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

First Edition : 2020
Second Edition : 2021

Third Edition : 2022

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Heat Transfer

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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.**

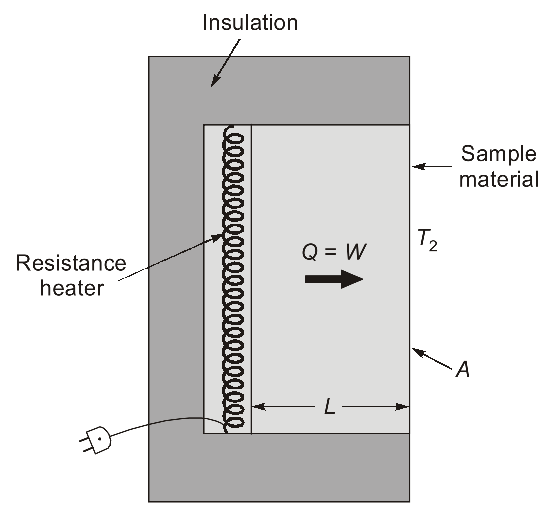
Radiation is the transfer of heat through space or matter by means other than conduction or convection. Radiation of heat is thought of as electromagnetic waves or quanta (as convenient) an emanation of the same nature as light and radio waves. All bodies radiate heat, so a transfer of heat by radiation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

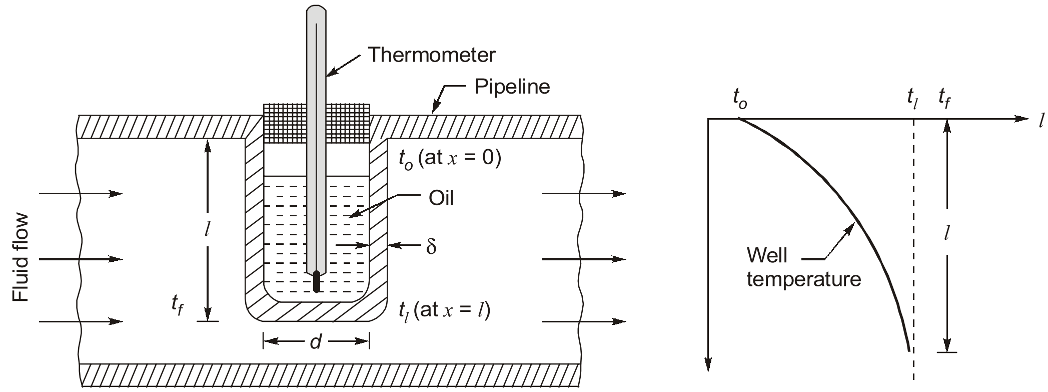
This equation is used for determination of thermal conductivity of a material. A layer of solid material of thickness L and area A is heated from one side by an electric resistance heater as shown in figure.

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

7.6.2 Estimation of Error in Temperature Measurement in a Thermometer Well



1. Thermometric error = $\dfrac{t_l - t_f}{t_o - t_f}$
2. Error in temperature in measurement = $(t_l - t_f)$

Estimate of error in Temperature Measurement in a thermometer well

Assume No heat flow in tip, i.e., **Insulated tip formula.**

$$\therefore \qquad \frac{\theta_x}{\theta_o} = \frac{\cosh\{m(l-x)\}}{\cosh(ml)}$$

At $x = l$,
$$\frac{\theta_1}{\theta_o} = \frac{t_l - t_f}{t_o - t_f} = \frac{1}{\cosh(ml)} = \text{Thermometric error}$$

Note : (i) If only wall thickness δ is given then

$$P = \pi(d_i + 2\delta) \approx \pi d_i$$
$$A_{cs} = \pi d_i \delta$$

$$\therefore \qquad m = \sqrt{\frac{hP}{kA_c}} = \sqrt{\frac{h \times \pi d_i}{k \times \pi d_i \delta}} = \sqrt{\frac{h}{k\delta}}$$

(ii) If (a) d_i & δ given   or (b) d_o & δ given then

or (c) d_i and δ given   where P = Actual = πd_o; $A = \dfrac{\pi(d_o^2 - d_i^2)}{4}$

Example 7.11 Aluminium fins of rectangular profile are attached on a plane wall with 5 mm spacing. The fins have thickness y = 1 mm, length l = 10 mm, and the thermal conductivity, k = 200 W/m K. The wall is maintained at a temperature 200°C, and the fins dissipate heat by convection into the ambient air at 40°C. with heat transfer coefficient h = 50 W/m^{2}K. Determine the heat loss.

