Principles of Chemical Engineering

Heat Transfer

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Syllabus Contents

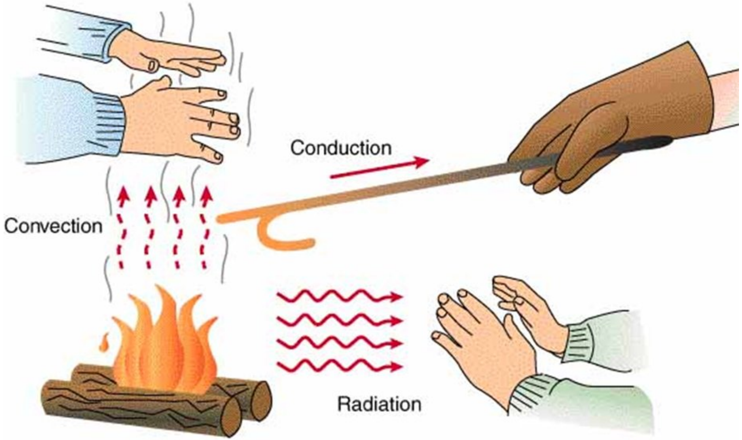
Heat transfer - conduction, convection and radiation (Omit correlations for heat transfer coefficient and change of phase)

Objectives

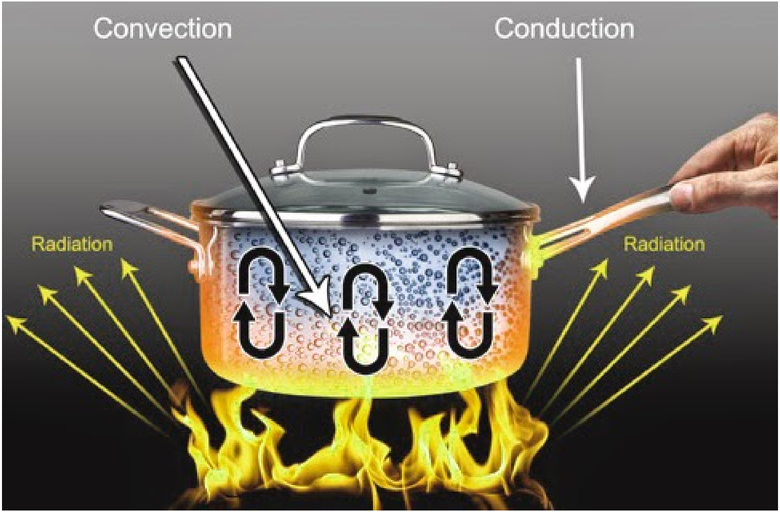
- To introduce the various modes of heat transfer:
  - conduction
  - convection
  - radiation

Introduction to Heat Transfer

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



Introduction to Heat Transfer (contd..)

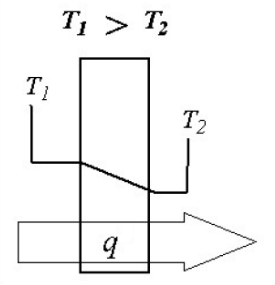
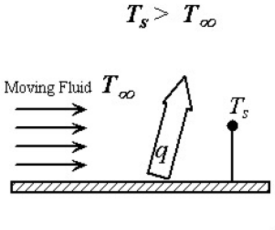
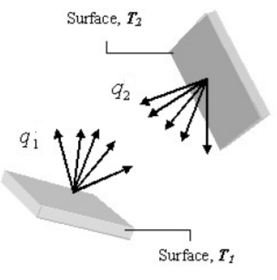


Introduction to Heat Transfer (contd..)

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.

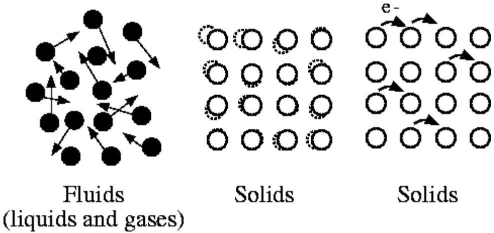
- Conduction heat transfer is due to a temperature gradient in a stationary medium or media.
- Convection heat transfer occurs between a surface and a moving heat transfer occurs between a surface and a moving fluid at different temperatures
- Radiation heat transfer occurs due to emission of energy 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 Through a solid or a stationary fluid	Convection from a surface to a moving fluid	Net radiation heat exchanges between surfaces
		

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.

