CHEMICAL ENGINEERING

Heat Transfer

Comprehensive Theory
with Solved Examples *and* Practice Questions

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CHAPTER

1

Introduction and Basic Concepts

LEARNING OBJECTIVES

The reading of this chapter will enable the students:

- To understand how thermodynamics and heat transfer are related to each other.
- To understand the various modes of heat transfer.
- To understand the physical mechanisms of different modes of heat transfer and the basic laws that govern the process of heat transfer in different modes.

1.1 INTRODUCTION

- Before 18th century, heat was defined as calorific fluid when it get added in any system, system get heated and when it released from any system, system get cooled.
- The definition of **'heat'** is provided by classical thermodynamics. It is defined as an energy that flows due to difference in temperature.
- Heat flows in a direction from higher temperature to lower temperature.
- Heat energy can neither be observed nor be measured directly. However, the effects produced by the transfer of this energy are amenable to observations and measurements.

1.1.1 Difference between Thermodynamics and Heat Transfer

- Thermodynamics deals with the amount of heat transfer as a system undergoes a process from one equilibrium state to another, and makes no reference to how long the process will take.
- Where as the science of heat transfer deals with the rate of heat transfer, which is the main quantity of interest in the design and evaluation of heat transfer equipment.
- Heat transfer deals with modes of heat transfer and temperature profile within the object.

1.1.2 Temperature

Temperature is measure of amount of energy caused by the molecules. It tells about the hotness and coldness of the object. Temperature difference is driving force for heat transfer.

1.2 MODES OF HEAT TRANSFER

The process of heat transfer taken as place by three distinct modes: Conduction, Convection and Radiation.

1.2.1 Conduction

The mechanism of heat transfer due to a temperature gradient in a stationary medium is called conduction. The medium may be a solid or a fluid. In liquids and gases, conduction is due to the collisions of molecules in course of their random motions. In solids, the conduction of heat is attributed to two effects:

(i) the flow of free electrons and

(ii) the lattice vibrational waves caused by the vibrational motions of the molecules at relatively fixed positions called a lattice.

The law which describes the rate of heat transfer in conduction is known as Fourier's law.

According to Fourier's law,

$$q_x = -k\frac{dT}{dx} \qquad \text{...(1.1)}$$

Assumptions of Fourier's Law

(i) Steady state heat conduction.

(ii) Linear temperature profile.

(iii) No heat generation within object.

(iv) Object faces are isothermal (means no change in temperature with time).

(v) One direction flow of heat.

(vi) Isotropic material (thermal conductivity must be constant)

- Where q_x is the rate of heat flow per m^2 of heat area normal to the direction of heat flow.
- The minus sign in Equation (1.1) indicates that heat flows in the direction of decreasing temperature.
- The constant k is known as thermal conductivity.

When the temperature becomes a function of three space coordinates, say, x, y, z in a rectangular Cartesian frame, heat flows along the three coordinate directions. Equation (1.1) under the situation, is written in vector form as

$$q = -k\nabla T \qquad \text{...(1.2)}$$

where,

$$q = iq_x + jq_y + kq_z$$

and,

$$\nabla T = i\frac{\partial T}{\partial x} + j\frac{\partial T}{\partial y} + k\frac{\partial T}{\partial z}$$

Example 1.1 The rate of heat transfer from a hot surface to a cold surface is directly proportional to the difference in temperature between the two surfaces and the surface area normal to the direction of heat flow. This is

(a) Newton's law of cooling

(b) Kirchhoff's law

(c) Fourier's law

(d) Wien's law

Answer : (c)

Example 1.2 Heat transfer takes place according to

(a) Fick's law

(b) Zeroth law of thermodynamics

(c) First law of thermodynamics

(d) Second law of thermodynamics

Answer : (d)

NOTE

- Thermal conductivity is a transport property of the medium through which heat is conducted.
- For an isotropic medium, the thermal conductivity *k* is a scalar quantity which depends upon temperature only.

1.2.2 Convection

The mode by which heat is transferred between a solid surface and the adjacent fluid in motion when there is a temperature difference between the two is known as convection heat transfer.

- The mode of convective heat transfer comprises of two mechanisms:
  (i) Conduction at the solid surface and
  (ii) Advection by the bulk or macroscopic motion of the fluid a little away from the solid surface.
- The convection is of two types: **Forced convection** and **Free convection**.
- In **Forced convection**, the fluid is forced to flow over a solid surface by external means such as fan, pump or atmospheric wind.
- When the fluid motion is caused by the buoyancy forces that are induced by density differences due to the variation in temperature in the fluid, the convection is called **Natural** (or **Free**) **convection**.

