Heat Transfer

Modes of Heat Transfer

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Objectives

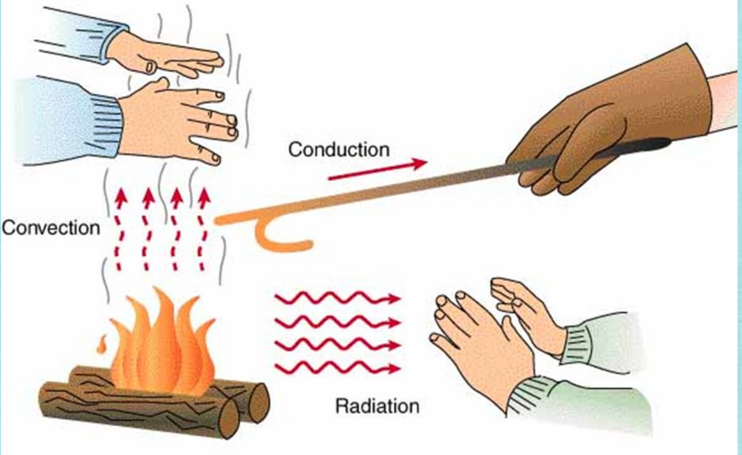
- Introduce the various modes of heat transfer.
- Illustrate the conditions of occurrence of the various modes.
- Give an idea about the variables of heat transfer.

Outcome

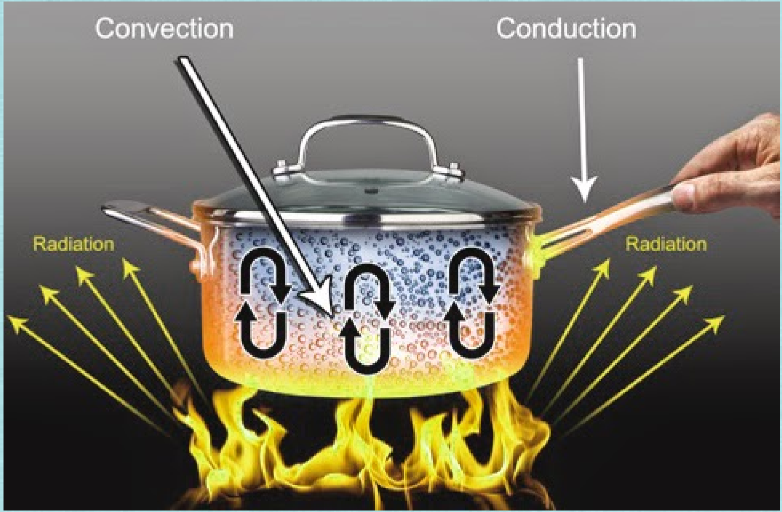
- To calculate the rate of steady heat transfer under simplified conditions.

Introduction to Heat Transfer

- Heat transfer is the study of the flow of heat.



Introduction to Heat Transfer (contd..)

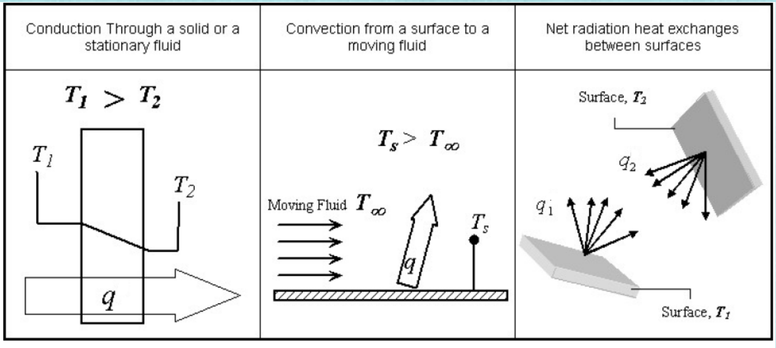


Introduction to Heat Transfer (contd..)

Heat transfer is energy transfer due to a temperature difference in a medium or between two or more media.
Different types of heat transfer processes are called different modes of heat transfer.

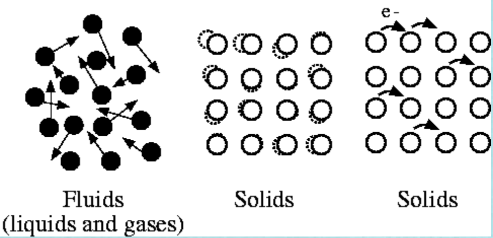
- Conduction heat transfer is due to a temperature gradient in a stationary medium or media.
- Convection heat transfer occurs between a solid surface and a moving fluid.
- Radiation heat transfer occurs due to emission of energy in the form of electromagnetic waves by all bodies above absolute zero temperature.
  Net radiation heat transfer occurs when there exists a temperature difference between two or more surfaces emitting radiation energy.

