

Production & Industrial Engineering

General Engineering Vol. VII : Heat Transfer



Comprehensive Theory
with Solved Examples and Practice Questions





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**General Engineering: Vol. VII :
Heat Transfer**

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General Engineering

Heat Transfer

In heat transfer problems, we often interchangeably use the terms heat and temperature. Actually, there is a distinct difference between the two. Temperature is a measure of the amount of energy possessed by the molecules of a substance. It manifests itself as a degree of hotness, and can be used to predict the direction of heat transfer. The usual symbol for temperature is T . The scales for measuring temperature in SI units are the celsius and kelvin temperature scales. Heat, on the other hand, is energy in transit. Spontaneously, heat flows from a hotter body to a colder one. The usual symbol for heat is Q . In the SI system, common units for measuring heat are the joule and calorie.

7.1 Difference between Heat Transfer and Thermodynamics

Thermodynamics tells us :

- how much heat is transferred (δQ)
- how much work is done (δW)
- final state of the system

Heat transfer tells us :

- how (with what **modes**) δQ is transferred
- at what **rate** δQ is transferred
- temperature distribution inside the body



7.2 Modes of Heat Transfer

Heat transfer may be defined as the transmission of energy from one region to another as a result of temperature gradient and it takes place by three modes :

1. **Conduction.**

Conduction is the transfer of heat from one part of a substance to another part of the same substance or from one substance to another in physical contact with it, without appreciable displacement of molecules forming the substance.

2. **Convection.**

Convection is the transfer of heat within a fluid by mixing of one portion of the fluid with another.

- (i) **Free or natural convection** : It occurs when the fluid circulated by virtue of the natural differences in densities of hot and cold fluids, the denser portions of the fluid move downward because of the greater force or gravity, as compared with the force on the less dense.
- (ii) **Forced convection** : When work is done to blow or pump the fluid, it is said to be forced convection.

3. Radiation.

Radiation is the transfer of heat through space or matter by means other than conduction or convection. Radiation of heat is thought of as electromagnetic waves or quanta (as convenient) an emanation of the same nature as light and radio waves. All bodies radiate heat, so a transfer of heat by radiation occurs because hot body emits more heat than it receives and a cold body receives more heat than it emits. Radiant energy (being electromagnetic radiation) requires no medium for propagation, and will pass through a vacuum.

7.3 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.

The thermal conductivity, k can be defined by Fourier law, equation.

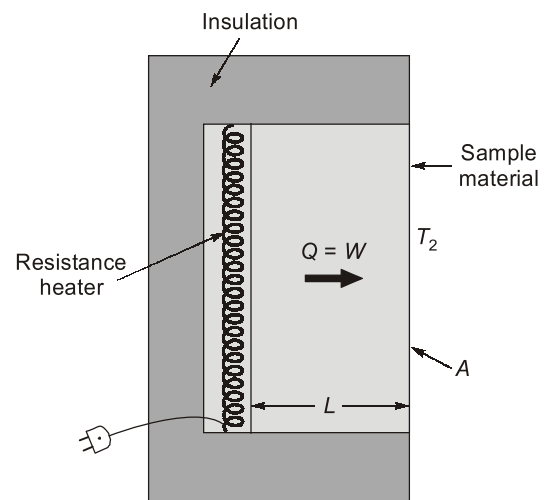
$$k = -\frac{(Q/A)}{(dT/dx)}$$

This equation is used for determination of thermal conductivity of a material. A layer of solid material of thickness L and area A is heated from one side by an electric resistance heater as shown in figure.

If the outer surface of heater is perfectly insulated, then all the heat generated by resistance heater will be transferred through the exposed layer of material. When steady state condition is reached, the temperature of two surface of material T_1 and T_2 are measured and thermal conductivity of material is determined by relation.

