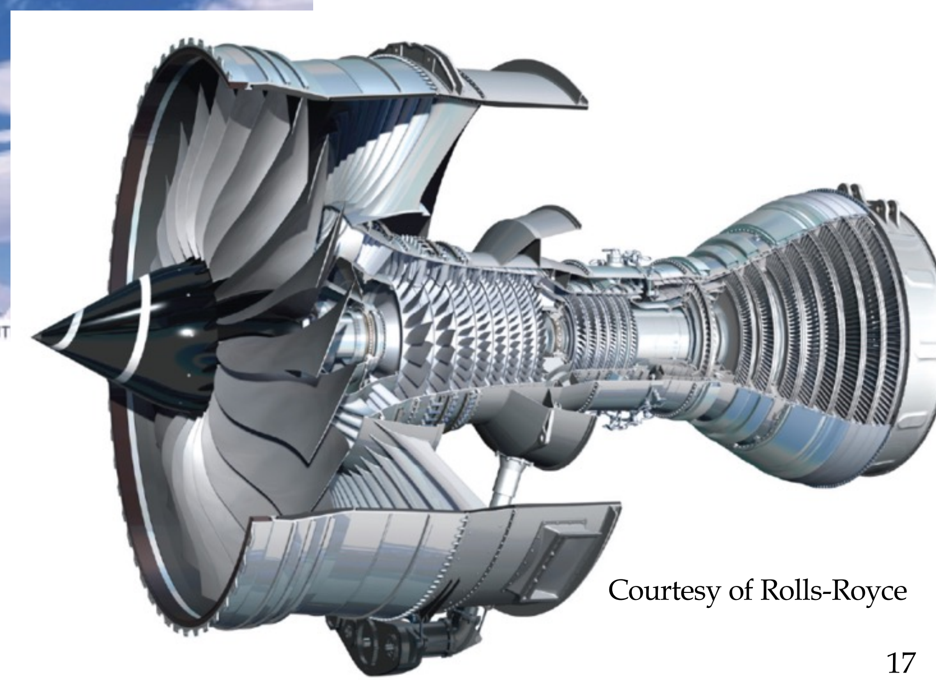
Similarly, if there is a difference in the concentration of some chemical species in a mixture, mass transfer must occur.

"Mass transfer is mass in transit as the result of a species concentration difference in a mixture."

Just as a temperature gradient constitutes the driving potential for heat transfer, a species concentration gradient in a mixture provides the driving potential for transport of that species.

