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**GATE-2018 Chemical Engineering**

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## GATE-19 &amp; 20 Syllabus: Chemical Engineering - CH

**Heat Transfer:** Steady and unsteady heat conduction, convection and radiation, thermal boundary layer and heat transfer coefficients, boiling, condensation and evaporation; types of heat exchangers and evaporators and their process calculations. Design of double pipe, shell and tube heat exchangers, and single and multiple effect evaporators.

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**1.  
CHAPTER****INTRODUCTION**

**Heat Transfer:** It is the science that seeks to product the energy (Heat) transfer that may take place between material bodies as a result of temperature difference.

- It explains how and at which rate heat energy is transferred between material bodies.
- Any transport takes place due to the presence of driving force.
- In heat transfer, the driving force is thermo potential difference that is also called temperature difference.
- Heat transfer takes place by various modes or mechanisms.
- These mechanisms and the related principles enable us to calculate the rate and extent of transport of thermal energy.
- Heat transfer also explains temperature history w.r.t. time and w.r.t place or co-ordinate.

**Difference between Thermodynamics and Heat Transfer:**

- Thermodynamics deal with the relation between heat and other forms of energy whereas heat transfer concerned with the analysis of the rate of heat transfer.
- Thermodynamics deals with the systems at equilibrium, heat transfer deals with the system that lack of thermal equilibrium, and hence it is a non-equilibrium phenomenon.
- Thermodynamics is used to find out the amount of thermal energy is needed for changing a system from one equilibrium state to another.
- Thermodynamics doesn't tell anything about the history of the heat transfer rate or temperature while changing from one equilibrium state to another between material bodies.

**Modes of Heat Transfer:**

1. Conduction                      2. Convection                      3. Radiation

**1. Conduction**

- Conduction takes place in solid or stagnant liquid or gaseous medium due to existence of a temperature difference.
- It is not associated with the movement and displacement of particles of the medium from their original position.
- It is achieved by two mechanisms:
  - (i) Molecular interaction where heat transfer takes place by the kinetic motion or direct impact of molecules.
    - Molecules at a high energy level impart energy to adjacent molecules at lower energy levels.
    - Conduction energy transfer always exist so long as there is a temperature gradient in a system comprising molecules of a solid, liquid or gas.
  - (ii) By the drift of 'free' electrons as in the case of metallic solids.
    - The metallic alloys have a different concentration of free electrons and their ability to conduct heat energy is directly proportional to the concentration of free electrons in them.

- Heat energy is transferred from one molecule to the adjacent one through molecular vibrations in general solids, drift of free electrons in metals, collisions in gases and liquids etc but in all types, there is no change of original positions of the molecules.

**Basic Law of Conduction = Fourier Law**

**Fourier Law :**

- It is also called Joseph Fourier phenomical law. This law is an empiricial law based on observation.
- According to this law the rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, and inversely proportional to the thickness of the layer.

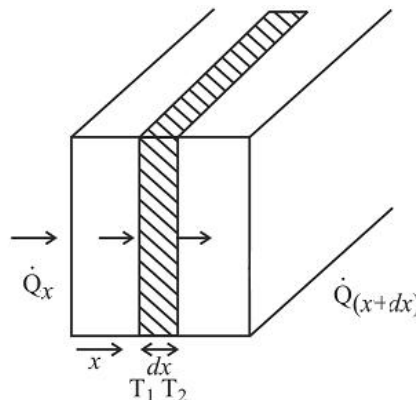
$$i.e. \quad \frac{\dot{Q}_x}{A} \propto \frac{\partial T}{\partial x}$$

where  $\frac{\partial T}{\partial x}$  = Temperature gradient in  $x$ -direction.

$$\dot{Q}_x = -k A \frac{dT}{dx}$$

where,  $k$  = Thermal conductivity  $\dot{Q}_x$  = Heat transfer rate  
 $A$  = Area Unit of  $k$  = W/mK  $k$  depends on properties of material

- If  $k$  changes with position of material = Anisotropic material



- If  $k$  does not changes with position of material = Isotropic material.
- For simplicity of the problem, we always assume material is isotropic.
- $k$  can be function of temperature.

$$k = k_o (1 + aT) \quad k = k_o (1 + aT + bT^2)$$

where  $a$  and  $b$  are constants

- $k_{\text{metal}}$  = Very high,  $k_{\text{gaseous, non metal}}$  = very low.

