Production & Industrial Engineering

General Engineering

Vol. VII : Heat Transfer

Comprehensive Theory

with Solved Examples and Practice Questions

MADE EASY Publications

MADE EASY Publications

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016
E-mail: infomep@madeeasy.in
Contact: 011-45124660, 8860378007
Visit us at: www.madeeasypublications.org

General Engineering : Vol. VII – Heat Transfer

First Edition : 2020

Contents

Heat Transfer

7.1 Difference between Heat Transfer and Thermodynamics 1

7.2 Modes of Heat Transfer 1

7.3 Thermal Conductivity 2

7.4 One Dimensional Steady State Heat Conduction 4

7.5 Unsteady State Heat Conduction 19

7.6 Extended Surface or Fins 20

7.7 Convective Heat Transfer 32

7.8 Free Convection 36

7.9 Radiation Heat Transfer 40

Student's Assignments 60

■■■■

VOLUME VII

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 of pump the fluid, it is said to be forced convection.

3. **Radiation.**

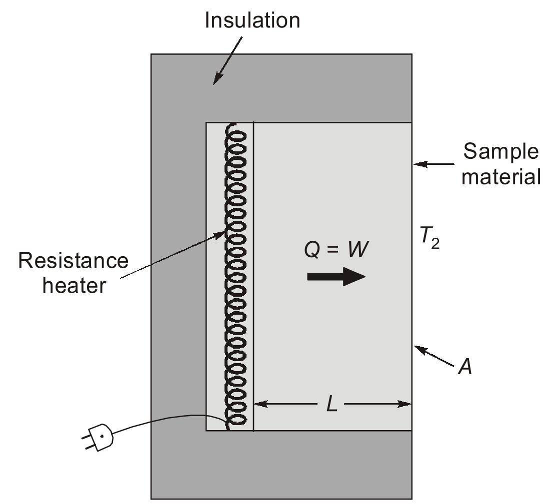
Radiation is the transfer of heat through space or matter by means other than conduction or convection. Radiation of heat is thought of as electromagnetic waves or quanta (as convenient) an emanation of the same nature as light and radio waves. All bodies radiate heat, so a transfer of heat by radiation occurs because hot body emits more heat that 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.

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



Experimental set-up for determination of thermal conductivity

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)

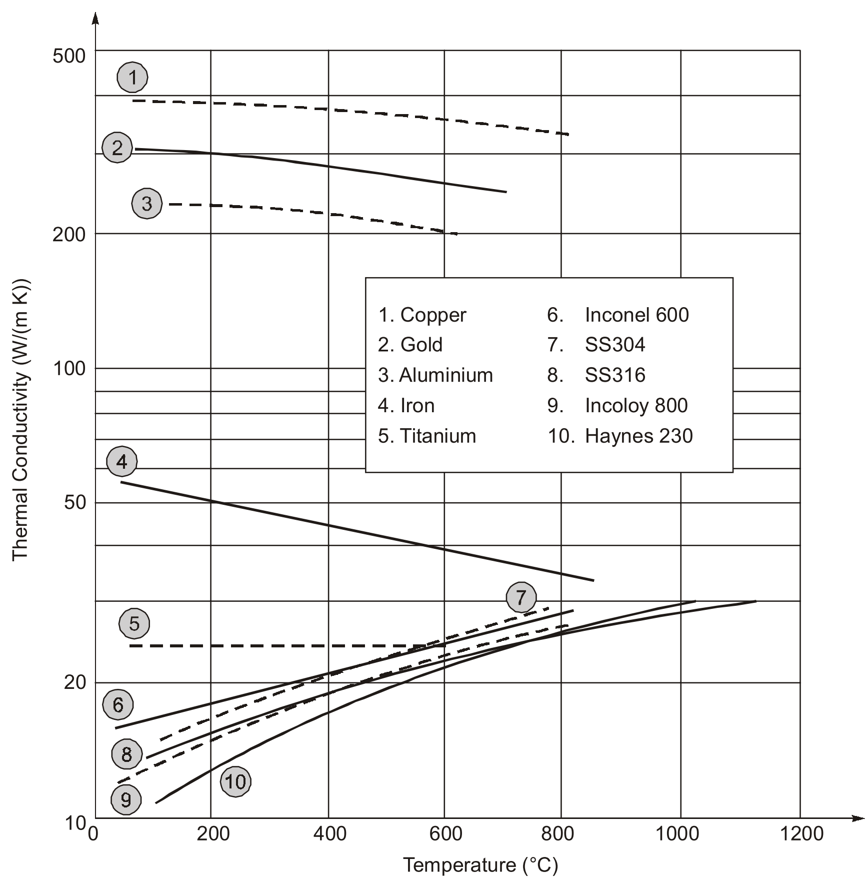
Material	k(W/(m°C))	Material	k(W/(m°C))
Diamond	2300	Mercury (liquid)	8.54
Silver	429	Glass	0.78
Copper	401	Brick	0.72
Gold	317	Water (liquid)	0.613
Aluminium	237	Human skin	0.37
Iron	80.2	Wood (oak)	0.17
Helium (g)	0.152	Glass fibre	0.043
Soft rubber	0.13	Air (g)	0.026
Refrigerant-12	0.072	Urethane,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

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 be 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 :
$$\text{W} \times \frac{1}{\text{m}^2} \times \frac{\text{m}}{\text{K}} = \frac{\text{W}}{\text{mK}}$$

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

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.).

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