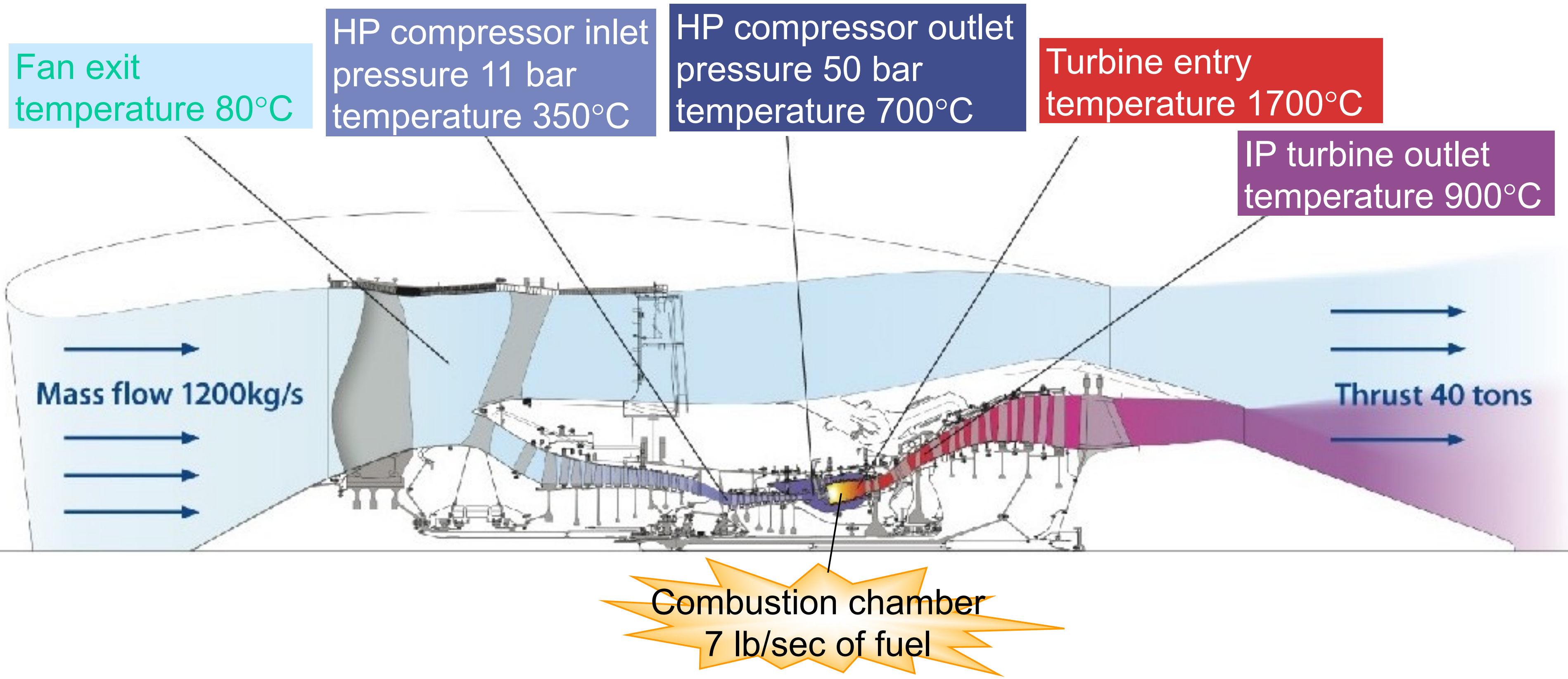
Application

Trent XWB – Latest Aero Gas Turbine



Courtesy of Rolls-Royce

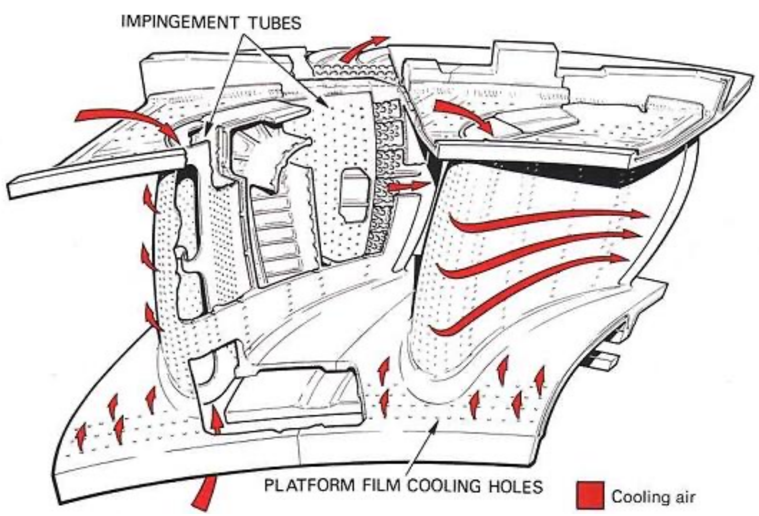
Typical Operating Condition of Aero Gas Turbine

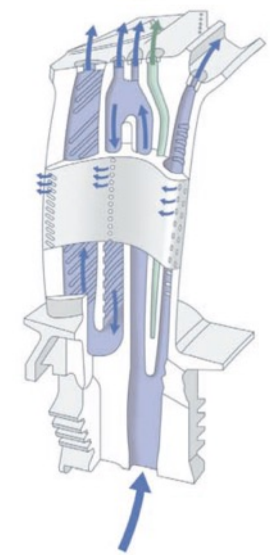


Steel starts to glow red at 700°C

Courtesy of Rolls-Royce

Turbine Cooling Design Considerations





Courtesy of Rolls-Royce