SSC-JE 2025

Staff Selection Commission

Junior Engineer Examination

Mechanical Engineering

Heat Transfer

Well Illustrated **Theory** *with*
Solved Examples and **Practice Questions**

MADE EASY PUBLICATIONS

Heat Transfer

Contents

Chapter 01

Basic Concepts and Dimensionless Numbers

1.1 Introduction

- Heat flows in a direction from higher temperature to lower temperature.

1.1.1 Difference between Thermodynamic and Heat Transfer

- Thermodynamics deals with the amount of heat transfer as a system undergoes a process, and makes no reference to how long the process will take.
- Whereas 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 has direction as well as magnitude. The rate of heat conduction in a specified direction is proportional to the temperature gradient. Which is the change in temperature per unit length in that direction.
- $T = T(x, y, z, t)$, the temperature in a medium varies with position as well as time.
- Heat conduction in a medium is said to be steady when the temperature does not vary with time, and unsteady or transient when it does.
- Determining the rate of heat transfer to or from a system and thus the rate of cooling or heating as well as the variation of the temperature is the subject of heat transfer.
- The first law requires that the difference of rate of heat transfer into a system and from the system be equal to the rate of increase of energy of that system. The second law requires that heat be transferred in the direction of decreasing temperature.
- There can be no net heat transfer between two mediums that are at same temperature. The larger the temperature difference, the higher the rate of heat transfer.
- The rate of heat transfer per unit surface area is called heat flux.

$$q = \frac{Q}{A} \text{ W/m}^2$$

heat flux may vary with time as well as position on the heat transfer surface.

1.2 Conduction

- Conduction can take place in solids, liquids or gases. In gases and liquids; conduction is due to the collisions and diffusion of the molecules during their random motion.
- In solids, it is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.

- The rate of heat conduction through a medium depends on the geometry of the medium, its thickness; and the material of the medium as well as temperature difference across the medium.

$$Q_{\text{Cond}} = KA\frac{\Delta T}{\Delta x}$$

where,

K is the thermal conductivity

Q_{cond} is in Watt

A = Area in m^2

ΔT = Temperature difference

Δx = Distance between two points between which heat is conducted.

- It is also called Fourier's law of heat conduction
- The heat transfer surface Area 'A' is always normal to the direction of heat transfer.

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

1.3 Convection

- The convection heat transfer refers to the heat transfer occurring due to random molecular motion (diffusion) and the bulk or macroscopic, motion of the fluid.
- The random molecular motion (diffusion) is conduction.
- Whereas the bulk or macroscopic motion is termed 'advection'.

  In free convection the flow is induced by buoyancy forces which are due to density difference caused by temperature variations in the fluid.

  When the flow is caused by external means, such as by fan, pump, or atmospheric winds it is called forced convection.
- Newton's law of cooling

$$Q_{\text{conv}} = hA(T_s - T_\infty) \text{ Watt}$$

$h \rightarrow$ Convection heat transfer coefficient (W/m^2°C)

$A \rightarrow$ Surface area (m^2)

- The value of (h) depends on surface geometry, the nature of fluid motion, the properties of the fluid and the bulk fluid velocity.

1.4 Radiation

- Unlike conduction and convection, the transfer of energy by radiation does not require the presence of an intervening medium.
- Energy transfer by radiation is fastest and occurs most efficiently in vacuum.
- All bodies at a temperature above absolute zero emit thermal radiation according to Stefan-Boltzmann law.

$$q_{max} = \sigma T^4 (\sigma = 5.67 \times 10^{-8} W/m^2K^4)$$

- The radiation emitted by all real surfaces is less than the radiation emitted by a black body at the same temperature.

$$q = \in \sigma T^4 \qquad \text{where, } \in \text{ is the emissivity of the surface}$$

- The property emissivity whose value is in the range of $0 \le \in \le 1$ is a measure of how closely a surface approximates a blackbody.
- Also the rate at which radiant energy is absorbed per unit surface area may be evaluated from knowledge of a surface radiative property termed the absorptivity 'α' where $0 \le \alpha \le 1$.
- If $\alpha = \in$ (a gray surface), then the net rate of radiation heat transfer from the surface, is expressed as:

$$Q = \in \sigma A \left(T^4 - T_{Surr.}^4\right)$$

- Radiation heat transfer is dominant mostly at high temperature only.