Solution:

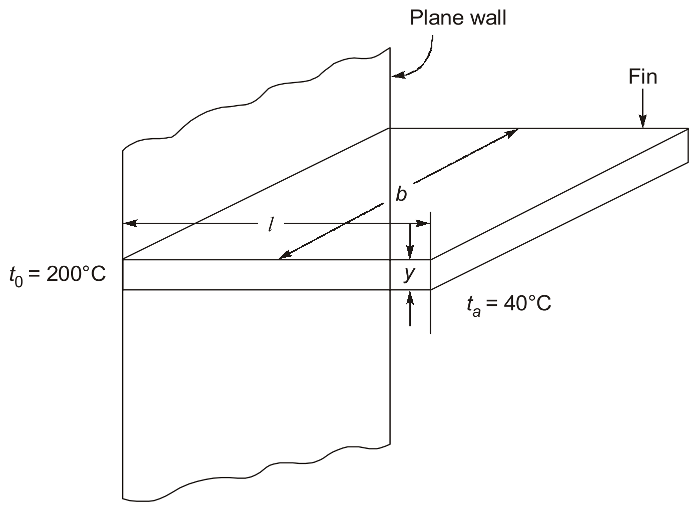
Given : t = 1 mm = 0.001 m; l = 10 mm = 0.01 m; y = 1 mm = 0.001 m; k = 200 W/mK; t_o = 200°C; t_a = 40°C; h = 50 W/m^{2}K.

Heat loss, Q :

$$m = \sqrt{\frac{hP}{kA_{cs}}} = \sqrt{\frac{h(b+y)\times 2}{k(b\times y)}} = \sqrt{\frac{h\times 2b}{k\times by}}, \text{ assuming } b >> y$$

$$= \sqrt{\frac{2h}{ky}} = \sqrt{\frac{2\times 50}{200\times 0.001}} = 22.36$$

For unit width of the fin, (b = 1 m)



$$Q = \sqrt{PhkA_{cs}}(t_0 - t_a)\tanh(ml)$$

$$= \sqrt{(2\times1)\times50\times200\times(1\times0.001)}\times(200-40)\times\tanh(22.36\times0.01)$$

$$= 157.38 \text{ W/m}$$

Example 7.12 Find out the amount of heat transferred through an iron fin of length 50 mm, width 100 mm and thickness 5 mm. Assume k = 210 kJ/mh°C and h = 42 kJ/m²h°C for the material of the fin and the temperature at the base of the fin as 80°C. Also determine the temperature at tip of the fin, if the atmosphere temperature is 20°C.

Solution :

Given : l = 50 mm = 0.05 m; b = 100 mm = 0.1 m; y = 5 mm = 0.005 m; k = 210 kJ/mh°C; h = 42 kJ/m²h°C; t_0 = 80°C; t_a = 20°C.

Amount of heat transferred through the fin. Q :

Perimeter, $P = 2(b + y) = 2(0.1 + 0.005) = 0.21$ m

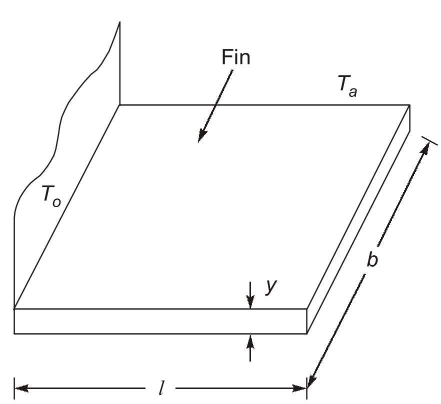
Area, $A_{cs} = b \times y = 0.1 \times 0.005 = 0.0005$ m²

$$m = \sqrt{\frac{hP}{kA_{cs}}} = \sqrt{\frac{42\times0.21}{210\times0.0005}} = 9.165$$