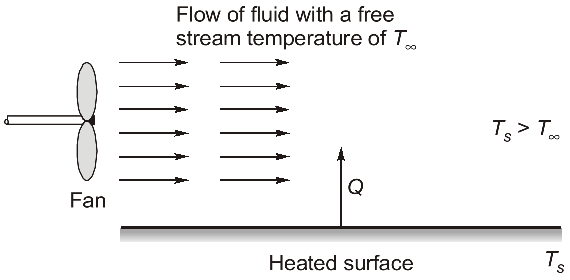


Figure 1.1 Forced convective heat transfer from a horizontal surface

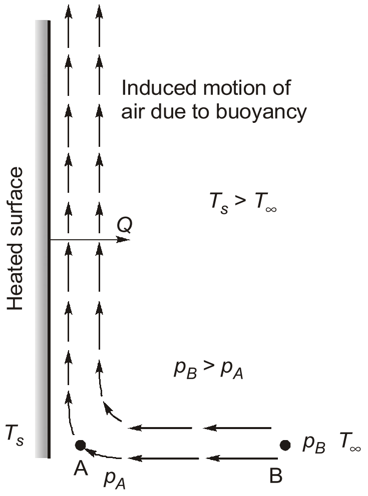


Figure 1.2 Free convective heat transfer from a heated vertical surface

- Irrespective of the details of the mechanism, the rate of heat transfer by convection (both forced and free) between a solid surface and a fluid is calculated from the relation

$$Q = \bar{h} A \Delta T \qquad \text{...(1.3)}$$

This equation is known as Newton's law of cooling.

where, Q = Rate of heat transfer by convection

A = Heat transfer area

$\Delta T = (T_s - T_f)$, is the difference between the surface temperature T_s and the temperature of the fluid T_f at some reference location.

$\bar{h}$ = Average convective heat transfer coefficient over the area A.

NOTE

The convection heat transfer coefficient *h* is not a property of the fluid. It is an experimentally determined parameter whose value depends on all the variables influencing convection such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity.

Example 1.3 The average forced convective heat transfer coefficient for a hot fluid flowing over a cold surface is 200 W/(m² °C). The fluid temperature upstream of the cold surface is 100°C and the surface is held at 20°C. Determine the heat transfer rate per unit surface area from the fluid to the surface.

Solution :

The rate of heat transfer per unit area, q

$$q = \frac{Q}{A} = \bar{h}\left(T_\infty - T_s\right) = 200\ (100 - 20) = 16{,}000\ \text{W/m}^2 = 16\ \text{kW/m}^2$$

1.2.3 Radiation

Radiation is a mode of heat transfer which does not require any medium between objects for transfer of heat. For example, we receive sun light from sun. Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as result of the changes in the electronic configurations of the atoms or molecules.

The maximum rate of radiation that can be emitted from a surface at a thermodynamic temperature T_s (in K) is given by the Stefan-Boltzmann law as

$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \qquad \text{...(1.4)}$$

where $\sigma = 5.67 \times 10^{-8}$ W/m² K⁴ is the Stefan-Boltzmann constant.

The idealized surface that emits radiation at this maximum rate is called as black body, and the radiation emitted by a black body is called black body radiation.

The radiation emitted by all real surface is less than the radiation emitted by a black body at the same temperature, and is expressed as

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \qquad \text{...(1.5)}$$

where ε is the emissivity of the surface. The property emissivity, whose value is in the range $0 \le \varepsilon \le 1$, is a measure of how closely a surface approximates a black body.

NOTE

- The heat transfer by conduction or convection requires the presence of a medium. But the radiation heat transfer does not necessarily require a medium, rather it occurs most efficiently in a vacuum.
- Radiation is a volumetric phenomenon, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees. However, radiation usually considered to be a surface phenomenon for solids that are opaque to thermal radiation such as metal, wood and rocks.

Example 1.4 After sunset, radiant energy can be sensed by a person standing near a brick wall. Such walls frequently have a surface temperature around 50°C, and the typical brick emissivity value is approximately 0.9. What would be the radiant heat flux per square metre from a brick wall at this temperature?

Solution :

Applying equation (1.5), we have

$$\frac{E}{A} = \in \sigma T^4 = 0.9 \times 5.67 \times 10^{-8} \times (50 + 273)^4 = 555.44 \text{ W/m}^2$$

1.3 THERMAL CONDUCTIVITY

Thermal conductivity of a material can be defined as the rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference. The thermal conductivity of a material is a measure of the ability of the material to conduct heat. A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or insulator. The thermal conductivities of some common materials at room temperature are given in Table 1.1.

