

Heat Transfer - Intro.

- Heat transfer is the study of mechanisms by bodies exchange energy. The goal of this study is the prediction of rates and efficiencies of the process.
- Note: Heat transfer is distinct from thermo since it concentrates on the non-equilibrium state, while thermo concentrates on systems in equilibrium.
- Example: Consider tossing a freshly forged steel ball into a tank of water.
 - Thermo would help us determine what the final state of the steel ball/water system would be.
 - Heat Transfer will tell us how it got there and how fast.

Heat Transfer - Intro. (cont.)

- Realize that: Heat \equiv Energy. However, the word heat is reserved for discussing processes or potentials for energy exchange.
- There are 3 modes of heat transfer:
 - **Conduction:** energy exchange through a solid body or across bodies at the point of contact.
 - **Radiation:** energy exchange through electromagnetic radiation and absorption.
 - **Convection:** energy conveyance by the bulk motion of a fluid accompanied by conduction between the fluid and the bodies it comes in contact with.
- We will study all of these in this course.

Intro. To Conduction

- The basic concept in heat conduction is **Fourier's Law:**
 - When two differing temperatures occur on opposing sides of a material, the rate of heat transfer through the material is directly proportional to the surface area and temperature difference but inversely proportional to the thickness.

– Mathematically:

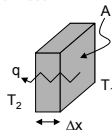
$$q \propto A \Delta T / \Delta x$$

q \equiv heat transfer rate or heat flux (J/sec or W)

A \equiv area (m^2)

ΔT \equiv temperature difference = $T_2 - T_1$ ($^{\circ}C$ or $^{\circ}K$)

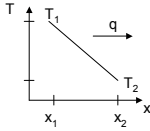
Δx \equiv thickness (m)



Intro. To Conduction (cont)

- The constant of proportionality is called the thermal conductivity, k ($\text{W/m}^2\text{K}$), so that:

$$q = -kA \frac{\Delta T}{\Delta x} = -kA \frac{dT}{dx}$$



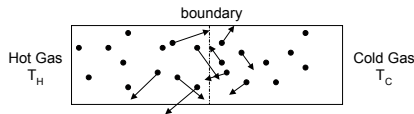
– Where the negative sign is necessary if q is positive when flowing in the positive x direction, but $dT/dx < 0$!

- Some texts also define the heat flux per unit area by:

$$q'' = \frac{q}{A} = -k \frac{dT}{dx} = -k \frac{\Delta T}{\Delta x}$$

Thermal Conductivity

- Thermal conductivity depends strongly upon the material and usually also varies temperature.
- For fluids (gasses and liquids) conduction occurs through the random motion of the fluid particles.
- Consider the flux across an imaginary boundary between two gasses at different temperatures.



Thermal Conductivity (cont)

- Particles crossing the boundary carry with them energy in proportion to the gas temperature.
- As a result of this random motion, energy is transferred from side of the partition to the other - this is conduction.
- It also follows that as temperature increases, there is more random motion, and thus the conduction rate increases.
- This is particularly true for gasses.
- For liquids, the situation is complicated by the intermolecular forces, and this rule is not generally true.

Thermal Conductivity (cont)

- For solids, there are two mechanisms of heat transfer: the migration of free electrons and crystal lattice vibration.
- The migration of free electrons is similar to the conduction by random particle motion in gases.
- Since the number of free electrons is proportional to the electrical conductance of the material, better electrical conductors are better heat conductors.
- Lattice vibration is associated with vibrations of the atoms and molecules bound in the structure of solids. Basic, shake one side of a crystal and the other side moves in response.

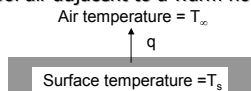
Thermal Conductivity (cont)

- For lattice vibration, the thermal conductivity is usually associated with the packing density of the crystal.
- Typical values at 300°K:
- Note that different references give different values - the experimental measurement of k is very difficult!