Introduction to Heat Transfer (contd..)



Conduction

Conduction is the transfer of energy due to either random molecular motion or due to the motion of "free" electrons.



In different phases of matter, the modes of conduction are slightly different:

gases: conduction is due to collisions of randomly moving molecules.

liquids: similar to gases, but with a much smaller "mean free path".

solids: conduction is due to lattice vibrations and/or motion of "free" electrons.

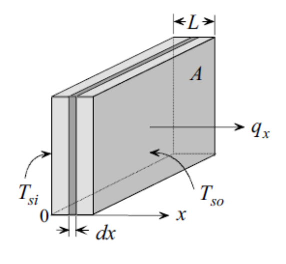
In solid bodies, conduction is the significant heat transfer mechanism because no material flows in the process. With flowing fluids, conduction dominates in the region very close to the solid boundary, where the flow is laminar and parallel to the surface where there is no eddy motion.

Heat Transfer rate and Heat flux:

$$Q = qA$$

$$\text{where} \quad \begin{aligned} Q &= \text{heat transfer rate (W)} \\ q &= \text{heat flux (W/m}^2\text{)} \\ A &= \text{heat transfer area (m}^2\text{)} \end{aligned}$$

Conduction (contd..)



$$\text{Rate of heat conduction} \propto \frac{\text{Area} \times \text{Temperature difference}}{\text{Thickness}}$$

$$\boxed{Q = -kA\frac{dT}{dx}} \qquad \text{(Fourier's law)}$$

Fourier's law is a phenomenological; that is developed from observed phenomena rather than being derived from first principles.

- Heat transfer rate in x direction is proportional to the temperature gradient, dT/dx. The proportionality constant k is a transport property known as the thermal conductivity (W/m.K) and is a characteristic of the wall material. The minus sign is a consequence of the fact that heat is transferred in the direction of decreasing temperature.

Increasing the surface area increases the rate of heat transfer.

Thermal Conductivity, k

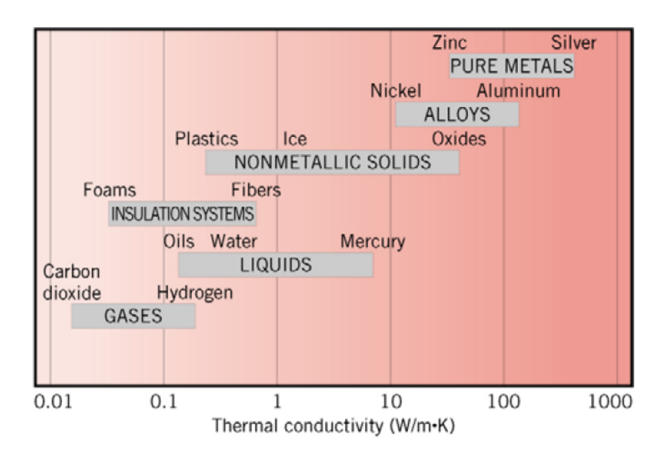
Definition

The thermal conductivity is the rate of thermal energy transfer per unit area and per unit temperature gradient.

- Thermal energy is transported within a solid by the electrons and the photons (lattice vibrations) inside the material. The transport of energy is hindered by the presence of imperfections or by any kind of scattering sites.
- Thermal conductivities of solids at room temperature vary from 0.1 W/(m.K) for good insulators (e.g. asbestos) up to 400 W/(m.K) for good conductors (e.g. silver).
- The conductivity changes mildly with temperature except at very low temperatures where it can acquire very large values. For instance, pure copper at 10 K has a conductivity of about 20,000 W/(m.K).

Thermal Conductivity (contd..)

- Pure crystals and metals have the highest thermal conductivities, and gases and insulating materials the lowest.
- The thermal conductivity of a substance is normally highest in the solid phase and lowest in the gas phase.



- Specific heat C_P is a measure of a material's ability to store thermal energy. For example $C_P = 4.184$ kJ/kg.°C for water and $C_P = 0.45$ kJ/kg.°C for iron at room temperature, which indicates that water can store almost 10 times the energy that iron can per unit mass.
- Likewise thermal conductivity k is a measure of a material's ability to conduct heat. For example, $k = 0.608$ W/m.°C for water and $k = 80.2$ W/m.°C for iron at room temperature, which indicates that iron conducts heat more than 100 times faster than water can.
- Thus water is a poor heat conductor relative to iron, although water is an excellent medium to store thermal energy.