Table 1.1 Thermal conductivity of some materials at room temperature (300 K)

Material	k(W/(m°C))
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminium	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.613
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Refrigerant-12	0.072
Glass fibre	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

1.3.1 Solids

In solids, heat conduction is due to two effects - **flow of free electrons** and **propagation of lattice vibrational waves**. The thermal conductivity is therefore determined In the addition of these two components. In a pure metal, the electronic component is more prominent than the component of lattice vibration and gives rise to a very high value of thermal conductivity. The lattice component of thermal conductivity strongly depends on the way the molecules are arranged. Highly ordered crystalline non-metallic solids like diamond, silicon, quartz exhibit very high thermal conductivities (more than that of pure metals) due to lattice vibration only, but are poor conductors of electricity.

NOTE

- Thermal conductivity of an alloy of two metals is usually much lower than that of either metals. (Refer to Table 1.2)
- Thermal conductivity of pure metals decreases with increase in temperature (Refer to Figure 1.3), because with increase in temperature lattice vibrations increases and that lowers the flow of free electrons.
- Thermal conductivity of alloys increases with increase in temperature. (Refer to Figure 1.3).
- Thermal conductivity of non-metallic solids increases with increases in temperature because lattice vibration increases.

Table 1.2 The comparison of thermal conductivities of metallic alloys with those of constituting pure metals

Pure metal or alloy	*k* (W/(m°C))
Copper	401
Aluminium	237
Nickel	91
Constantan (55% Cu, 45% Ni)	23
Commercial bronze (90% Cu, 10% Al)	52

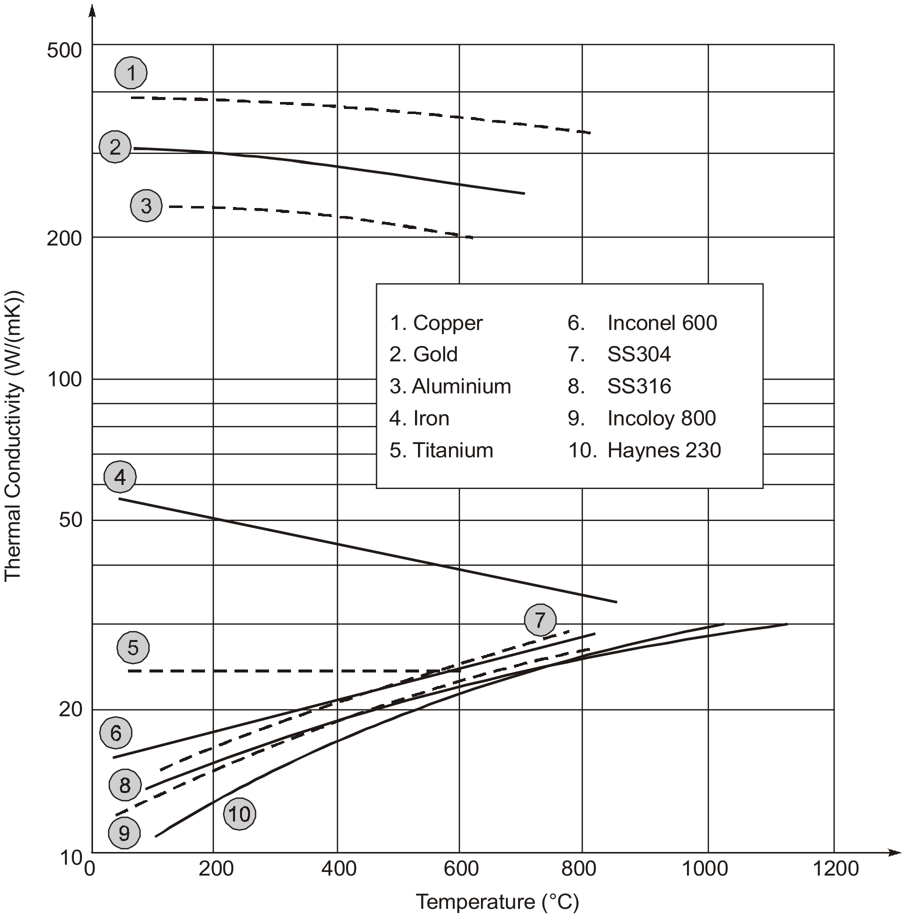


Figure 1.3 The variation of thermal conductivity with temperature for typical metals and their alloys

1.4 THERMAL CONDUCTIVITY OF LIQUIDS AND GASES

The thermal conductivity for liquids and gases is attributed to the transfer of kinetic energy between the randomly moving molecules due to their collisions. The kinetic theory of gases predicts and the experiments confirm that the thermal conductivity of gases is proportional to the square root of the thermodynamic temperature T, and inversely proportional to the square root of the molar mass M. Therefore, the thermal conductivity of a gas increases with increasing temperature and decreasing molar mass. So it is not surprising that the thermal conductivity of helium ($M = 4$) is much higher than those of air ($M = 29$) and argon ($M = 40$).