**Assumption of Fourier Law:**

- The heat (energy) flow is in uni-directional.
- $\frac{dT}{dx}$  = constant and temperature profile linear.
- There is no internal heat generation.
- Material is isotropic and homogeneous.
- Conduction of heat takes place under steady state conditions.

**Important Features of Fourier Law:**

1. It is useful to all matter *i.e.* solid, liquid, gas.
2. It is a vector expression representing that heat flow is in the direction of decreasing temperatures.
3. It is applicable to define thermal conductivity of medium through which energy is conducted.

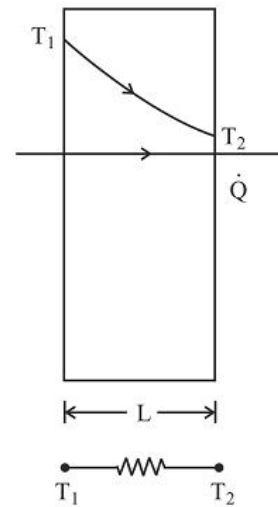
$$\text{Heat flow} = \frac{\text{Temperature difference}(dT)}{\frac{L}{kA}}$$

$$\dot{Q}_x = \frac{T_1 - T_2}{\left(\frac{L}{kA}\right)} = \frac{\text{Driving force}}{\text{Resistance}}$$

4. Thermal resistance,

$$(R_{th})_{conduction} = \frac{L}{kA}$$

5. The reciprocal of thermal resistance is known as thermal conductance it is denoted by C.

**Conduction in Gases, Liquids and Solids:**

- In gases rate of heat transfer by conduction increases with temperature.
- Thermal conductivity ( $k$ ) of gases increases with increase in temperature.
- Thermal conductivity of gases ranges from 0.006 to 0.6 W/(m.K) while that of liquids ranges from 0.09 to 0.7 W/(m.K).
- $K_{\text{metal}}$  varies from 2.3 to 420 W/(m.K).
- The materials having low values of thermal conductivity (less than 0.2 W/(m.K)) are called as and used as heat insulators.
- $k_{\text{gas}}$  is almost independent of pressure upto a moderate pressure.
- $k_{\text{gas}}$  Changes when pressure is critical pressure of gas or more.
- In gases, Hydrogen has highest thermal conductivity of 0.175 W/(m.K) at 0°C.
- $k$  (thermal conductivity) of water increases with temperature
- $k_{\text{liquid}}$  is almost independent of pressure.
- In liquid and gases, conduction takes place due to collisions between molecules of varying temperature.
- In solid conduction, thermal energy conducted by lattice vibration and transport by free electrons.
- Good electrical conductors are also good thermal conductors like metals.
- Good electrical insulators are also good thermal insulators except diamond.
- Diamond is an electrical insulator but thermal conductivity is 5 times as high as Cu and Ag.
- Solid with low  $k$  values are thermal insulators. (Ceramic materials, diatomaceous earth, expanded polymeric forms)

**2. Convection**

It is possible only in presence of a fluid medium.

- If a fluid flows inside a duct or over a solid body and the temperatures of the fluid and the solid surfaces are different, therefore, heat transfer takes between the fluid and solid surface will take place. The carrying of heat here is inseparably linked with the movement of fluid itself.
- Convective heat transfer is associated with displacement of fluid element
- Depending upon type of displacement, it is divided into free/natural convection and forced convection.

**Free/Natural Convection:**

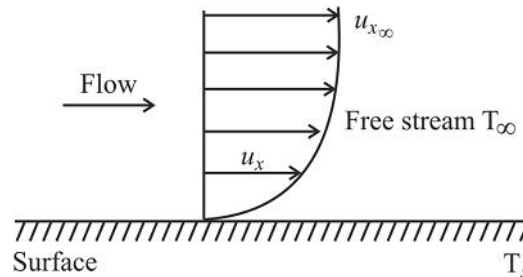
• When the fluid motion set up by buoyancy effects resulting from the density variation caused by the temperature difference in the fluid, hence, heat transfer is said to be free or natural convection.

**Forced Convection:**

When the fluid motion is artificially generated with the help of an external medium *i.e.* fan or blower.

**Newton's law of cooling :**

For a fluid flowing at a temperature  $T_\infty$  over a surface at a temperature  $T_s$  as shown in figure below, and  $T_\infty < T_s$ .