Conduction (contd..)

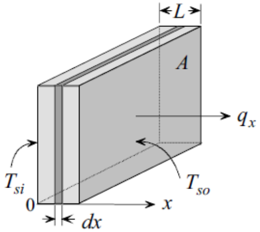
In solid bodies, conduction is the significant heat transfer mechanism because no material flows in the process. With flowing fluids, conduction dominates in the region very close to the solid boundary, where the flow is laminar and parallel to the surface where there is no eddy motion.

Heat transfer rate and Heat flux:

$$Q = qA$$

where Q = heat transfer rate (J/s = W)
q = heat flux (W/m^2)
A = heat transfer area (m^2)

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 law; that is developed from observed phenomena rather than being derived from first principles.

Conduction (contd..)

$$Q = -kA\frac{dT}{dx} = kA\frac{\Delta T}{L}$$

where $\Delta T = T_{\text{in}} - T_{\text{out}}$ (where $T_{\text{in}} > T_{\text{out}}$)
$L =$ thickness of the wall

- 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.

Central hole in the vadai – leads to increasing the area available for heat transfer. Increasing the surface area increases the rate of heat transfer, and hence faster cooking.

Thermal Conductivity, k

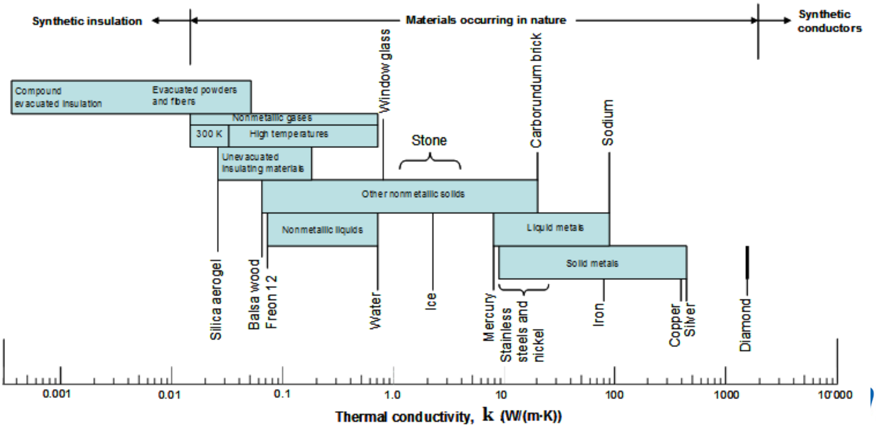
Definition

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

- 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.



Thermal Conductivity (contd..)

- 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 the medium.
The convective heat transfer between a surface and an adjacent fluid is prescribed by Newton's law of cooling.

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

where

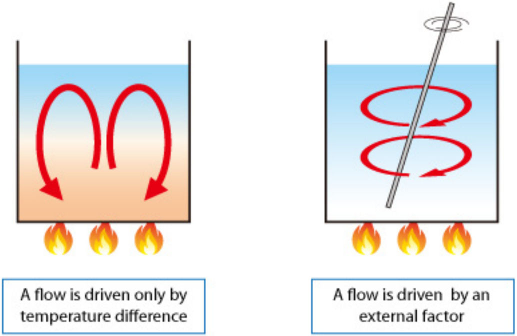
$$\begin{aligned} Q &= \text{Rate of heat transfer (W)} \\ A &= \text{Area exposed to heat transfer (m}^2\text{)} \\ T_s &= \text{Surface temperature of solid (}^\circ\text{C)} \\ T_\infty &= \text{Fluid temperature (}^\circ\text{C), and} \\ h &= \text{Heat transfer coefficient (W/m}^2.^\circ\text{C)}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

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

Convection (contd..)

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...").



(a) Natural convection (b) Forced convection

Convection (contd..)