Example 1.1 One face of a copper plate is maintained at 400°C, the other face is maintained at 200°C. How much heat is transferred through the plate per unit and for 1 m length. [Given K_{copper} = 370 W/mK]

Solution :

From Fourier's law:

$$\frac{q}{A} = -\frac{kdT}{dx}$$

$$\frac{q}{A} = (-k)\frac{\Delta T}{\Delta x} = \frac{(-370)(200-400)}{1}$$

$$\frac{q}{A} = \frac{(370)(200)}{1} = 74000 \text{ W/m}^2 = 74 \text{ kW/m}^2$$

Example 1.2 Air at 20°C blows over a hot plate (50 × 50) cm maintained at 270°C. The convection heat transfer coefficient is 25 W/m²K. Calculate heat transfer.

Solution :

From Newton's law of cooling.

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

$$q = (25)(0.5)(0.5)[270 - 20]$$

$$q = (25)(0.25)(250) = 1562.5 \text{ W}$$

Example 1.3 Two infinite black plates at 727°C and 227°C exchange heat by radiation. calculate the heat transfer per unit area.

Solution :

$$\frac{q}{A} = \sigma\left(T_1^4 - T_2^4\right)$$

$$\frac{q}{A} = (5.67 \times 10^{-8})[1000^4 - 500^4]$$

as (227°C = 1000 K, 227°C = 500 K)

$$\therefore \qquad \frac{q}{A} = (5.67)(10^{-8})[10000 - 625](10^{8})$$

$$\frac{q}{A} = (5.67)(9375) = 53156.25 \text{ W/m}^2 = 53.156 \text{ kW/m}^2$$

Observation: In this question temperatures are high therefore radiation heat transfer is significant.

Example 1.4 Suppose a person stated that heat cannot be transfer in a vacuum. how do you respond?

Solution :

We will say that the person is wrong as there is heat transfer between sun and the earth without any medium i.e., vacuum. This kind of heat transfer only occurs by radiation mode.

For Solids

NOTE

- Thermal conductivity of an alloy of two metals is usually much lower than that of either metals.
- Thermal conductivity of pure metals decreases with increase in temperature.
- Thermal conductivity of alloys increases with increase in temperature.

For Liquids and Gases

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.

1.5 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

1.6 Dimensionless Numbers

Selected dimensionless groups of heat and mass transfer

Table 1.2

Group	Definition	Interpretation
Biot No. (Bi)	$\frac{hL}{k_s}$	Ratio of the internal thermal resistance of a solid to the boundary layer thermal resistance.
Mass transfer Biot No. (Bi_m)	$\frac{h_m L}{D_{AB}}$	Ratio of the internal species transfer resistance to the boundary layer species transfer resistance
Coefficient of friction (C_f)	$\frac{\tau_s}{\rho V^2/2}$	Dimensionless surface shear stress.
Fourier No. (Fo)	$\frac{\alpha t}{L^2}$	Ratio of the heat conduction rate to the rate of thermal energy storage in a solid dimensionless time.
Mass Transfer Fourier No. (FO_m)	$\frac{D_{AB} t}{L^2}$	Ratio of the species diffusion rate to the rate of species storage dimensionless time.
Factor friction (f)	$\frac{\Delta p}{(L/D)(\rho m_m^2/2)}$	Dimensionless pressure drop for internal flow.
Grashof No. (Gr_L)	$\frac{g\beta(T_s - T_\infty)L^3}{v^2}$	Measure of the ratio of buoyancy forces to viscous forces.
Nusselt No. (NU_L)	$\frac{hL}{k_f}$	Ratio of convection to pure conduction heat transfer.
Peclet No. (Pe_L)	$\frac{VL}{\alpha} = Re_L Pr$	Ratio of advection to conduction heat transfer rates.
Prandtl No. (Pr)	$\frac{c_p \mu}{k} = \frac{hL}{k_f}$	Ratio of the momentum and thermal diffusivities.
Reynolds No. (Re_L)	$\frac{VL}{\nu}$	Ratio of the inertia and viscous forces.
Schemidt No. (Sc)	$\frac{v}{D_{AB}}$	Ratio of the momentum and mass diffusivities.
Stanton No. (St)	$\frac{h}{\rho V_{Cp}} = \frac{Nu_L}{Re_L Pr}$	Modified Nusselt number.

