1

Basic Concepts of Heat Transfer

1.1 INTRODUCTION

Heat transfer may be defined as the science that predicts the transfer of energy from one body to another by virtue of temperature difference. Thermodynamics is the science which deals with the systems in equilibrium. It predicts the extent of heat and work interactions when a system passes from one equilibrium state to another. Heat transfer provides the answers to the questions to the extent and manner of transfer of heat in any process.

There must be a potential difference for the transfer of heat. The difference in temperature provides the necessary potential difference. According to the second law of thermodynamics, heat cannot flow from a body at low temperature to a body at higher temperature without employing external work. Thus, heat must flow from a higher temperature region to a lower temperature region until equilibrium is reached when the two bodies attain the same temperature. Thus heat transfer is essentially an irreversible process.

1.2 DIFFERENCES BETWEEN THERMODYNAMICS AND HEAT TRANSFER

The basic differences between thermodynamics and heat transfer may be summarised as given in Table 1.1.

Table 1.1 Differences between thermodynamics and heat transfer

Thermodynamics	*Heat transfer*
1. It is concerned with the equilibrium state of matter.	1. It is concerned with the non-equilibrium process.
2. It precludes the existence of a temperature gradient.	2. Temperature gradient is essential for heat transfer.
3. It helps to determine the quantity of work and heat interaction when a system undergoes a change from one equilibrium state to another.	3. It provides the information on the nature of interactions and the time rate at which interactions occur between work and heat.
4. It does not provide the information about the temperature distribution in the body.	4. It helps to predict the temperature distribution within the body and the rate at which energy is transferred.

1.3 APPLICATIONS OF HEAT TRANSFER

The applications of heat transfer are in the following disciplines:

1. Design of steam generators, condensers, solar energy conversion and for electric power generation.
2. Internal combustion engines.
3. Refrigeration and air-conditioning units.
4. Design of cooling systems for electric motors, generators and transformers.
5. Evaporation, condensation, heating and cooling of fluids in chemical operations.
6. Construction of dams and other heavy structures.
7. Thermal expansion of suspension bridges and railway tracks.
8. Minimisation of heat losses in buildings by using improved insulation techniques.
9. Thermal control of space vehicles.
10. Heat treatment of metals.
11. Proper functioning of thermal valves and devices.
12. Dispersion of atmospheric pollutants.

1.4 MODES OF HEAT TRANSFER

The three modes of heat transfer are:

1. Conduction
2. Convection
3. Radiation.

1. Conduction. The heat is transferred within a stationary medium by conduction, *viz*, from particle to particle, whether it be a solid, liquid or gas, as illustrated in Fig. 1.1. Heat is transmitted by conduction through a wall, an air gap, and so on.

Fig. 1.1 Principle of heat conduction.

In solids like metals and alloys, heat is conducted by lattice vibrations and transport of free electrons. In liquids and gases, the kinetic energy of molecules is a function of temperature. The heat energy is transferred from one molecule to the other by collisions of molecules.

2. Convection. Convection is the transfer of heat within a fluid by mixing of one portion of the fluid with another. In convection, there must be a flow of liquid or gas. Heat is carried away by the flow of the fluid as illustrated in Fig. 1.2.

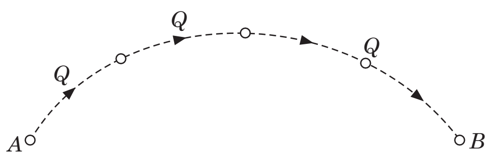

Fig. 1.2 Principle of heat convection.

Heat convection takes place in two ways:

(*a*) Forced convection

(*b*) Natural or free convection.

In forced convection, the flow of a fluid is produced by an external source such as a pump or a fan. Examples of forced convection are:

Water tube boiler, shell and tube condenser of a refrigeration plant, etc., in which flow of water is maintained by a pump. Other examples are radiator of a car, air-cooled condenser of an air conditioner, etc., where flow of air is maintained by a fan.

In natural or free convection, the flow of fluid is produced by the difference in density due to temperature difference. Higher temperature fluid, being lighter, rises up and lower temperature fluid, being heavier, settles down. Thus, a natural convection current is set up in the fluid. Examples are: heating of water in a vessel, the flow of wind on land surface, condenser of a domestic refrigerator.

3. Radiation. Radiation is the transfer of heat in the form of electromagnetic waves. Thus, thermal radiation reaches B from A directly, like the throw of an object, as illustrated in Fig. 1.3. For radiative heat transfer, therefore, the presence of a medium is not necessary.

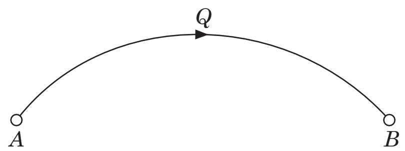

Fig. 1.3 Principle of heat radiation.

Some of the properties of radiant heat transfer are:

(*i*) It does not require a medium for transmission.

(*ii*) Radiant heat energy obeys ordinary laws of reflection from surfaces.

(*iii*) It travels with the velocity of light.

(*iv*) It follows the law of inverse square.

(*v*) The wavelength of heat radiations is longer than that of light waves.

Hence, they are invisible to eye.

1.5 FOURIER'S LAW OF HEAT CONDUCTION

This law states that the rate of flow of heat through a homogeneous solid is directly proportional to the area of the section at right angles to the direction of heat flow and the temperature gradient that exists within the body.

Thus at any point A in a body, if the temperature gradient is $\frac{dT}{dx}$, as shown in Fig. 1.4, then rate of heat transfer is,

$$\dot{Q} \ \alpha - A_c \frac{dT}{dx} = -kA_c \frac{dT}{dx} \quad ...(1.1)$$

where k = constant of proportionality and is known as thermal conductivity of the body. It is a property of the material of the body.

A_c = area of cross-section.

The minus sign is inserted to make $\dot{Q}$ positive since $\frac{dT}{dx}$ is negative, as per second law of thermodynamics, heat must flow in the direction of decreasing temperature.

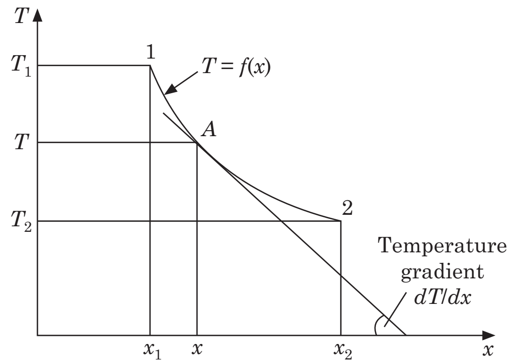

Fig. 1.4 Temperature distribution through a medium and temperature gradient.

For the case of steady state heat conduction through a uniform slab, Eqn. (1.1) can be integrated to give

$$\dot{Q} = -kA_c \frac{\Delta T}{\Delta x} = kA_c \left[\frac{T_1 - T_2}{x_2 - x_1}\right] \quad ...(1.2)$$

The heat transfer rate per unit area of a surface is called heat flux and is denoted by the symbol q.

$$q = \frac{\dot{Q}}{A_c} = -k \cdot \frac{\Delta T}{\Delta x} \quad ...(1.3)$$

1.5.1 Assumptions of Fourier's law. The assumptions made in the Fourier's law are:

1. Conduction of heat takes place under steady state conditions.
2. The heat flow is unidirectional.
3. The temperature gradient is constant and temperature profile is linear.
4. There is no internal heat generation.
5. The bounding surfaces are isothermal in character.

6. The thermal conductivity is constant in all directions.
7. The law is based on experimental evidence.

1.5.2 Thermal Conductivity. From Eqn. (1.1), we have

$$k = \frac{\dot{Q}}{A_c} \times \frac{\Delta x}{\Delta T}$$

when $\dot{Q} = 1, A_c = 1$ and $\frac{\Delta T}{\Delta x} = 1$, then $k = 1$.