Convection

Convection refers to any transfer of thermal energy by motion of a medium.

The rate equation or the convective heat transfer (regardless of particular nature) between a surface and an adjacent fluid is prescribed by Newton's law of cooling.

$$\boxed{Q = hA(T_s - T_\infty)}$$

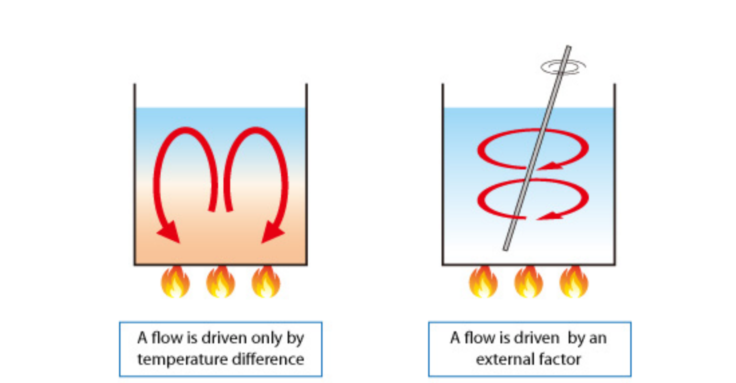
where

$$\begin{aligned} Q &= \text{Rate of heat transfer (W)} \\ A &= \text{Area exposed to heat transfer (m}^2\text{)} \\ T_s &= \text{Surface temperature of solid (}^\circ\text{C)} \\ T_\infty &= \text{Fluid temperature (}^\circ\text{C), and} \\ h &= \text{Heat transfer coefficient (W/m}^2.^\circ\text{C)} \end{aligned}$$

$$\boxed{h = f(\text{geometry, fluid motion, fluid properties, } \Delta T)}$$

Forced vs. Natural:

- forced convection refers to the case when the fluid is made to flow by some external agent, using a pump, fan, stirrer, etc.
- natural convection refers to fluid motion which naturally occurs from the heat transfer itself, due to buoyancy differences (“hot air rises...”).



Convection (contd..)

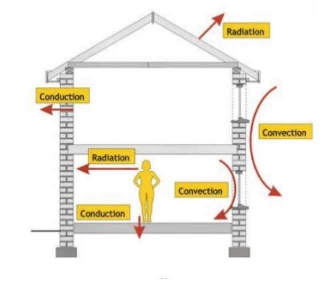
Typical values of heat transfer coefficient [$W/(m^2.°C)$]:

Free convection	gases: 2 – 25 liquids: 50 – 100
Forced convection	gases: 25 – 250 liquids: 50 – 20,000
Boiling/Condensation	2500 – 100,000

Boiling water has a higher heat transfer coefficient than subcooled water.

Radiation

- Radiation heat transfer involves the transfer of heat by electromagnetic radiation that arises due to the temperature of the body. Radiation does not need matter.
- Radiation is the primary source of heat generated by the sun. As the materials in your home (e.g., walls, floor, ceiling, etc.) absorb the suns radiant energy, this creates conductive heat. Surrounding materials further absorb the conductive heat through convection when surrounding air carries the conductive heat to other objects.



Radiation (contd..)

Emissive power per unit surface area:

$$q = \sigma \epsilon T^4 \qquad \text{(Stefan's Boltzmann law)}$$

where

$$\begin{aligned} \sigma &= \text{Steffan-Boltzmann constant} \\ &= 5.67 \times 10^{-8}\ \mathrm{W/m^2.K^4} \\ \epsilon &= \text{emissivity, which is a surface property} \\ & (\epsilon = 1 \text{ is black body}) \\ T &= \text{absolute temperature of the surface (K)} \end{aligned}$$

The above equation describes a gross heat emission rather than heat transfer.

The rate of radiation heat exchange between a small surface of area A at T_1 and a large surrounding at T_2 is given by the following expression:

$$Q = \sigma \epsilon A (T_1^4 - T_2^4)$$

Radiation (contd..)

Surfaces with emissivities nearly unity are good absorbers and hence poor reflectors of incident radiation. Most highly polished, unoxidized metal surfaces are good reflectors of thermal radiations with emissivities less than 0.1. A roughened or an oxidized surface has correspondingly higher emissivities.