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

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



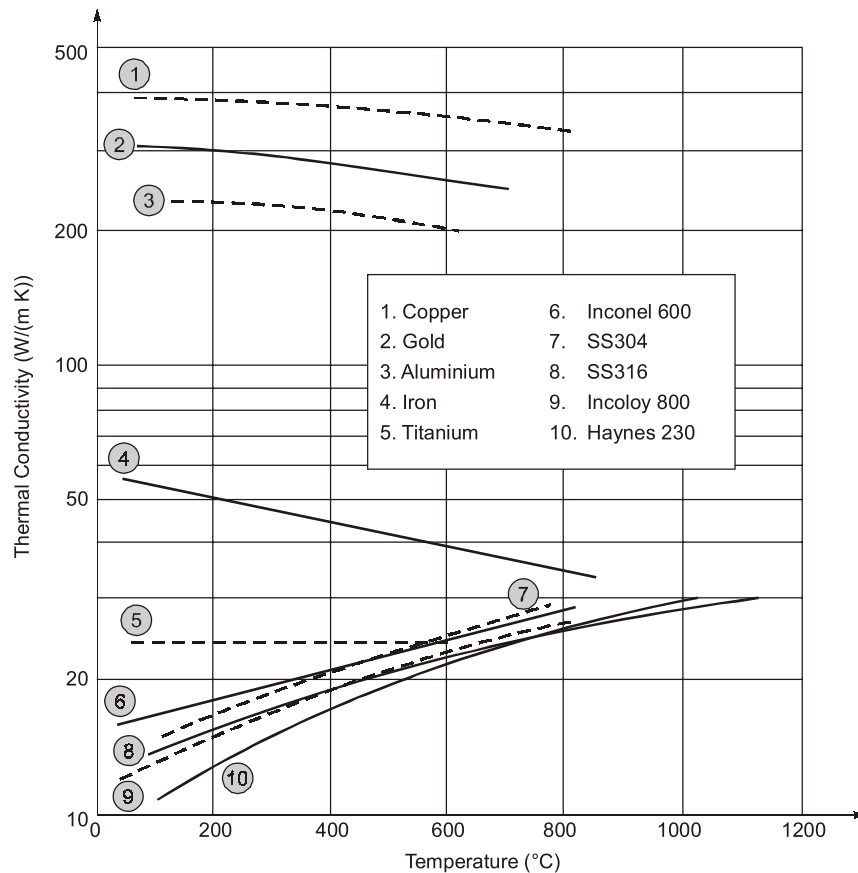
Experimental set-up for determination of thermal conductivity

7.3.1 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.

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

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



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

7.3.2 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.

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.

7.4 One Dimensional Steady State Heat Conduction

7.4.1 Fourier's Law of Conduction

This is an empirical law based on observation and states.

That the rate of flow of heat through a single homogeneous solid is directly proportional to the area of the section at right angles to the direction of heat flow, and the change of temperature with respect to the length of the path of the heat flow.

It is represented by the equation,

$$Q \propto A \cdot \frac{dt}{dx}$$

Thus,

$$Q = -k.A \frac{dt}{dx}$$

where k = constant of proportionality and is known as thermal conductivity of the body.

The -ve sign of k is to take care of the decreasing temperature along with the direction of increasing thickness of the direction of heat flow. The temperature gradient $\frac{dt}{dx}$ is always negative along positive x direction and therefore the value of Q becomes +ve.

Now,
$$k = \frac{Q}{A} \cdot \frac{dx}{dt}$$

Unit of k :
$$W \times \frac{1}{m^2} \times \frac{m}{K} = \frac{W}{mK}$$

From the above equation, materials with high thermal conductivities are good conductors of heat, whereas materials with low thermal conductivities are good thermal insulators. Conduction of heat occurs most readily in pure metals, less so in alloys, and much less readily in non-metals. The very low thermal conductivities of certain thermal insulators, e.g., cork is due to their porosity, the air trapped within the material acting as an insulator.

Sequence of materials of decreasing thermal conductivity

- (i) Pure metal
- (ii) Metal alloys
- (iii) Non-metallic crystalline and amorphous substance
- (iv) Liquid
- (v) Gases

7.4.2 Conduction through Plane Wall

The rate of heat transfer through the wall can be written according to Fourier's law of heat conduction

$$q_x = -k \frac{dT}{dx}$$

or

$$Q_x = q_x A = -kA \frac{dT}{dx} \quad \dots(i)$$

Upon integration of Eqn. (i) in consideration of the fact that Q_x and A are both independent of x , we have