Typical values of heat transfer coefficient [W/(m^2.$^\circ$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.
- Emissive power per unit surface area:

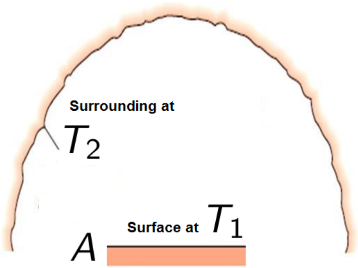
$$q = \sigma \epsilon T^4 \qquad \text{(Stefan's Boltzmann law)}$$

where

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

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

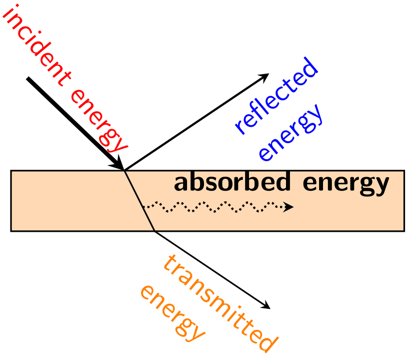
Radiation Exchange



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:

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

Radiative Property of Materials



Thermal radiation incident upon a surface may be either absorbed, reflected, or transmitted. If ρ, α, and τ are the fractions of the incident radiation which are reflected, absorbed and transmitted, respectively, then

$$\boxed{\rho + \alpha + \tau = 1}$$

where ρ is reflectivity, α is absorptivity, and τ is transmissivity.

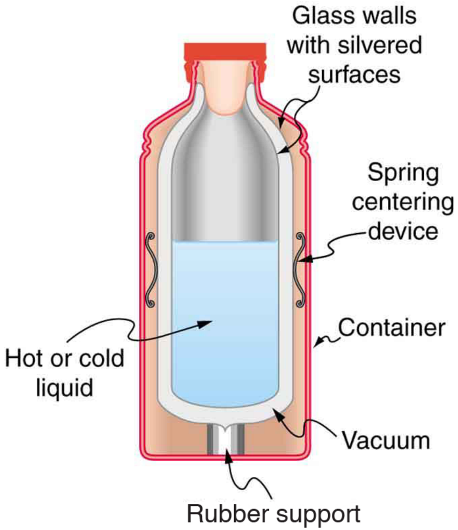
Radiative Property of Materials (contd..)

- The relation $\alpha = \epsilon$ is known as Kirchhoff's law of radiation.
- 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

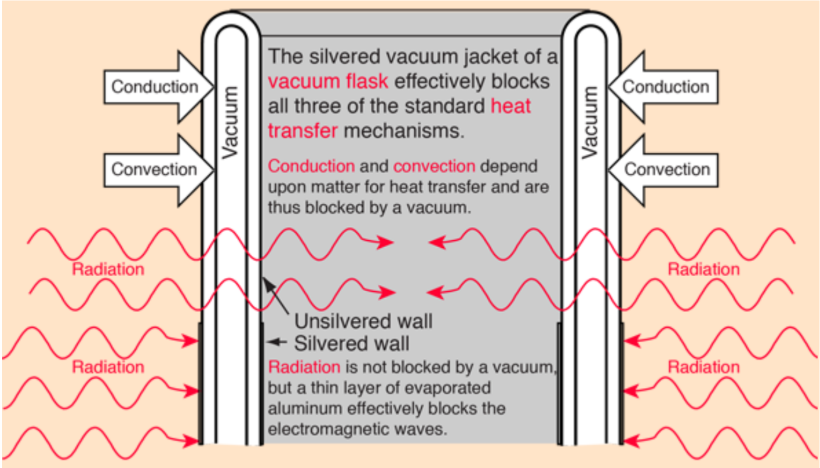
Plumeria Tree — Shining / glossy leaves have lesser emissivity (i.e., lesser absorptivity).

Thermo Flask - Parts



(Ref: https://www.thermosfacts.com/how-does-a-thermos-work-2/)

Thermo Flask - Heat Transfer



(Ref: http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/vacfla.html)

Quiz

1. What are the variables affecting the rate of heat transfer by conduction?
2. Compare between "free convection" and "forced convection".
3. What is the effect of roughness on emissivity of a metallic surface?
4. What is the role of vacuum in thermo flask?