Material	k (W/m ² °K)
Diamond	1000+
Silver (pure)	429
Copper (pure)	385
Aluminum	237
Iron	80
Water	0.613
Oil	0.145
Air	0.026

Intro. To Convection

- Consider cool air adjacent to a warm horizontal wall.



- If the air remains at rest (like trapped between layers of clothes), the problem is simply one of conduction and the air is an effective insulator.
- If the air is in motion, however, the heat transfer rate increases dramatically. Think wind chill factor!
- The difference between the two cases has to do with the ability of fluid to carry energy through motion.

Intro. To Convection (cont)

- In this situation, there are really two mechanisms at play:
 - Near the wall surface (where velocity is low due to fluid viscosity), conduction heat transfer dominates.
 - Away from the wall, the bulk motion of the fluid carrying heat (advection) dominates.
- Thus, convective heat transfer is really a combined effect and, as a result, is rather difficult to analyze in detail.
- However, experimentation has indicated that there is a basic relation governing this type of heat transfer....

Intro. To Convection (cont)

- The basic concept which describes this convective heat transfer is **Newton's Law of Cooling**:

$$q = hA(T_s - T_\infty)$$

q \equiv heat transfer rate (J/sec or W)

positive for heat flux away from the wall!

A \equiv area (m^2)

h \equiv convective heat transfer coefficient or film conductance ($W/m^2/^\circ K$)

- Our study of convection will be ways to calculate values of h under different flow conditions.

Intro. To Convection (cont)

- We should also differentiate between when the fluid motion is forced, free or mixed:
 - Forced convection is when an external source (like a fan) is responsible for the fluid motion across the surface.
 - Free (natural) convection occurs when buoyancy effects resulting from temperature differences near the surface induce fluid motion.
 - Mixed convection occurs when both forced and natural convection are simultaneously present.
- Finally, when phase changes occur (boiling or condensation), the heat transfer is enhanced due to the high latent heats of these processes.

Intro. To Convection (cont)

- Typical value of h are:

Process	h (W/m ² /°K)
<u>Free Convection</u>	
Gases	2-25
Liquids	50-1000
<u>Forced Convection</u>	
Gases	25-250
Liquids	50-20,000
<u>Phase Changes</u>	
Boiling or condensation	2500-100,000

Intro. To Radiation

- All bodies at a temperature above absolute zero emit thermal energy as electromagnetic radiation.
- The theoretical radiation from an idealized surface (a black body) is give by the Stefan-Boltzmann Law:

$$q_{emis} = E_b = \sigma AT_s^4 \quad \sigma \equiv \text{Steffan - Boltzmann constant}$$

$$\equiv 5.669 \times 10^{-8} \text{ W/m}^2/\text{°K}^4$$

- For real bodies, the total emitted radiation is less than the black body amount called the emissivity, ε , such that:

$$q_{emis} = E = \varepsilon \sigma AT_s^4 \quad \varepsilon \equiv \text{emissivity} \quad (0 \leq \varepsilon \leq 1)$$

Intro. To Radiation (cont)

- Bodies also tend to absorb some fraction of the radiation incident upon them. If we give the total incident radiant flux as G, then

$$q_{abs} = G_{abs} = \alpha G \quad \alpha \equiv \text{absorptivity} \quad (0 \leq \alpha \leq 1)$$

- The radiation not absorbed is either reflected or transmitted or some combination of the two.
- If we are considering radiation between two bodies, the amount of radiant heat transfer will also depend upon the geometries and orientation of the two.
- Part of what we will study later is how to calculate these factors, called view factors.

Intro. To Radiation (cont)

- However, a useful assumption for some cases is to assume the entire world surrounding a body is at the same uniform temperature, T_{sur} .
- Also, for a wide range of radiation types and surfaces, it is accurate to assume that $\alpha = \epsilon$.
- For this case, geometry isn't important and $G = E_b(T_{sur})$ such that:

$$q = \epsilon\sigma A(T_s^4 - T_{sur}^4)$$

- The only problem with this equation is that it is non-linear. The book discusses at least one way to overcome this limitation.