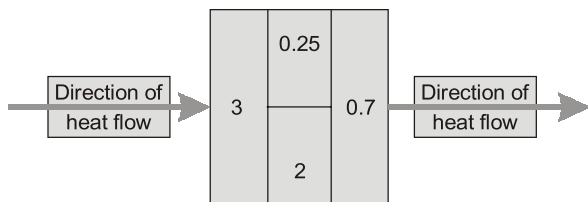
$$Q_x \int_1^2 dx = -kA \int_1^2 dT$$

The thermal conductivity k is assumed to be constant. The subscripts 1 and 2 correspond to the two faces of the wall which are kept at temperatures T_1 and T_2 respectively (as shown in fig.).

$$Q_x L = -kA(T_2 - T_1)$$

**Student's
Assignments****1**

- Q.1** The wavelength at which the black body emissive power reaches its maximum value at 1000 K
 (a) $5.1 \mu\text{m}$ (b) $2.9 \mu\text{m}$
 (c) $15.5 \mu\text{m}$ (d) $38.0 \mu\text{m}$
- Q.2** A straight fin of constant cross-sectional area for all along its length and made of a material of thermal conductivity k serves to dissipate heat to surroundings from a surface held at a constant temperature. What additional data is required to workout the rate of heat dissipation?
 (a) The root and tip temperature
 (b) The temperature gradient at the root
 (c) The temperature gradient at the tip
 (d) The convective heat transfer coefficient and the fin parameter
- Q.3** A tube with 20 mm outside diameter is covered with an insulation ($k = 0.18 \text{ W/mK}$). The outside surface convection coefficient is $15 \text{ W/m}^2\text{K}$. The critical thickness of insulation is _____ mm.
- Q.4** A composite wall is made of four different materials of construction in the fashion shown below. The resistance (in K/W) of each of the section of the wall is indicated in the diagram.



The overall resistance of the composite wall, in the direction of heat flow, is _____ K/W.

- Q.5** A coolant fluid at 30°C flows over a heated flat plate maintained at a constant temperature of 110°C . The boundary layer temperature distribution at a given location on the plate may be approximated as $T = 30 + 160e^{-y}$ where y (in m) is the distance normal to the plate and T is in $^\circ\text{C}$. If thermal conductivity of the fluid is 1.0 W/m-K , the local convective heat transfer coefficient at that location will be _____ $\text{W/m}^2\text{-K}$.

- Q.6** The fin efficiency for a circular infinitely long fin of diameter d , length L and thermal conductivity k exposed to convection to a medium at T_∞ with a heat transfer coefficient h , is

$$(a) \quad \eta = \frac{1}{L} \sqrt{\frac{kd}{h}} \quad (b) \quad \eta = \frac{1}{L} \sqrt{\frac{h}{kd}}$$

$$(c) \quad \eta = \frac{1}{2L} \sqrt{\frac{h}{kd}} \quad (d) \quad \eta = \frac{1}{2L} \sqrt{\frac{kd}{h}}$$

- Q.7** A surface at 150°C is placed in an environment at 25°C . The maximum rate of heat that must be emitted from per unit area of this surface, is
 (a) 28.70 W/m^2 (b) 1368.14 W/m^2
 (c) 1815.28 W/m^2 (d) 1193.20 W/m^2

- Q.8** A 100 mm diameter steel pipe is placed horizontally in ambient at 25°C . Take Nusselt number as 20 and thermal conductivity of air as 0.06 W/mK . The heat transfer coefficient is _____ $\text{W/m}^2\text{K}$.

- Q.9** Water at 10°C flows over a flat plate (at 90°C) with a velocity of 3 m/s. Properties of water at 50°C are :
 $\rho = 988.1 \text{ kg/m}^3$, $\nu = 0.56 \times 10^{-6} \text{ m}^2/\text{s}$, $Pr = 3.54$, $k = 0.648 \text{ W/mK}$. The flow will be laminar upto the length of
 (a) 8.33 cm (b) 9.33 cm
 (c) 10.33 cm (d) 11.33 cm