The SI units of thermal conductivity may be derived as:

$$k = \frac{W}{m^2} \cdot \frac{m}{K} = \text{W/(m.K) or W/(m.°C)}.$$

Thermal conductivity may be defined as the amount of heat that will flow per unit of time, per unit of area normal to the direction of flow of heat, through a unit thickness of the material and when the temperature difference across the thickness is unity.

The thermal conductivity of various common materials at 273 K is given in Table 1.2. It is seen that the order of decreasing thermal conductivity is as follows:

Metals—Non-metals—Liquids—Gases.

It is seen that copper has the highest thermal conductivity and is the best material for heat transfer equipment. In general, thermal conductivity is strongly dependent upon temperature. In most cases, it increases with temperature and the dependent can be expressed as:

$$k = k_0 (1 + \beta t) \qquad ...(1.4)$$

where k_0 = thermal conductivity at 0°C.

β = temperature coefficient of thermal conductivity, 1/°C.

General observations for change in thermal conductivity with rise in temperature are:

1. Thermal conductivity of pure metals decreases with increase of impurity and increase in temperature (aluminium and uranium being exceptions)

Table 1.2 Thermal Conductivities of Materials

Material	*Thermal Conductivity* $Wm^{-1}\,K^{-1}$
Metallic Solids	
Sliver	418
Copper	387
Aluminium	203
Zinc	112.7
Brass	112
Iron	73
Tin	66
Lead	34.7
18–8 Chrome-nickel steel	16.3
Non-metallic Solids	
Marble	2.08–2.94
Ice	2.22
Glass, window	0.78
Concrete (ACC)	1.6
Plaster	1.3
Bricks, frontage	0.82
—, light weight	0.58
Wood (dried)	0.16
Refractory Materials	
Fire brick	0.14
Clay	1.04
Insulating Materials	
Asbestos, hard	0.234
Asbestos, loose	0.154
Magnesia (85%)	0.07
Mineral wool	0.047
Glass wool	0.045
Cork	0.038
Liquids	
Mercury	8.21
Water	0.556
Ammonia	0.54
Lubricating oil, SAE 50	0.147
Freon-12	0.073
Gases	
Air	0.024
Water vapour (saturated)	0.0206
Carbon dioxide	0.0145

2. Thermal conductivity of most liquids decreases with increase in temperature (water being an exception).

3. Thermal conductivity of gases increases with increase in temperature.

4. Dampness increases the thermal conductivity of materials.

5. The ratio of thermal and electrical conductivities is same for all metals at the same temperature; and that the ratio is directly proportional to the absolute temperature of the metal. This is known as Wiedemann and Frenz law.

$$\text{Now} \quad \frac{k}{\sigma} \propto T \quad \text{or} \quad \frac{k}{\sigma T} = C \qquad \text{...(1.5)}$$

where k = thermal conductivity of metal at temperature $T(K)$

σ = electrical conductivity of metal at temperature $T(K)$

C = constant known as Lorenz number

$= 2.45 \times 10^{-8}$ WΩ/K^2, where Ω stands for ohms.

1.5.3 Guarded Hot Plate Apparatus for Measurement of Thermal Conductivity. This is a standard method for measurement of thermal conductivity of insulating materials. Two identical test samples (Fig. 1.5) are taken, placed on each side of a hot plate and identical cooling units are in turn clamped against the outside faces of these samples. This hot plate is surrounded by guard sections which are maintained at the same temperature as the central plate so that edgewise heat flow from the test area is prevented. The heat generated in the central hot plate therefore flows equally through the two samples. The temperatures at the hot and the cold faces of both the samples are measured. Knowing the heat generated in central heating plate, its area, the thickness of the test samples and the temperatures at their hot and cold faces, the value of thermal conductivity can be computed.

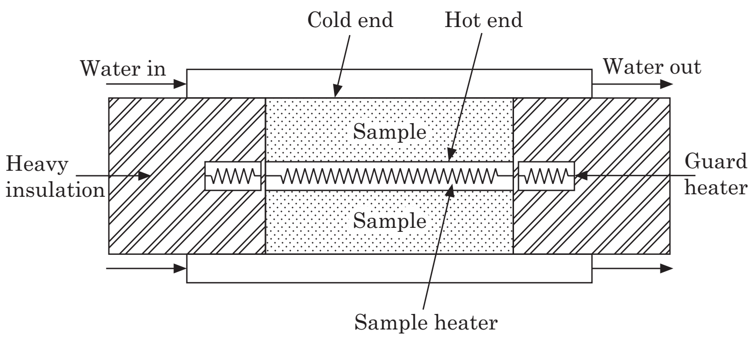

Fig. 1.5 Guarded hot plate apparatus.

1.5.4 Thermal Resistance. The heat transfer processes may be compared by analogy with the flow of electricity in an electrical resistance. As the flow of electric current in the electrical resistance is directly proportional to potential difference (dV), similarly heat flow rate, $\dot{Q}$, is directly proportional to temperature difference (dT).

According to Ohm's law,

Current, $$I = \frac{\text{potential difference, dV}}{\text{electrical resistance, R}}$$

According to Fourier's law,

Heat flow rate, $$\dot{Q} = \frac{\text{temperature different, dT}}{\left(\dfrac{dx}{kA_c}\right)} = \frac{dT}{(R_t)_{\text{cond.}}}$$

By analogy, the quantity $\dfrac{dx}{kA_c}$ is called thermal conduction resistance, R_t, *i.e.* $(R_t)_{\text{cond.}} = \dfrac{dx}{kA_c}$

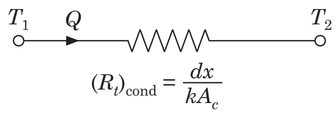

Fig. 1.6 Conduction thermal resistance.

Thermal conductance = $\dfrac{1}{R_t}$

The concept of conduction thermal resistance is depicted in Fig. 1.6.

1.6 NEWTON'S LAW OF COOLING FOR CONVECTION

When a fluid flows over a wall which is at a different temperature than the fluid, heat will flow from the wall to the fluid or from the fluid to the wall depending on the direction of temperature gradient. Although this mode of heat transfer is named convection, the physical mechanism of heat transfer at the wall is a conduction process.

Consider a fluid flowing along a wall which is at temperature T_w as shown in Fig. 1.7. The free stream temperature of the fluid is T_∞. Then a temperature field varying from T_w to T_∞ will establish in the fluid near the wall. Let δ be the distance from the wall, of the point in the fluid at which temperature of the fluid just becomes equal to the free stream temperature T_∞. This distance δ is called the *thermal boundary layer*, representing the thickness of a film over which the temperature drop or rise takes place.

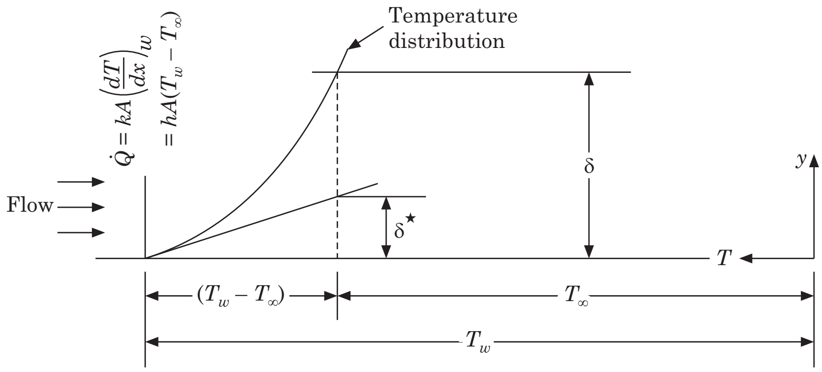

Fig. 1.7 Heat transfer between a wall and a flowing fluid.