Unlike gases, the thermal conductivities of most liquids decrease with increasing temperature, with water being a notable exception. Like gases, the conductivity of liquids decreases with increasing molar mass.

NOTE

- The thermal conductivity of gases is independent of pressure in a wide range of pressures encountered in practice.
- Because of large intermolecular spaces and hence a smaller number of molecular collisions, the thermal conductivities exhibited by gases are lower than those of the liquids.

Example 1.5 In general, the thermal conductivity of a substance is

(a) independent of temperature
(b) a strong function of pressure
(c) strongly temperature dependent
(d) independent of pressure

Answer : (c)

Example 1.6 With increase in temperature, the thermal conductivity of gases

(a) decreases
(b) increases
(c) remain constant
(d) first increase and then decreases

Answer : (b)

Example 1.7 Which liquid metal can be taken as the best conductor?

(a) Tin
(b) Mercury
(c) Bismuth
(d) Sodium

Answer : (d)

Example 1.8 Choose the correct statement.

(a) The thermal conductivity of insulating solids increases with temperature
(b) The thermal conductivity of good electrical conductors is generally low
(c) The thermal conductivity of gases decreases with temperature
(d) The thermal conductivity of liquids is a strong function of temperature

Answer : (a)

Example 1.9 Which of the following has the lowest thermal conductivity?

(a) Air (b) Water

(c) Brick (d) Copper

Answer : (a)

1.5 THERMAL DIFFUSIVITY

The ratio of thermal conductivity to the heat capacity appears to be an important property and is termed thermal diffusivity α. Therefore,

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho c} \qquad ...(1.6)$$

Thermal conductivity k represents how well a material conducts heat, and the heat capacity ρc represents how much energy a material stores per unit volume.

The thermal diffusivity of a material is the measure of its ability to conduct thermal energy relative to its ability to store thermal energy. Materials having large values of α will respond quickly to a change in the thermal environment in establishing a steady-state temperature field within the material in transporting heat, while materials having small values of α will do it sluggishly.

Summary

- The science of thermodynamics deals with the amount of heat transfer a system undergoes a process from one equilibrium state to another, whereas the science of heat transfer deals with the rate of heat transfer, which is the main quantity of interest in the design and evaluation of heat transfer equipment.
- Heat can be transferred in three different modes : **Conduction, Convection,** and **Radiation**.
- **Conduction** is the transfer of heat from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles, and is expressed by Fourier' law of heat conduction as

$$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx}$$

- **Convection** is the mode of heat transfer between a solid surface and the adjacent liquid or gas that is in motion and involves the combined effects of conduction and fluid motion. The rate of convection heat transfer is expressed by Newton's law of cooling as

$$\dot{Q}_{\text{convection}} = hA_s(T_s - T_\infty)$$

- **Radiation** is the energy emitted by matter is in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules. The maximum rate of radiation that can be emitted from a surface at a thermodynamic temperature T_s is given by the Stefan-Boltzmann law as $\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4$.

Objective Brain Teasers

1. Eggs with a mass of 0.15 kg per egg and a specific heat of 3.32 kJ/kg°C are cooled from 32°C to 10°C at a rate of 300 eggs per minute. The rate of heat removal from the eggs is
   (a) 11 kW (b) 80 kW
   (c) 25 kW (d) 55 kW

2. Which equation below is used to determine the heat flux for conduction?
   (a) $-kA\dfrac{dT}{dx}$ (b) $-k$ grad T
   (c) $h(T_2 - T_1)$ (d) $\varepsilon\sigma T^4$

3. A 2 kW electric resistance heater submerged in 30 kg water is turned on and kept on for 10 min. During the process, 500 kJ of heat is lost from the water. The temperature rise of water is
   (a) 5.6°C (b) 9.6°C
   (c) 13.6°C (d) 23.3°C

4. A 1 kW electric resistance heater in a room is turned on and kept on for 50 minutes. The amount of energy transferred to the room by the heater is
   (a) 1 kJ (b) 50 kJ
   (c) 3000 kJ (d) 3600 kJ

5. Which equation below is used to determine the heat flux for convection?
   (a) $-kA\dfrac{dT}{dx}$ (b) $-k$ grad T
   (c) $h(T_1 - T_2)$ (d) $\varepsilon\sigma T^4$