1.7 Thermal diffusivity

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

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho c}$$

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.

STUDENT'S ASSIGNMENTS

1. Heat transfer takes place according to
   (a) Zeroth Law of thermodynamics
   (b) First Law of the thermodynamics
   (c) Second Law of thermodynamics
   (d) Third Law of thermodynamics

[IES 1996]

2. Match **List-I** with **List-II** and select the correct answer using the codes given below the lists:

List-I
A. Reynolds Number
B. Prandtl Number
C. Nusselt Number
D. Mach Number

List-II
1. Film coefficient, pipe diameter, thermal conductivity
2. Flow velocity, acoustic velocity.
3. Heat capacity, dynamic viscosity, thermal conductivity.
4. Flow velocity, pipe diameter, kinematic viscosity.

Codes:

	A	B	C	D
(a)	4	1	3	2
(b)	4	3	1	2
(c)	2	3	1	4
(d)	2	1	3	4

[IES 1996]

3. Match **List-I** (Process) with **List-II** (Predominant parameter associated with the flow) and select the correct answer using the code given below the lists:

List-I
A. Transient conduction
B. Mass transfer
C. Forced convection
D. Free convection

List-II
1. Sherwood Number
2. Nusselt Number
3. Biot Number
4. Grashof Number

Codes:

	A	B	C	D
(a)	2	4	3	1
(b)	3	1	2	4
(c)	2	1	3	4
(d)	3	4	2	1

[IES 2004]

Q.4 Two parallel plates are kept horizontally with small distance between them. The gap between them is filled with air. The upper plate is maintained at higher temperature than the lower plate. The mode of heat transfer between them will be
   (a) Convection and radiation
   (b) Convection only
   (c) Conduction and radiation
   (d) Radiation only

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

Q.6 Thermal diffusivity is a
   (a) function of temperature
   (b) physical property of a substance
   (c) dimensionless parameter
   (d) all of these

Q.7 Thermal conductivity of water __________ with rise in temperature.
   (a) remains same
   (b) decrease
   (c) increase
   (d) may increase or decrease depending on temperature available

ANSWER KEY // STUDENT'S ASSIGNMENTS

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

■■■■

CHAPTER 02

Conduction

2.1 Introduction

In the case of steady-state heat conduction, the temperature ceases to be a function of time, it becomes a function of space coordinates only. Hence, we can express steady-state conduction

$$T = f(x, y, z)$$

Under many practical situations, the conduction of heat is significant in only one direction of the coordinate axes, and is negligible in the other two directions. The heat conduction is then termed one-dimensional heat conduction and temperature becomes $T = f(x, t)$

In the case of a steady one-dimensional heat conduction, the temperature is a function of one space coordinate only.

2.1.1 Fourier's Law

- The rate of heat conduction is proportional to the area measured normal to the direction of heat flow and to the temperature gradient in that direction.

  $$Q = -KA\frac{\partial T}{\partial x}$$

  The ratio dT/dx represent the change in temperature per unit thickness, i.e. the temperature gradient. The negative sign indicate that heat flows in the direction of –ve temperature gradient.
- Fourier Law is valid for all matter regardless of its state; solid, liquid or gas.
- Unit of thermal conductivity K is W/m°C and heat flux, q is W/m^2 and of Temperature gradient is (°C/m)

2.2 Thermal Conductivity

- It can be defined as the rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference.