The concept of a *heat transfer* or so called *film coefficient* was introduced by Newton in 1701. He recommended the following equation to describe the convective heat transfer.

$$\dot{Q} = hA_s(T_w - T_\infty) \qquad ...(1.6)$$

where h is called the *film* or *heat transfer coefficient.* Although this is often referred to as *Newton's Law of Cooling,* it has proved to be really a definition of h rather than a law. It states that the heat transfer rate from a surface to a fluid, flowing along it, is equal to the product of the temperature difference between the surface and the free stream of the fluid and a quantity h, which depends on the convective character of the flowing fluid. It must be noted that h is not a property of the fluid although it depends on the properties of the fluid as well, such as thermal conductivity k, viscosity μ, density ρ and specific heat c_p. These properties shall be referred to as *heat transport* properties. It is clear that higher the thermal conductivity, higher will be the value of h. Similarly, higher the value of heat capacity c_p the less will be the temperature rise of the fluid. With heat gain greater will be the temperature difference available for heat transfer and hence heat transfer and h will be greater. Further a low value of viscosity will result in faster movement of the fluid hence better heat transfer and higher h. In addition to these properties, h also depends on the flow conditions involving velocity and geometry of flow.

Appropriate values of h can be determined analytically or experimentally for various convective situations and various fluids. The use of these values in Eqn. (1.6) can thus provide a simple and reliable procedure for design calculations.

1.6.1 Film Heat Transfer Coefficient

The SI unit of film heat transfer coefficient may be derived.

$$[h] = \frac{[\dot{Q}]}{[A]\,[\Delta T]} = \frac{J/s}{m^2 K} = \text{Wm}^{-2}\,\text{K}^{-1}$$

It will be noted that the units of h differ from those of k by only a length factor. This similarity leads to the comparison of the Newton's law of cooling with the Fourier's law of heat conduction, *viz*.,

$$\dot{Q} = hA_s(T_w - T_\infty) = \frac{kA_c\,(T_w - T_\infty)}{\delta'} \qquad ...(1.7)$$

This comparison suggests that if an appropriate value of δ' is used, the heat transfer occurring could be treated as simple conduction.

The question arises as to what is the appropriate value of δ^*. Unfortunately, it is not possible to define a value which is physically significant. It is, however, useful to consider the flow of heat at the wall, to the fluid. If $\left(\frac{dT}{dy}\right)_w$ is the temperature gradient in the fluid at the wall, then we can write

$$\dot{Q} = hA_s(T_w - T_\infty) = -\,kA_c\left(\frac{dT}{dy}\right)_w \qquad ...(1.8)$$

Therefore,

$$h = \frac{-\,k\left(\frac{dT}{dy}\right)_w}{(T_w - T_\infty)} = \frac{k}{\delta'} \qquad ...(1.9)$$

and

$$\delta^* = -\,\frac{T_w - T_\infty}{\left(\frac{dT}{dy}\right)_w} \qquad ...(1.10)$$

We see that heat transfer coefficient is a measure of the temperature gradient at the wall and δ' represents an imaginary film thickness over which the temperature drops from T_w to T_∞ *linearly*.

It is evident that if temperature gradient at the wall could be measured, heat transfer rate between the fluid and the wall could be determined. But the temperature variation is very rapid in the vicinity of the wall and measurement of temperature gradient, if not difficult, would be extremely erroneous. Measurements pertaining to heat transfer coefficient are very simple and hence, it provides still the best and simple treatment of all convective situations.

An approximate idea of the numerical values of the film heat transfer coefficients can be had from Table. 1.3.

Table 1.3 Typical Values of Convective Heat Transfer Coefficients

Medium and Mode	*h*, $Wm^{-2}\,K^{-1}$
Free convection, air	5–25
Forced convection, air	10–500
Forced convection, water	100–15,000
Boiling water	2,500–25,000
Condensing water vapour	5,000–100,000

The quantity $\frac{1}{hA_s}$ is called the convection thermal resistance, $(R_t)_{\text{conv}}$, to heat flow, as shown in Fig. 1.8.

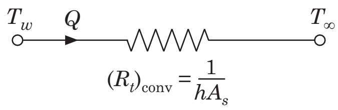

Fig. 1.8 Convection thermal resistance.

$$\dot{Q} = \frac{T_w - T_\infty}{(R_t)_{\text{conv}}} \qquad ...(1.11)$$

1.7 STEFAN – BOLTZMANN LAW FOR THERMAL RADIATION

This law states that thermal radiation emitted by a body is proportional to the fourth power of the absolute temperature, *viz*

$$\dot{Q} \propto T^4$$

For a black body, the radiation emitted is given by

$$\dot{Q} = \sigma\, AT^4 \qquad ...(1.12)$$

where A = surface area
σ = Stefan-Boltzmann constant
$= 5.67 \times 10^{-8}$ W/(m^2.K^4)

Thus if two black bodies at temperatures T_1 and T_2 having the same area A, exchange heat with each other only, then the net radiant heat exchange between them will be,

$$\dot{Q} = \sigma\, A(T_1^{\,4} - T_2^{\,4}) \qquad ...(1.13)$$

Thermal radiation emitted by a gray (non-black) radiator may be expressed by,

$$\dot{Q} = \varepsilon\, \sigma\, A T^4 \qquad ...(1.14)$$

where ε = emissivity of the gray body.

If two bodies are not black and also do not exchange heat with each other, only the radiant heat exchange between two bodies can be expressed by,

$$\dot{Q} = A_1 F_{12}\, \sigma\, (T_1^4 - T_2^4) \qquad ...(1.15)$$

where $F_{12} = f(F_\varepsilon, F_G)$

F_ε = emissivity function, $f(\varepsilon_1, \varepsilon_2)$

F_G = geometric 'view factor' function (a function of the geometry and orientation of the two bodies).

Eqn. (1.14) may be written as:

$$Q = F_{12}\, \sigma\, A_1 (T_1^2 - T_2^2)(T_1^2 + T_2^2)$$

$$= F_{12}\, \sigma\, A_1 (T_1 - T_2)(T_1 + T_2)(T_1^2 + T_2^2)$$

$$= \frac{T_1 - T_2}{\dfrac{1}{F_{12}\, \sigma\, A_1 (T_1 + T_2)(T_1^2 + T_2^2)}} = \frac{T_1 - T_2}{(R_t)_{rad}} \qquad ...(1.16)$$

1.7.1 Radiation Coefficient

For combined convection and radiation from a wall,

$$\dot{Q} = \dot{Q}_c + \dot{Q}_r = A h_c (T_w - T_\infty) + A_1 F_{12}\, \sigma\, (T_w^4 - T_\infty^4)$$

By analogy with convection,

$$\dot{Q}_r = A_1 h_r (T_w - T_\infty) = A_1 F_{12}\, \sigma\, (T_w^4 - T_\infty^4)$$

Radiative coefficient,

$$h_r = \frac{F_{12}\, \sigma \left(T_w^4 - T_\infty^4\right)}{\left(T_w - T_\infty\right)} \qquad ...(1.17)$$

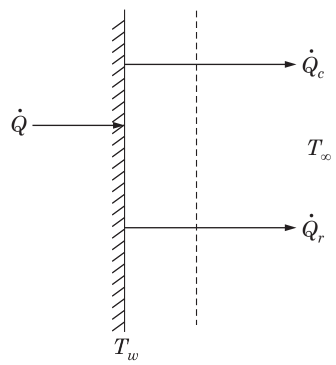

Fig. 1.9 Combined convection and radiation between wall and fluid.

1.8 HEAT TRANSFER THROUGH COMPOSITE BODIES

1.8.1 Resistances in Series. When resistances are in series, as shown in Fig. 1.10, then heat transfer rate through all the resistances is the same. There is a temperature drop through every resistance. Then

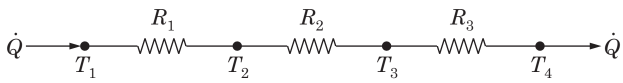

Fig. 1.10 Resistances in series.

$$\dot{Q} = \frac{T_1 - T_2}{R_1} = \frac{T_2 - T_3}{R_2} = \frac{T_3 - T_4}{R_3} = \frac{\Delta T}{R} \qquad ...(1.18)$$

So that individual temperature drops are:

$$T_1 - T_2 = \dot{Q}R_1$$
$$T_2 - T_3 = \dot{Q}R_2$$
$$T_3 - T_4 = \dot{Q}R_3$$

....