**Figure:** Convection from a heated pipe

To express the total effect of convection, we can apply Newton's law of cooling:

$$\dot{Q}_x = hA(T_s - T_\infty) = \frac{(T_s - T_\infty)}{\left(\frac{1}{hA}\right)}$$

$h$  = Convective heat transfer coefficient or Film conductance ( $W/m^2K$ ).

$A$  = Surface Area

$$\dot{Q}_x = \frac{(T_s - T_\infty)}{\frac{1}{hA}} = \frac{\text{Driving force}}{\text{Resistance}}$$

$$\dot{Q}_x = \text{Rate of heat transfer in watt}$$

- $h = f(\mu, \rho, C_p, k, \nu)$
- The value of heat transfer coefficient depends upon.
  - (i) Thermodynamic and transport properties, for example-viscosity, density, specific heat etc.
  - (ii) Nature of heat flow
  - (iii) Geometry of the surface

- $(R_{th})_{\text{convection}} = \frac{1}{hA}$

**3. Radiation**

When two bodies at different temperatures are placed in an evacuated adiabatic enclosure so that they are not in contact through a solid or fluid medium, the temperature of the two bodies will tend to become identical.

- The mechanism or mode of heat transfer by which this equilibrium is obtained is called thermal radiation.
- Radiation heat transfer is an electromagnetic wave phenomenon, and no medium is necessitated for its propagation.
- In fact the heat transfer by radiation is maximum if the two bodies exchanging energy are separated by a perfect vacuum.
- Thermal radiation depends only on the temperature and on the optical properties of the emitter.

**Stefan Boltzmann Law:**

The maximum rate of radiation that can be emitted from a surface at thermodynamic temperature is

$$\dot{Q}_{\text{emit,max}} = \sigma A_s T_s^4 \quad (\text{W})$$

where,  $\sigma$  = Stefan Boltzmann constant =  $5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$

$A_s$  = surface Area ( $\text{m}^2$ )       $T_s$  = Absolute temperature of surrounding in K.

The law states that emissive power of black body is directly proportional to fourth power of its absolute temperature.

$$\text{i.e.,} \quad Q \propto T^4$$

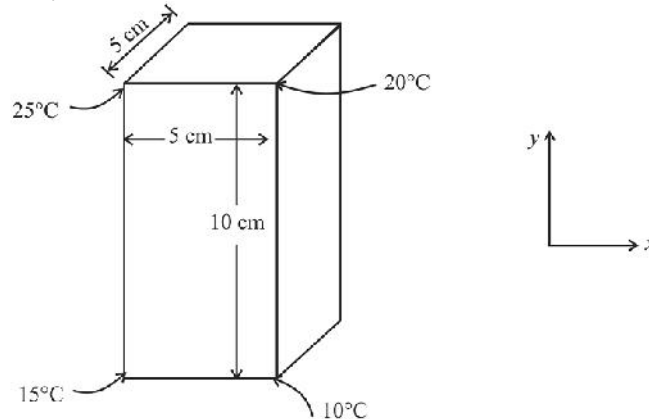
- $\dot{Q}_{\text{emit,max}} = \sigma A_s T_s^4$  (only applicable for Black Body)
- For Gray or other body:  $\dot{Q}_{\text{net}} = f_\epsilon f_G \sigma A (T_1^4 - T_2^4)$   
 where,  $f_\epsilon$  = Emissivity function       $f_G$  = Geometric factor, view factor  
 $T_1, T_2$  = Temperature of two different surfaces

**Why to Study Heat Transfer in Engineering:**

- Almost all industrial processes are involved with heating or cooling, which requires heat transfer.
- For a better process engineer, we should have sound knowledge and understanding of principles, mechanisms and applications of heat transfer.
- It is used for optimal design of heat exchangers.
- The design of chemical plants is done on the basis of heat transfer and the analogous to the mass transfer processes.
- Civil engineers must take care of the thermal effects in buildings and other structures.

## Practice Question (Introduction)

- Q. 1.** The block of stainless steel shown below is well insulated on the front and back surfaces, and the temperature in the block varies linearly in both the  $x$  and  $y$ -directions, find:
- The heat flux and heat flows in the  $x$  and  $y$ -directions.
  - The magnitude and direction of heat flux vector.
- Thermal conductivity of material =  $14.4 \text{ W/(mK)}$ .