6. A hot 16 cm × 16 cm × 16 cm cubical iron block is cooled at an average rate of 80 W. The heat flux is
   (a) 195 W/m^2 (b) 521 W/m^2
   (c) 3125 W/m^2 (d) 7100 W/m^2

7. Which equation below is used to determine the heat flux emitted by thermal radiation from a surface?
   (a) $-kA\dfrac{dT}{dx}$ (b) $-k$ grad T
   (c) $h(T_2 - T_1)$ (d) $\varepsilon\sigma T^4$

■ ANSWERS

1. (d)	**2.** (b)	**3.** (a)	**4.** (c)	**5.** (c)
6. (b)	**7.** (d)			

■ Hints & Explanation

1. (d)

$$m = 0.15 \text{ kg/egg}$$
$$c = 3.32 \text{ kJ/kg°C}$$
$$T_{\text{initial}} = 32°\text{C}$$
$$T_{\text{final}} = 10°\text{C}$$

Number of eggs cooled = 300 per minute

The rate of heat removal

= Mass of 1 egg × Number of eggs cooled per minute × specific heat × $[T_{\text{initial}} - T_{\text{final}}]$

= 0.15 × 300 × 3.32 × [32 – 10] = 3286.8 kJ/min

= 54.78 kW ≈ 55 kW

2. (b)

$$\text{Heat flux} = \frac{Q}{A}$$

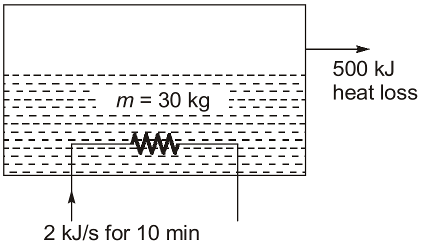
From Fourier's law

$$\frac{Q}{A} = \text{Heat flux} = -k\frac{dt}{dx}$$

$$\frac{dT}{dx} = \text{grad or slope}$$

$$\therefore \quad \text{Heat flux} = -k \text{ grad.}$$

3. (a)



$$Q_{\text{input}} = \frac{2 \text{ kJ}}{\text{s}} \times (10 \times 60)s = 1200 \text{ kJ}$$

$$Q_{\text{out}} = 500 \text{ kJ}$$

$$Q_{\text{stored}} = 1200 - 500 = 700 \text{ kJ}$$

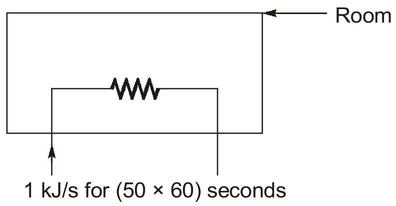
Heat stored is utilized in rise of temperature of water.

$$\text{Heat stored} = mcdT$$

$$700 = 30 \times 4.18 \times dT$$

$$dT = \frac{700}{30 \times 4.18} = 5.58°\text{C} \approx 5.6°\text{C}$$

4. (c)



Amount of energy transferred to the room by the heater

= Rate of energy × Time input

= 1 kJ/s × (50 × 60) second = 3000 kJ

5. (c)

$$Q = hA\Delta T \quad \text{(Connection heat transfer)}$$

$$Q/A = \text{heat flux for convection}$$

$$\text{Heat flux} = h\,\Delta T = h[T_1 - T_2]$$

6. (b)

Dimension of cube = 16 × 16 × 16 cm^3

$$\text{Area of cube} = 6a^2$$

Heat flux is Q/A

$$= \frac{80}{6 \times 16 \times 16} = \frac{0.3125}{6} \text{ W/cm}^2$$

$$= \frac{0.3125}{(10^{-2})^2} = \frac{3125}{6} \text{ W/m}^2$$

$$= 520.83 = 521 \text{ W/m}^2$$

7. (d)

$$Q = \sigma \in AT^4$$

Heat flux:

$$Q/A = \sigma \in T^4$$

STUDENT'S ASSIGNMENTS

1. An insulated pipe of 50 mm outside diameter ($\varepsilon = 0.8$) is laid in a room at 30°C. It the surface temperature is 250°C and the convective heat transfer coefficient is 10 W/m^2 K, calculate the heat loss per unit length of pipe.

Ans. $Q/L = 2232.4$ W/m

2. An immersion water heater of surface area 0.1 m^2 and rating 1 kW is designed to operate fully submerged in water. Estimate the surface temperature of the heater when the water is at 40°C and the heat transfer coefficient is 300 $\text{W/m}^2\text{K}$.

Ans. $T_s = 73.3°\text{C}$

■■■■