Adding, we get

$$T_1 - T_4 = \dot{Q}\,(R_1 + R_2 + R_3)$$

$$\dot{Q} = \frac{T_1 - T_4}{R_1 + R_2 + R_3} = \frac{\Delta T}{R}$$

where $\Delta T = T_1 - T_4$ = overall temperature difference

$R = R_1 + R_2 + R_3$ = overall thermal resistance.

In general, $$\dot{Q} = \frac{T_1 - T_{n+1}}{R} \qquad ...(1.19)$$

$$R = \sum_{i=1}^{n} R_i$$

We observe that the thermal resistances in series add to give the overall thermal resistance.

1.8.2 Resistances in Parallel

A symbolic representation of heat transfer through resistances in parallel is shown in Fig. 1.11. In this case, the net heat transfer rate is equal to the sum of heat transfer rates through all sections. At the same time, the temperature drop, $\Delta T = (T_1 - T_2)$, across each resistance, is the same. Then

$$\dot{Q}_1 = \frac{\Delta T}{R_1}$$

$$\dot{Q}_2 = \frac{\Delta T}{R_2}$$

$$\dot{Q}_3 = \frac{\Delta T}{R_3}$$

Adding, we get

$$\dot{Q} = \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3$$

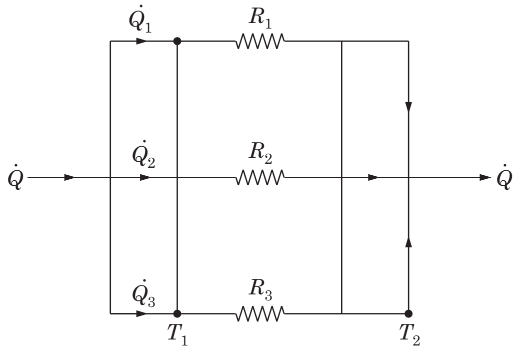

Fig. 1.11 Resistances in parallel.

$$= \Delta T \left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right] = \frac{\Delta T}{R}$$

where $$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

In general, $$\frac{1}{R} = \frac{1}{\sum_{i=1}^{n} R_i} \qquad \text{...(1.20)}$$

where R = overall thermal resistance.

Example 1.1 *Calculate the rate of heat transfer per unit area through a copper plate 30 mm thick whose one face is maintained at 300°C and the other face at 40°C. Take thermal conductivity of copper as 387 W/m.°C.*

Solution. Given : T_1 = 300°C, T_2 = 40°C,

Δx = 30 mm or 0.03 m,

k = 387 W/m.°C.

$\Delta T = T_1 - T_2 = 300 - 40 = 260$°C

Rate of heat transfer, $\dot{Q} = kA \dfrac{\Delta T}{\Delta x}$

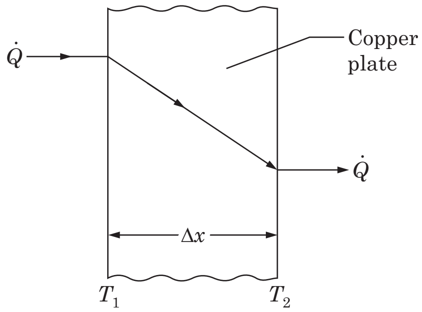

Fig. 1.12

Rate of heat transfer per unit area,

$$q = \frac{\dot{Q}}{A} = k\,\frac{\Delta T}{\Delta x} = 387 \times \frac{260}{0.03} = 3.354 \text{ MW/m}^2.$$

Example 1.2 *A hot plate 1 m × 1.25 m is maintained at 350°C. Air at 25°C is blowing over the plate. If the convective heat transfer coefficient is 20 W/m^2.°C, calculate the rate of heat transfer.*

Solution. Given: $A = 1 \times 1.25 = 1.25 \text{ m}^2$

$$T_w = 350°\text{C},\ T_\infty = 25°\text{C},\ h = 20 \text{ W/m}^2.°\text{C}.$$

Rate of heat transfer, $\dot{Q} = hA(T_w - T_\infty)$

$$= 20 \times 1.25\,(350 - 25) = 8125 \text{ W}$$

Example 1.3 *A surface having an area of 2 m^2 and maintained at 327°C exchanges heat by radiation with another surface at 37°C. The value of factor due to geometric location and emissivity is 0.5. Calculate:*

(*a*) *Heat lost by radiation,*

(*b*) *The value of thermal resistance, and*

(*c*) *The value of equivalent convection coefficient.*

Solution. Given: $A_1 = 2 \text{ m}^2,\ T_1 = 273 + 327 = 600 \text{ K},$

$$T_2 = 273 + 37 = 310 \text{ K},\ F_{12} = 0.5$$

(*a*) Heat lost by radiation,

$$\dot{Q} = A_1 F_{12}\,\sigma\,(T_1^4 - T_2^4)$$
$$= 2 \times 0.5 \times 5.67\,[6^4 - (3.1)^4] = 6824.7 \text{ W}$$

(*b*) Thermal resistance due to radiation,

$$(R_t)_r = \frac{T_1 - T_2}{\dot{Q}} = \frac{600 - 310}{6824.7} = 0.0425 \text{ K/W}$$

(*c*) Equivalent convection coefficient,

$$h_r = \frac{\dot{Q}}{A_1 (T_1 - T_2)} = \frac{6824.7}{2\,(600 - 310)}$$

$$= 11.76 \text{ W/m}^2.°\text{C}.$$

Example 1.4 *A steel plate 0.5 m × 1.0 m × 25 mm is maintained at 320°C. Air at 20°C blows over the hot plate. Thermal conductivity of plate is 42 W/m.°C and convective heat transfer coefficient is 20 W/m². °C. 260 W of heat is also lost from the plate due to radiation. Calculate the inside plate temperature.*

Solution. Surface area of plate,

$$A = 0.5 \times 1.0 = 0.5 \text{ m}^2$$

Plate thickness, $\Delta x = 0.025$ m

Plate wall temperature, $T_w = 320$°C.

Air temperature, $T_\infty = 20$°C

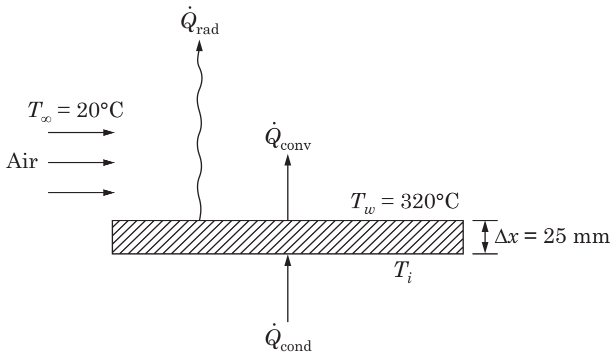

Fig. 1.13

Thermal conductivity of plate, $k = 42$ W/m.°C

Convective heat transfer coefficient, $h = 20$ W/m°.°C

Heat lost from plate due to radiation, $\dot{Q}_{\text{rad}} = 260$ W

Let T_i = inside plate temperature, °C

Then $\dot{Q}_{\text{comd}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}}$

$$kA\,\frac{\Delta T}{\Delta x} = hA(T_w - T_\infty) + \dot{Q}_{\text{rad}}$$

$$42 \times 0.5 \times \frac{(T_i - 320)}{0.025} = 20 \times 0.5\,(320 - 20) + 260$$

$$840\,(T_i - 320) = 3260$$

$$T_i = 323.88°C$$

Example 1.5 *The furnace wall of a combustion chamber is composed of fire bricks backed by masonry brick and then with a steel casing. The given data is as follows:*

Type of wall	*Thickness, cm*	*Thermal conductivity W/m.K*
1. Fire brick	*10*	*0.12*
2. Masonry brick	*15*	*0.15*
3. Steel plate	*2*	*50.0*

If the outside temperature of steel plate is 75°C and rate of heat loss is 450 W/m², calculate the skin temperature of fire bricks.