- Q.10** A 40 cm long, 0.4 cm diameter electric resistance submerged in water is used to determine the convective heat transfer coefficient in water during boiling at 1 atm pressure. The surface temperature of wire is measured to be 114°C . If the wattmeter indicates the power consumption as 7.6 kW, convective heat transfer coefficient is
 (a) $108 \text{ W/m}^2\text{K}$ (b) $108 \text{ kW/m}^2\text{K}$
 (c) $108 \text{ MW/m}^2\text{K}$ (d) $10.8 \text{ MW/m}^2\text{K}$

- Q.11** The temperature distribution in a sphere of constant thermal conductivity along radius is :
 (a) Parabolic (b) Hyperbolic
 (c) Logarithmic (d) Elliptic

- Q.12** A spherical thermocouple of diameter 0.70 mm is made up of alloys of Aluminium and Chromium. The surface convection resistance is 1050 K/W . Properties of alloys are given below :

Q.22 Match List-I with List-II and (all symbols have usual meaning). Select the correct answer using the codes given below the list:

List-I **List-II**

- | | |
|-------------------|-----------------------------|
| A. Lewis number | 1. $\frac{hL}{k}$ |
| B. Fourier number | 2. $\frac{LV}{\alpha}$ |
| C. Peclet number | 3. $\frac{\alpha\tau}{L^2}$ |
| D. Biot number | 4. $\frac{\alpha}{D}$ |

Codes:

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

Q.23 Two long parallel plates are maintained at different temperatures and have emissivities of 0.8 and 0.6 respectively. It is desired to reduce the net rate of radiation heat transfer between the plates by 90% by inserting thin parallel shields of emissivity of 0.29 on each side. The number of radiation shields required, is

- (a) 2 (b) 3
(c) 4 (d) 5

Q.24 A steam pipe having wall temperature of 200°C is running through a room at 25°C. The convection heat transfer coefficient is 6 W/m²K. Taking emissivity of the pipe surface as 0.8, the combined heat transfer coefficient due to convection and radiation is _____ W/m²K. (Correct upto two decimal places)

Q.25 If we increase the thickness of insulation inside in a given pipe or sphere which of the following is true?

- (a) conduction resistance increases and convection resistance decreases
(b) conduction resistance decreases and convection resistance increases
(c) both conduction and convection resistance increases
(d) both conduction and convection resistance decreases

ANSWERS

- | | | | |
|------------|-------------|---------------|-------------|
| 1. (b) | 2. (b) | 3. (2) | 4. (3.92) |
| 5. (2) | 6. (d) | 7. (c) | 8. (12) |
| 9. (b) | 10. (b) | 11. (b) | 12. (c) |
| 13. (338) | 14. (54.44) | 15. (2544.69) | 16. (a) |
| 17. (1.25) | 18. (4) | 19. (0.706) | 20. (d) |
| 21. (c) | 22. (d) | 23. (b) | 24. (16.93) |
| 25. (c) | | | |

HINTS

1. (b)

$$\lambda T = 2898 \mu\text{mK}$$

$$\lambda = \frac{2898}{T} = \frac{2898}{1000} = 2.898 \text{ mm}$$

2. (b)

Refer following relation

$$Q_{\text{fin}} = -kA \left[\frac{dT}{dx} \right]_{x=0}$$

3. (2)

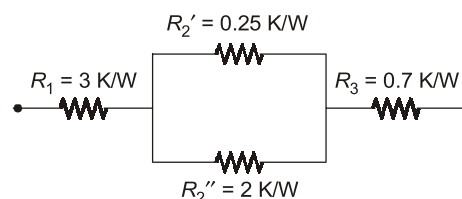
Critical radius of insulation

$$= \frac{k}{h_0} = \frac{0.18}{15} = 0.012 \text{ m} = 12 \text{ mm}$$

$$\text{Critical thickness} = 12 - 10 = 2 \text{ mm}$$

4. (3.92) (3.88 to 3.95)

Resistances(R) can be shown by,



$$\frac{1}{R_2} = \frac{1}{R_2'} + \frac{1}{R_2''} = \frac{1}{0.25} + \frac{1}{2} = 4 + 0.5 = 4.5$$

$$R_2 = \frac{1}{4.5} = 0.222 \text{ K/W}$$

∴ Overall resistance (R_o)

$$= R_1 + R_2 + R_3 = 3 + 0.222 + 0.7 = 3.922 \text{ K/W}$$