**Solution:**

(a) The cross-sectional areas are:

$$A_x = 10 \times 5 = 50 \text{ cm}^2 = 0.0050 \text{ m}^2 \quad A_y = 5 \times 5 = 25 \text{ cm}^2 = 0.0025 \text{ m}^2$$

So, the heat fluxes are:  $\hat{q}_x = -k \frac{\partial T}{\partial x} = -k \frac{\Delta T}{\Delta x} = -14.4 \frac{(-5)}{(0.05)} = 1440 \text{ W/m}^2$

$$\hat{q}_y = -k \frac{\partial T}{\partial y} = -k \frac{\Delta T}{\Delta y} = -14.4 \left( \frac{10}{0.1} \right) = -1440 \text{ W/m}^2$$

So, the heat flows are:  $q_x = \hat{q}_x A_x = 1440 \times 0.005 = 7.2 \text{ W}$

$$q_y = \hat{q}_y A_y = -1440 \times 0.0025 = -3.6 \text{ W}$$

(b)  $\vec{\hat{q}} = \hat{q}_x \vec{i} + \hat{q}_y \vec{j}$

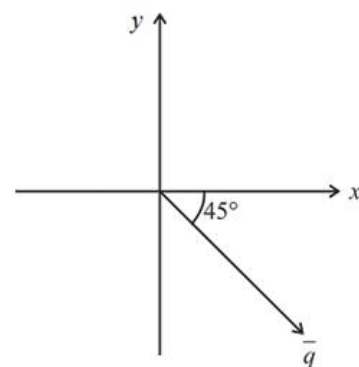
$$\vec{\hat{q}} = 1440 \vec{i} - 1440 \vec{j}$$

$$|\vec{\hat{q}}| = [(1440)^2 + (-1440)^2]^{0.5} = 2036.5 \text{ W/m}^2$$

The angle  $\theta$ , between the heat flux vector and the  $x$ -axis is calculated as follows:

$$\tan \theta = \frac{\hat{q}_y}{\hat{q}_x} = \frac{-1440}{1440} = -1.0 \quad \theta = -45^\circ$$

So the directions of heat flow:





**Q. 2.** The heat flux,  $q$  is  $5000 \text{ W/m}^2$  at the surface of an electrical heater. The heater temperature is  $150^\circ \text{C}$  when it is cooled by air at  $50^\circ \text{C}$ . What is the average convective heat transfer coefficient,  $\bar{h}$ ? What will the heater temperature be if the power is reduced so that  $q$  is  $3000 \text{ W/m}^2$ ?

**Solution :** 
$$\bar{h} = \frac{q}{\Delta T} = \frac{5000}{(150 - 50)} = 50 \text{ W/(m}^2\text{K)}$$

If the heat flux is reduced,  $\bar{h}$  should remain unchanged during forced convection. Thus,

$$\Delta T = T_{\text{heater}} - 50^\circ \text{C} = \frac{q}{h} = \frac{3000 \text{ W/m}^2}{50 \text{ W/(m}^2\text{.K)}} = 60 \text{ K}$$

So, 
$$\Delta T = T_{\text{heater}} = 60 + 50 = 110^\circ \text{C}$$

**Q. 3.** Consider a person standing in a room temperature maintained at  $22^\circ \text{C}$  at all times. The inner surfaces of the walls, floors, and the ceiling of the house are observed to be at an average temperature of  $5^\circ \text{C}$  in winter and  $25^\circ \text{C}$  in summer. Determine the rate of radiation heat transfer between the person and the surrounding surfaces if the exposed surface area and the average outer surface temperature of the person are  $1.0 \text{ m}^2$  and  $30^\circ \text{C}$ . Assume no convective heat transfer. The emissivity of person  $\epsilon = 0.95$ .

**Solution :** 
$$\dot{Q}_{\text{rad, winter}} = \epsilon \sigma A_s (T_s^4 - T_{\text{sur, winter}}^4)$$

$$= 0.95 \times \left( 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4} \right) (1.0 \text{ m}^2) \times [(30 + 273)^4 - (5 + 273)^4] \text{ K}^4 = 132.3 \text{ W}$$

$$\dot{Q}_{\text{rad, summer}} = \epsilon \sigma A_s (T_s^4 - T_{\text{sur, summer}}^4)$$

$$= 0.95 \times \left( 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4} \right) (1.0 \text{ m}^2) \times [(30 + 273)^4 - (25 + 273)^4] \text{ K}^4 = 29.23 \text{ W}$$

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