Solution. $\dot{Q} = kA \, . \, \dfrac{\Delta T}{\Delta x}$

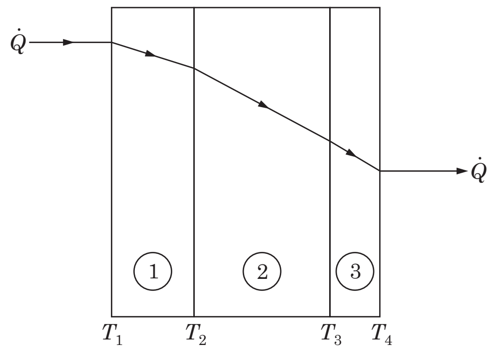

Fig. 1.14

Thermal resistances due to conduction of heat are:

$$R_{t_1} = \frac{\Delta x_1}{k_1 A} = \frac{0.1}{0.12 \times 1} = 0.833 \text{ K/W}$$

$$R_{t_2} = \frac{\Delta x_2}{k_2 A} = \frac{0.15}{0.15 \times 1} = 1.0 \text{ K/W}$$

$$R_{t_3} = \frac{\Delta x_3}{k_3 A} = \frac{0.02}{50} = 4 \times 10^{-4} \text{ K/W}$$

The three resistances are in series.

Total thermal resistance,

$$R_t = R_{t_1} + R_{t_2} + R_{t_3} = 0.833 + 1.0 + 4 \times 10^{-4}$$

$$= 1.8334 \text{ K/W}$$

$$\dot{Q} = \frac{T_1 - T_4}{R_t}$$

$$450 = \frac{T_1 - 75}{1.8334}$$

$$T_1 = 900°\text{C}$$

Example 1.6 *A solar pane 1 m × 1 m receives solar radiation of 1200 W. The ambient air temperature is 30°C. The convective heat transfer coefficient of air film, over the surface of pane is 12 W/m²·K. Calculate the surface temperature of the pane.*

Solution. Given : $A = 1 \times 1 = 1 \text{ m}^2$

$$\dot{Q} = 1200 \text{ W}, T_\infty = 30°\text{C}, h = 12 \text{ W/m}^2\text{.K}$$

Rate of heat transfer due to convection,

$$\dot{Q} = hA(T_w - T_\infty)$$

$$1200 = 12 \times 1\,(T_w - 30)$$

$$T_w = 130°\text{C}$$

Example 1.7 *The core temperature of a furnace is 800°C. Its fire brick wall is supported by a steel frame outside.*

Material	*Thickness, cm*	*Thermal conductivity W/m. K*
1. Fire brick	*25*	*0.15*
2. Steel plate	*2.5*	*50.0*

The convective heat transfer coefficient of gas film on the inside surface of fire brick is 25 W/m²·K and that of air film on the outside is 5 W/m²·K. Calculate the rate of heat loss through the furnace. Take ambient air temperature as 25°C.

Solution. Thermal resistances are:

Gas film, $$R_1 = \frac{1}{h_g A} = \frac{1}{25 \times 1} = 0.04 \text{ K/W}$$

Fire brick, $$R_2 = \frac{\Delta x_1}{k_1 A} = \frac{0.25}{0.15 \times 1} = 1.667 \text{ K/W}$$

Steel plate, $$R_3 = \frac{\Delta x_2}{k_2 A} = \frac{2.5 \times 10^{-2}}{50 \times 1} = 5 \times 10^{-4} \text{ K/W}$$

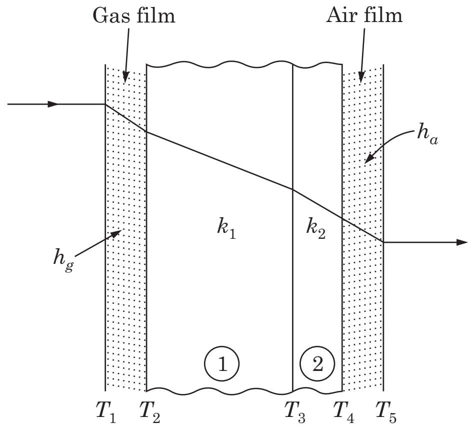

Fig. 1.15

Air film, $R_4 = \dfrac{1}{h_a A} = \dfrac{1}{5 \times 1} = 0.2$ K/W

Total thermal resistance,

$$R_t = R_1 + R_2 + R_3 + R_4$$
$$= 0.04 + 1.667 + 5 \times 10^{-4} + 0.2 = 1.9075 \text{ K/W}$$

Rate of heat loss,

$$\dot{Q} = \frac{T_1 - T_5}{R_t} = \frac{800 - 25}{1.9075} = 406.3 \text{ W/m}^2$$

Example 1.8 *Two black bodies at 1600°C. and 150°C undergo heat transfer by thermal radiation. Calculate the rate of heat transfer per unit area of the emitter whose emissivity is 0.85. Take shape factor equal to unity.*

Solution. Given : $T_1 = 273 + 1600 = 1873$ K,

$T_2 = 273 + 150 = 423$ K, $\varepsilon = 0.85$, $F_{12} = 1.0$

$$\dot{Q} = \varepsilon F_{12} \sigma A(T_1^4 - T_2^4)$$
$$= 0.85 \times 1 \times 5.67 \times 10^{-8} (1873^4 - 423^4)$$
$$= 0.85 \times 1 \times 5.67 \left[\left(\frac{1873}{100}\right)^4 - \left(\frac{423}{100}\right)^4\right] = 591.\ 591 \text{ kW}$$

Example 1.9 *A boiler tube carrying boiler feed water at 500°C receives heat in a furnace whose core temperature is 1200°C. Calculate the rate of heat flow per unit surface area of boiler tube wall normal to the path flow.*

Emissivity of outer surface of tubes = 0.85
Convective conductance for flue gas film = 25 W/K
Thermal conductivity of tube material = 58 W/m.K
Convective heat transfer coefficient for water film = 45 kW/m^2.K
Tube wall thickness = 3 mm
Temperature drop across flue gas film = 2°C.

Solution. Given: $T_1 = 273 + 1200 = 1473$ K,
$T_2 = 273 + 1198 = 1471$ K, $\varepsilon = 0.785$,
$A = 1$ m^2, $F_{12} = 1$, $h_g A = 25$ W/K,
$k = 58$ W/m.K,
$h_w = 45$ kW/m^2. K, $\Delta x = 3$ mm

Radiative thermal resistance of flue gas film,

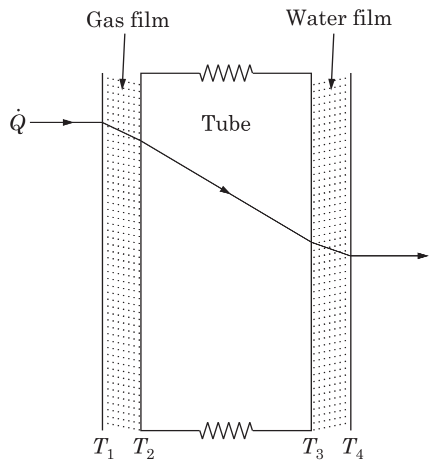

Fig. 1.16

$$(R_{tg})_{\text{rad}} = \frac{1}{F_{12}\ \varepsilon\ A\ \sigma\ (T_1 + T_2)\ (T_1^2 + T_2^2)}$$

$$= \frac{1}{1 \times 0.85 \times 1 \times 5.67 \times 10^{-8}\ (1473 + 1471)\ (1473^2 + 1471^2)}$$

$= 1.626 \times 10^{-3}$ K/W

Convective thermal resistance of flue gas film,

$$(R_{tg})_{\text{conv}} = \frac{1}{\text{K}_{\text{conv}}} = \frac{1}{25} = 0.04 \text{ K/W}$$

Equivalent thermal resistance of gas film,

$$\frac{1}{R_{tg}} = \frac{1}{(R_t)_{\text{rad}}} + \frac{1}{(R_{tg})_{\text{conv}}},$$