Material	Emissivity, ϵ (dimensionless)
Carbon	0.85 – 0.95
Aluminum	0.11
Brass (oxidized)	0.61
Brass (unoxidized)	0.030
Copper (oxidized)	0.60
Copper (unoxidized)	0.020
Black gloss paint	0.90
Gold (polished)	0.020
Fire brick	0.75

Plumeria Tree — Shining / glossy leaves have lesser emissivity (i.e., lesser absorptivity).

Example 1: Electric power requirement for heating of water

An electric current is passed through a wire 1 mm diameter and 10 cm long. This wire is submerged in liquid water at atmospheric pressure, and the current is increased until the water boils. For this situation $h = 5000$ W/m^2.°C. And the water will be at 100°C. How much electric power must be supplied to the wire to maintain the wire surface at 114°C? (Ans: 22 W)

Solution:

Heat transfer by convection from the wire surface is given by

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

Here, $h = 5000\ \mathrm{W/m^2.^\circ C}$; $T_s = 114^\circ\mathrm{C}$; $T_\infty = 100^\circ\mathrm{C}$; and,

$$A = \pi DL = 3.142 \times 0.001 \times 0.1 = 3.142 \times 10^{-4}\ \mathrm{m}^2$$

Therefore,

$$\begin{aligned} Q &= hA(T_s - T_\infty) \\ &= 5000 \times (3.142 \times 10^{-4}) \times (114 - 100) = 22\ \mathrm{W} \end{aligned}$$

And this is equal to the electric power which must be applied.

Example 2: Combination of Convection and Radiation

A horizontal steel pipe having a diameter of 10 cm is maintained at a temperature of 60°C in a large room where the air and wall temperature are at 20°C with the convective heat transfer coefficient of 6.5 W/m^2.K. The emissivity of the steel is 0.6 calculate the total heat lost from the pipe per unit length. (134.35 W/m)

Solution:

Heat is transferred from the pipe to air due to both convection and radiation. Hence, the total heat transfer rate per unit length of pipe is given by,

$$Q_{\text{total}} = Q_{\text{convection}} + Q_{\text{radiation}}$$
$$= hA(T_s - T_\infty) + \epsilon\sigma A(T_s^4 - T_\infty^4)$$

For the cylindrical pipe, A per unit length is $= \pi D$. Therefore,

$$Q_{\text{total}} = 6.5 \times (\pi \times 0.1) \times (60 - 20)$$
$$+ 0.6 \times (5.67 \times 10^{-8}) \times (\pi \times 0.1) \times \left(333^4 - 293^4\right)$$
$$= 81.692 + 52.658 = 134.35 \text{ W/m}$$

1. A fiber-glass insulating board of thermal conductivity 0.05 W/(m.°C) is to be used to limit the heat losses to 80 W/m^2 for a temperature difference of 160°C across the board. Determine the thickness of the insulating board. (Ans: 0.1 m)
2. A 25 cm thick concrete wall has a surface area of 40 m^2. The inner surface of the wall is at 20°C, and the other surface is at −10°C. Determine the rate of heat loss through the wall if the thermal conductivity is 0.75 W/(m.°C). (Ans: 3.6 kW)
3. A 25 cm diameter sphere at 120°C is suspended in air at 20°C. If the natural convection heat transfer coefficient between the sphere and the air is 15 W/(m^2.°C), determine the rate of heat loss from the sphere. (Ans: 294.5 W)

4. Pressurized water at $50°\mathrm{C}$ flows inside a 5 cm diameter, 1 m long tube with surface temperature maintained at $130°\mathrm{C}$. If the heat transfer coefficient between the water and the tube is 2000 $\mathrm{W/(m^2.°C)}$, determine the heat transfer rate from the tube to the water. (Ans: 25.13 kW)
5. One surface of a thin plate is exposed to a uniform heat flux of 500 $\mathrm{W/m^2}$, and the other side dissipates heat by radiation to an environment at $-10°\mathrm{C}$. Determine the temperature of the plate. Assume black body radiation conditions for radiation. (Ans: 341.5 K)
6. One surface of a thin metal sheet receives radiation from a large plate at $700°\mathrm{C}$, while the other side dissipates heat by convection to a coolant fluid at $20°\mathrm{C}$. The surfaces can be considered as a perfect absorber and a perfect emitter for radiation. The heat transfer coefficient for convection between the surface and the fluid is 120 $\mathrm{W/(m^2.°C)}$. Determine the temperature of the plate. (Ans: 638 K)