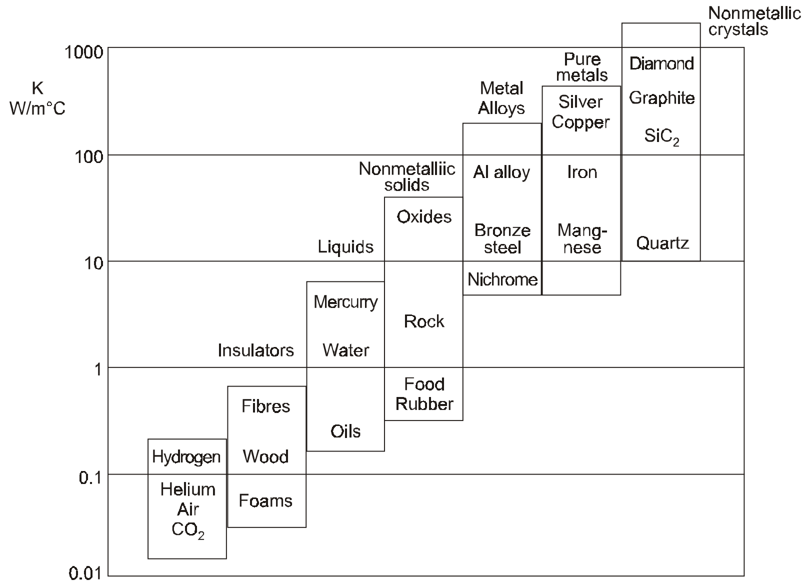

Figure 2.1

- Thermal conductivity of gases is proportional to the square root of the absolute temperature *T*, and inversely proportional to the square root of the molar mass *M*.

  Hence thermal conductivity of a gas increases with increasing temperature and decreasing molar mass.
- In the limiting case of absolute vacuum, the thermal conductivity will be zero since there will be no particles in this case to "conduct" heat from one surface to the other, and thus the conduction heat transfer will be zero.
- Materials having a crystal line structure have a high value of '*k*' than amorphous form.
- $k_{(\text{hardened steel})} < k_{(\text{Annealed steel})}$

  $k_{(\text{hot working})} < k_{(\text{cold working})}$
- Highest thermal conductivity = Graphene = 5000 W/mK. Thermal conductivity of diamond is also very high = 2300 W/mK.

  Lowest thermal conductivity = Freon 12 = 0.0083 W/mK.

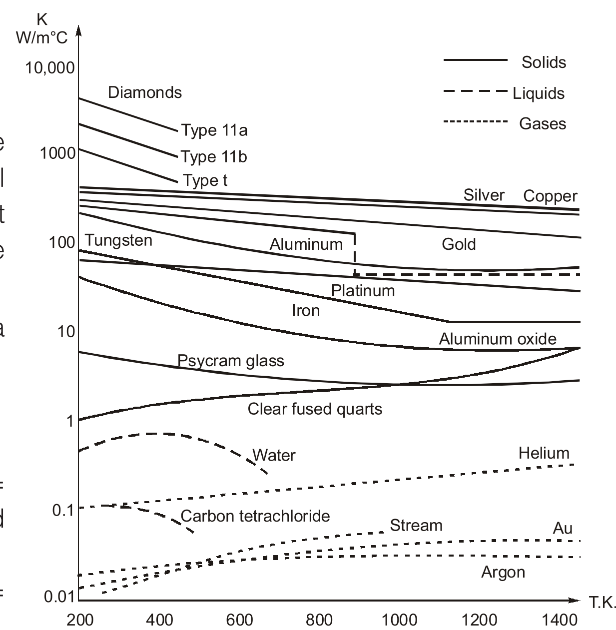

Figure 2.2

2.3 Some Points about Thermal Conductivity

- For solids and liquids the thermal conductivity in general decreases with temperature (exception aluminium and water)
- Thermal conductivity is always higher in purest form of metal and decreases with alloying and impurities
- Mechanical forming or heat treatment produces appreciable changes in thermal conductivity.
- Thermal conductivity of metals decrease with temperature.
- Thermal conductivity of damp material is considerably higher than dry material.
- In liquids and solids thermal and electrical conductivity are proportional to each other (exception is diamond)