(being in parallel)

$$R_{tg} = \frac{1.626 \times 10^{-3} \times 0.04}{1.626 \times 10^{-3} + 0.04} = 1.562 \times 10^{-3} \text{ K/W}$$

Conductive thermal resistance of tube,

$$(R_t)_{\text{cond}} = \frac{\Delta x}{kA} = \frac{0.003}{58 \times 1} = 5.172 \times 10^{-5} \text{ K/W}$$

Convective thermal resistance of water film,

$$(R_{tg})_{\text{conv}} = \frac{1}{h_w A} = \frac{1}{45 \times 10^3 \times 1} = 2.222 \times 10^{-5} \text{ K/W}$$

Total thermal resistance,

$$R_t = R_{tg} + (R_t)_{\text{cond}} + (R_{tw})_{\text{conv}}$$
$$= 1562 \times 10^{-3} + 5.172 \times 10^{-5} + 2.222 \times 10^{-5}$$
$$= 1.636 \times 10^{-3} \text{ K/W}$$

Rate of heat flow,

$$\dot{Q} = \frac{T_1 - T_4}{R_t} = \frac{1200 - 550}{1.636 \times 10^{-3}} = 397.31 \text{ kW/m}^2$$

Example 1.10 *A wire 1 mm in diameter and 10 cm long is submerged in water at 100°C. An electric current is passed through the wire. When water begins to boil the current through the wire and its resistance are measured. From these measurements it is found that the temperature of wire is 114°C and heat dissipated is 22 W. Find the boiling heat transfer coefficient of water.*

Solution. Given: $d = 1$ mm, $l = 10$ cm,

$$T_1 = 100°\text{C}, T_2 = 114°\text{C}, \dot{Q} = 22 \text{ W}$$

Surface area of wire,

$$A = \pi dl = \pi \times 1 \times 10^{-3} \times 0.1 = 3.1416 \times 10^{-4} \text{ m}^2$$

$$\dot{Q} = hA(T_2 - T_1)$$
$$22 = h \times 3.1416 \times 10^{-4} (114 - 100)$$
$$h = 5000 \text{ W/m}^2.°\text{C}.$$

Example 1.11 *The temperature distribution through a furnace wall consisting of firebrick and high temperature block insulation and steel plate is measured as shown in Fig. 1.17.*

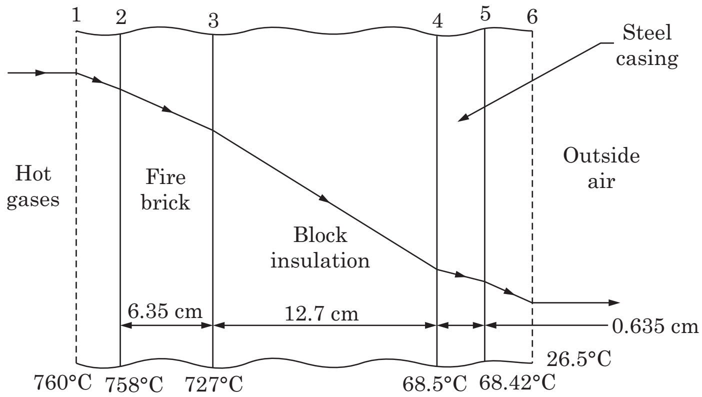

Fig. 1.17

The thermal conductivity of fire brick is 1.13 W/(m.K).

Determine:

(*a*) *Heat loss per unit area of furnace wall.*

(*b*) *Thermal conductivities of block insulation and steel.*

(*c*) *Combined convective and radiative heat transfer coefficient for the outside surface of the furnace wall.*

(*d*) *Heat exchange by radiation between the hot gases and inside surface of furnace wall. Given the absorptivity and emissivity of fire brick wall surface is 0.85.*

(*e*) *Convective heat transfer coefficient for the inside surface of furnace wall.*

Solution. For steady state heat flux and resistances in series, we have

$$q = q_{1-2} = q_{2-3} = q_{3-4} = q_{4-5} = q_{5-6}$$

(*a*) Heat flux, $q_{2-3} = \left[\dfrac{\Delta T}{\dfrac{\Delta x}{k}}\right]_{\text{fire brick}} = \dfrac{758 - 727}{\dfrac{0.0635}{1.13}} = 550 \text{ W/m}^2$

(*b*) Thermal conductivity of block insulation,

$$k_b = q\left[\frac{\Delta x}{\Delta T}\right]_{3-4} = 550\left[\frac{0.127}{727 - 68.5}\right]$$

$$= 0.106 \text{ W/(m.K)}$$

Thermal conductivity of steel,

$$k_s = q\left[\frac{\Delta x}{\Delta T}\right]_{4-5} = 550\left[\frac{0.00635}{68.5 - 68.42}\right] = 44 \text{ W/(m.K)}$$

(*c*) Combined convective and radiative coefficient on the outside surface

$$h = h_r + h_c = \frac{q}{T_5 - T_6} = \frac{550}{68.42 - 26.5} = 13.1 \text{ W/(m}^2\text{. K)}$$

(*d*) Net thermal radiation gain of wall,

$$q_r = \varepsilon_w \, \sigma \, (T_1^4 - T_2^4)$$

$$= 0.85 \times 5.67 \left[\left(\frac{760 + 273}{100} \right)^4 - \left(\frac{758 + 273}{100} \right)^4 \right]$$

$$= 199 \text{ W/m}^2$$

(*e*) Convective and radiative heat transfers between gases and wall are in parallel.

Hence, $q_{1-2} = q_r + q_c = q$

or $q_c = q - q_r = 550 - 199 = 351 \text{ W/m}^2$.

Convective heat transfer coefficient on the inside surface,

$$h_i = \frac{q_c}{T_1 - T_2} = \frac{351}{760 - 758} = 175.5 \text{ W/(m}^2\text{.K)}.$$

Example 1.12 *The following data relate to an oven:*

Thickness of side wall of oven = 80 mm

Thermal conductivity of wall insulation = 0.045 W/m.K.

Inside temperature of wall = 200°C.

Energy dissipated by electric coil within the oven = 50 W.

Calculate the area of wall surface required, perpendicular to heat flow, to limit the temperature to 70°C on the other side of wall.

Solution. Given: $x = 80$ mm, $k = 0.045$ W/m.K,

$$t_1 = 200°\text{C}, \; t_2 = 70°\text{C}, \; \dot{Q} = 50 \text{ W or } 50 \text{ J/s}$$

$$\dot{Q} = -kA \, \frac{\Delta T}{\Delta x} = \frac{kA(t_1 - t_2)}{x}$$

$$50 = \frac{0.045 \times A \, (200 - 70)}{0.08}$$

$$A = 0.684 \text{ m}^2.$$

Example 1.13 *A wire 2 mm in diameter and 200 mm long is submerged in water at atmospheric pressure. An electric current is passed through the wire until the water boils at 100°C. The convective heat transfer coefficient is 4500 W/m²·K. How much electric power must be supplied to the wire to maintain its temperature at 120°C?*

Solution. Given: d = 2 mm, l = 200 mm, h = 4500 W/m^2.K,

T_s = 120ºC, T_w = 100ºC

$$A = \pi dl = \pi \times 0.002 \times 0.2 = 1.257 \times 10^{-3}\ \text{m}^2$$

$$Q = hA(T_s - T_w)$$

$$= 4500 \times 1.25 \times 10^{-3}\ (120 - 100) = 113.1\ \text{W}$$

Example 1.14 *A surface having an area of 2 m*^{2} *is maintained at a temperature of 327ºC. It exchanges heat by radiation with another surface at 40ºC. The geometric view factor is 0.5. Calculate (a) heat lost by radiation, (b) thermal resistance, and (c) equivalent convection coefficient.*

Solution. Given : A = 2 m^2, T_1, = 273 + 327 = 600 K,

T_2 = 273 + 40 = 313 K, F_g = 0.5

(a) Heat lost by radiation,

$$\dot{Q} = F_g\,\sigma A(T_1^4 - T_2^4) = 0.5 \times 5.67 \times 10^{-8} \times 2\ (600^4 - 313^4)$$

$$= 6804\ \text{W}$$

(b) $$\dot{Q} = \frac{T_1 - T_2}{R_{th}}$$

Thermal resistance,

$$R_{th} = \frac{600 - 313}{6804} = 0.0422\ \text{ºC/W}$$

(c) $$\dot{Q} = h_r A\ (T_1 - T_2)$$

Equivalent convection coefficient,

$$h_r = \frac{\dot{Q}}{A\ (T_1 - T_2)} = \frac{6804}{2\ (600 - 313)} = 11.85\ \text{W/m}^2.\text{K}$$

Example 1.15 *A steel plate 500 mm × 1000 mm × 20 mm is maintained at a temperature of 320ºC. Air at a temperature of 15ºC blows over the hot plate. The thermal conductivity of plate is 45 W/m. K and convection heat transfer coefficient is 22.5 W/m*^{2}*. K. If 250 W heat is lost from the plate surface by radiation, determine the inside plate temperature.*

Solution. Given : t_s = 320ºC, t_a = 15ºC, k = 45 W/m.K,

h = 22.5 W/m^2.K, Q_{rad} = 250 W,

A = 0.5 × 1 = 0.5 m^2,

L = 0.02 m

Let t_i = inside plate temperature.

For heat balance, we have

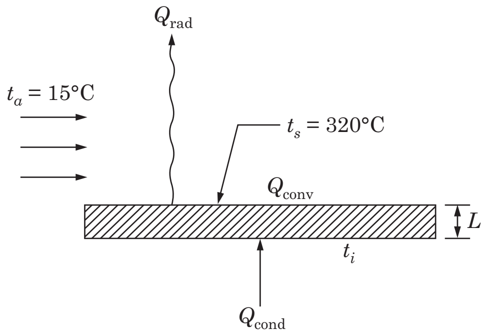

Fig. 1.13

$$Q_{\text{cond}} = Q_{\text{conv}} + Q_{\text{rad}}$$

$$-kA\left(\frac{\Delta T}{\Delta x}\right) = hA(t_s - t_a) + F_g\,\sigma\,A(T_s^{\,4} - T_a^{\,4})$$

$$\Delta x = L,\ \Delta T = t_s - t_i$$

$$-45 \times 0.5\left(\frac{320 - t_i}{0.02}\right) = 22.5 \times 0.5\,(320 - 15)$$

$$+\,250 - 112.5\,(320 - t_i) = 3481.25$$

$$t_i = 352.\ 7°\text{C}$$

Example 1.16 *A steel pipe 50 mm in diameter is maintained at a temperature of 70°C in a large room where the air and wall temperatures are 27°C. The surface emissivity of steel is 0.65. Calculate the total heat loss per unit length of pipe if convective heat transfer coefficient is 6.5 W/m²·K.*

Solution. Given: $d = 0.05$ m, $t_s = 70$°C, $t_w = 27$°C,

$$\varepsilon = 0.65,\ h = 6.5\ \text{W/m}^2\text{.K}$$

Surface area of pipe,

$$A = \pi dl = \pi \times 0.05 \times 1 = 0.157\ \text{m}^2$$

$$Q_{\text{conv}} = hA(t_s - t_w)$$

$$= 6.5 \times 0.157\ (70 - 27) = 43.9\ \text{W}$$

$$Q_{\text{rad}} = \varepsilon\,A\,\sigma\,(T_s^{\,4} - T_w^{\,4})$$

$$= 0.65 \times 0.157 \times 5.67\left[\left(\frac{343}{100}\right)^4 - \left(\frac{300}{100}\right)^4\right]$$

$$= 33.22\ \text{W}$$

Total heat loss,

$$Q = Q_{conv} + Q_{rad} = 43.9 + 33.22 = 77.12 \text{ W}$$

HIGHLIGHTS

1. Heat transfer is the transmission of energy from one body to another by virtue of temperature difference or gradient.

2. Heat transfer is based on the second law of thermodynamics.

3. Heat transfer is an irreversible process.

4. There are three modes of heat transfer: conduction, convection and radiation.

5. Fourier's law of heat conduction:

Rate of heat flow, $\dot{Q} = -kA_c \dfrac{dT}{dx}$.

6. Heat, flux, $q = \dfrac{\dot{Q}}{A_c} = -k\dfrac{dT}{dx}$.

7. S.I. units of thermal conductivity are! W/m.K or W/m.ºC.

8. Thermal conduction resistance, $(R_t)_{cond} = \dfrac{dx}{kA_c}$.

9. Newton's law of cooling:

$$\dot{Q} = hA_s (T_w - T_\infty)$$

where A_s = surface area.

10. S.I. units of convective heat transfer coefficient k are: W/m^2.K

11. Thermal convective resistance, $(R_t)_{conv} = \dfrac{1}{hA_s}$.

12. Stefan – Boltzmann law for thermal radiation :

$$\dot{Q} = \varepsilon \sigma A (T_1^4 - T_2^4).$$

13. Thermal radiation resistance,

$$(R_t)_{rad} = \frac{1}{F_{12} \sigma A_1 (T_1 + T_2)(T_1^2 + T_2^2)}.$$

14. Radiative coefficient, $h_r = \dfrac{F_{12} \sigma (T_w^4 - T_\infty^4)}{T_w - T_\infty}$.

15. Equivalent thermal resistance:

$$(R_t)_e = \sum R_i \quad \text{for resistance in series}$$

$$\left(\frac{1}{R_t}\right)_e = \frac{1}{\sum R_i} \quad \text{for resistances in parallel.}$$

MULTI-CHOICE QUESTIONS

1. Identify the very good insulator
(*a*) saw dust (*b*) glass wool
(*c*) cork (*d*) asbestos sheet.

2. Which of the following forms of water have the highest value of thermal conductivity?
(*a*) boiling water (*b*) steam
(*c*) solid ice (*d*) melting ice.

3. Heat conduction in gases is due to
(*a*) motion of electrons
(*b*) elastic impact of molecules
(*c*) mixing motion of the different layers of the gas
(*d*) electromagnetic waves.

4. Consider the following statements: The Fourier heat conduction equation

$$Q = -kA \frac{dT}{dx} \text{ presumes}$$

1. Steady state conditions
2. Constant values of thermal conductivity
3. Uniform temperature at the wall surfaces
4. One-dimensional heat flow.

Which of these statements are correct?
(*a*) 1, 2 and 3 (*b*) 1, 2 and 4
(*c*) 2, 3 and 4 (*d*) 1, 3 and 4.

5. Most unsteady heat flow occurs
(*a*) through the walls of a refrigerator
(*b*) during annealing of castings
(*c*) through the walls of a furnace
(*d*) through lagged (insulated) pipes carrying steam.

6. The material medium between the heat source and receiver is not affected during the process of heat transmission by
(*a*) conduction (*b*) convection
(*c*) radiation (*d*) conduction as well as convection.

7. Heat transfer in liquids and gases is essentially due to
(*a*) conduction (*b*) convection
(*c*) radiation
(*d*) conduction and radiation put together.

8. A satellite in space exchanges heat with the surroundings essentially by

(*a*) conduction (*b*) convection

(*c*) radiation

(*d*) conduction and convection put together.

9. The essential condition for the transfer of heat from one body to another is

(*a*) both bodies must be in physical contact

(*b*) heat content of one body must be more that that of the other

(*c*) One of the bodies must have a high value of thermal conductivity

(*d*) there must exist a temperature difference between the bodies.

10. Identify the wrong statement

(*a*) the process of heat transfer is thermodynamically an irreversible process

(*b*) a material medium is always necessary for heat transmission

(*c*) for heat exchange, a temperature gradient must exist

(*d*) heat flow is always from a higher temperature to a lower temperature in accordance with second law of thermodynamics.

11. Heat transmission is directly linked with the transport of medium itself,. *i.e.*, there is actual motion of heated particles during

(*a*) conduction only (*b*) convection only

(*c*) radiation only (*d*) conduction as well as radiation.

12. Thermal conductivity of solid metals with rise in temperature generally

(*a*) increases (*b*) decreases

(*c*) remains same (*d*) may increases or decrease.

13. Heat transfer takes place as per the following law of thermodynamics

(*a*) zeroth law (*b*) first law

(*c*) second law (*d*) third law.

14. Thermal conductivity of non-metals with decrease in temperature generally

(*a*) increases (*b*) decreases

(*c*) remains same (*d*) may increases or decrease.

15. Thermal conductivity of air with rise in temperature

(*a*) increases (*b*) decreases

(*c*) remains same (*d*) may increase or decrease

16. Heat received by a person from a room heater takes place by

(*a*) conduction (*b*) convection

(*c*) radiation (*d*) all of the above.

17. Cork is a good insulator because it has

(*a*) free electrons (*b*) atoms colliding frequently

(*c*) low density (*d*) porous body.

18. Which of the following has highest thermal conductivity?

(*a*) aluminium (*b*) steel

(*c*) copper (*d*) lead

19. Which of the following has least value of thermal conductivity?

(*a*) glass (*b*) plastic

(*c*) rubber (*d*) air.

20. Heat is transferred by the combined effect of conduction, convection and radiation in

(*a*) electric heater (*b*) steam condenser

(*c*) boiler (*d*) melting of ice.

21. The S.I. units of thermal conductivity are:

(*a*) W/m.K (*b*) $W/m^2.K$

(*c*) $m^2.K/W$ (*d*) m.K/W.

22. If P = metals, Q = non-metals, R = liquids, and S = gases, then the order of decreasing thermal conductivity is

(*a*) $P - S - Q - R$ (*b*) $P - Q - R - S$

(*c*) $Q - R - P - S$ (*d*) $S - R - Q - P$.

23. The S.I. units of film heat transfer coefficient are

(*a*) W/m.K (*b*) $W/m^2.K$

(*c*) m.K/W (*d*) $m^2.K/W$.

24. Thermal conduction resistance is

(*a*) $\frac{dx}{kA}$ (*b*) $\frac{k}{Adx}$

(*c*) $\frac{A.dx}{k}$ (*d*) $\frac{kdx}{A}$.

25. If T is the absolute temperature of body then heat transfer due to radiation is proportional to

(*a*) T (*b*) T^2

(*c*) T^3 (*d*) T^4.

ANSWERS

1. (*b*)	**2.** (*c*)	**3.** (*b*)	**4.** (*d*)
5. (*b*)	**6.** (*c*)	**7.** (*b*)	**8.** (*c*)
9. (*d*)	**10.** (*b*)	**11.** (*b*)	**12.** (*b*)
13. (*c*)	**14.** (*b*)	**15.** (*a*)	**16.** (*c*)
17. (*d*)	**18.** (*c*)	**19.** (*d*)	**20.** (*c*)
21. (*a*)	**22.** (*b*)	**23.** (*b*)	**24.** (*a*)
25. (*d*).			

REVIEW QUESTIONS

1. What is heat transfer?
2. What are the various modes of heat transfer?
3. State the Fourier's law of heat conduction:
4. Define thermal conductivity and give its units.
5. Which metal has the maximum thermal conductivity?
6. Name five insulating materials.
7. What is the method to determine thermal conductivity of insulating materials?
8. State the Newton's law of cooling.
9. What is film heat transfer coefficient? What are its units?
10. Define thermal resistance.
11. State the law for convective heat transfer.
12. What is equivalent convective coefficient?
13. State the Stefan-Boltzmann law for thermal radiation.
14. What is radiation coefficient?
15. Define convective resistance and radiative resistance.

EXERCISES

1. The temperature gradient in a wall in a particular direction is 0.2ºC/cm. Calculate the heat flux in that direction if the thermal conductivity of the material of the wall is 1.6 W/(mK). [**Ans.** 32 W]

2. A heated vertical plate is 1 m high and 0.5 m wide. The temperature of the surrounding air is 40ºC. The surface temperature of the plate is found to vary according to the relation

$$t = 50x + 60$$

where t is in ºC and x is the distance in m from the bottom end of the plate. The total heat loss from the plate to the surrounding air is 0.8 kW. The local heat transfer coefficient at any section can be expressed by the relation

$$h_x = ax^{-1/5}\,\Delta T$$

Determine the value of the constant a is the above equation.

[**Ans.** 0.0758]

3. A flat wall is exposed to an environmental temperature of 38ºC. The wall is covered with a layer of insulation 2.5 cm thick whose thermal conductivity is 1.4 W/(mK) and the temperature of the wall on the inside of insulation is 315ºC. Compute the value of the convection heat transfer coefficient which must be maintained on the outside surface of insulation to ensure that the outer surface temperature does not exceed 100ºC. [**Ans.** 194.2 Wm^{-2} K^{-1}]

4. The arch of an annealing furnace has an inside temperature t_1 = 1000ºC and outside temperature t_2 = 200ºC while the ambient air temperature is 40ºC. It is made up of fire bricks with 25.4 cm thickness which possesses a mean thermal conductivity k = 1.28 W/(mK).

(*a*) Calculate the heat loss rate per m^2 of area.

(*b*) What is the heat transfer coefficient for the outside surface of the furnace to the surrounding still air?

(*c*) What will be the error involved in heat flux if outside surface heat transfer coefficient of air is assumed as 20 W(m^{2}K) and outside surface temperature of the furnace is not known? Also what will be the outside surface temperature thus determined?

(*d*) Discuss the two results.

[**Ans.** (*a*) 4032 W/m^2, (*b*) 25.2 Wm^{-2} K^{-1}, (*c*) 4.1%, 233ºC]

5. Data obtained during a typical test on a guarded hot plate apparatus are as follows:

Temperature at top of sample	= 60ºC
Temperature at bottom of sample	= 30ºC
Sample heater current	= 0.125 A
Sample heater voltage	= 25 V
Sample size	= 10 cm × 10 cm
Sample thickness	= 0.5 cm

Calculate the thermal conductivity of the sample.

[**Ans.** 0.026 Wm^{-1} K^{-1}]

6. A 1 m × 1 m black metallic plate is exposed to the Sun's rays on one side. The other side is completely insulated. The solar radiation incident on the surface is 500 W. The surrounding air temperature is 44ºC. The heat transfer coefficient by convection from the plate to the air can be taken as 25 W/(m^2 K). The absorptivity and emissivity of the plate surface are 0.75. Find the equilibrium temperature of the plate. [**Ans.** 54ºC]

7. A cyclindrical rod 2 m long 2 cm in diamter is heated electrically in a furnace whose interior walls are at 1000 K temperature. The temperature of rod is maintained at 1200 K. Calculate the power supplied to the heating rod if its surface has an emissivity of 0.92.

[**Ans.** 7037.6 W]

8. A 6 cm diameter steel pipe maintaind at a temperature of 70ºC is kept in a large room at 25ºC. The surface emissivity of steel is 0.72. Calculate the total heat loss per unit length of pipe if convective heat tranfer coefficient is 6.3 W/m^2. K. [**Ans.** 99.26 W]

9. A surface at 500 K convects and radiates heat to the surroundings at 350 K. If the surface conducts this heat through a solid plate of thermal conductivity 12 W/m.K, determine the temperature gradient at the surface in the solid. Take convective coefficient = 80 W/m^2. K and emissivity = 0.9. [**Ans.** 1202 K/m]

10. A black metal plate 1.2 m in diameter and 1 cm thick is exposed to sun's rays. The rate of heat received on one face equals the rate of heat lose by convection and radiation from both surfaces. If solar energy flux = 200 W/m^2 plate temperature = 300 K, ambient air temperature = 290 K, and net radiation heat flux leaving the plate = 80 W/m^2, calculate the heat transfer by convection.