∴ $$Q_{fin} = \sqrt{PhkA_{cs}}(t_0 - t_a)\tanh(ml)$$

$$= \sqrt{0.21\times42\times210\times0.0005} \times (80-20)\tanh(9.165 \times 0.05)$$

$$= 0.9263 \times 60 \times 0.4286 = 24.75 \text{ kJ/h}$$



Temperature at the tip of the fin, Q_L :

We know that,

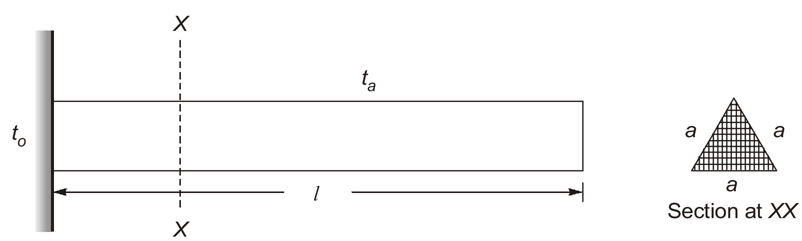
$$\frac{\theta}{\theta_0} = \frac{t - t_a}{t_0 - t_a} = \frac{\cosh\{m(l-x)\}}{\cosh(ml)}$$

or
$$t = \frac{60}{\cosh(9.165 \times 0.05)} + 20 = 74.21°C$$

Example 7.13 A carbon steel {k = 54 W/m°C) rod with a cross-section of an equilateral triangle (each side 5 mm} is 80 mm long. It is attached to a plane wall which is maintained at a temperature of 400°C. The surrounding environment is at 50°C and unit surface conductance is 90 W/m²°C. Compute the heat dissipated by the rod.

Solution :

Refer to Fig., a = 5 mm = 0.005 m; l = 80 mm = 0.08 m; t_0 = 400°C; t_a = 50°C; h = 90 W/m²°C; k = 54 W/m°C



Heat dissipated by the rod, Q :

The heat flow from the rod (considering tip of the fin be insulated) is given by

$$Q = kA_{cs}m(t_o - t_a)\tanh(ml)$$

where,
$$m = \sqrt{\frac{hP}{kA_{cs}}};\ P = 3a,\ A_{cs} = \frac{1}{2} \times a \times \left(\frac{\sqrt{3}}{2}a\right) = \frac{\sqrt{3}}{4}a^2$$

∴
$$\frac{P}{A_{cs}} = \frac{3a}{\frac{\sqrt{3}}{4} \times a^2} = \frac{4\sqrt{3}}{a} = \frac{6.93}{0.005} = 1386$$

and
$$m = \sqrt{\frac{90}{54} \times 1386} = 48.06$$

Substituting the values in the above equation, we have

$$Q = 54 \times \left[\frac{\sqrt{3}}{4} \times (0.005)^2\right] \times 48.06 \times (400 - 50)\tanh(48.06 \times 0.08)$$

$$= 9.82 \text{ W}$$

Example 7.14 One end of a long rod, 35 mm in diameter, is inserted into a furnace with the other end projecting in the outside air. After the steady state is reached, the temperature of the rod is measured at two points 180 mm apart and found to be 180°C and 145°C. The atmospheric air temperature is 25°C. If the heat transfer coefficient is 65 W/m² °C, calculate the thermal conductivity of the rod.

Solution :

Diameter of the rod, d = 35 mm = 0.035 in

The atmospheric air temperature, t_a = 25°C

Heat transfer coefficient; $h = 65$ W/m^2°C

The starting point $x = 0$ is considered at the first point where the temperature is measured; $x = l$ is considered at the outer point. Assume that the end of the fin is insulated.

For insulated end, we have

$$\frac{\theta}{\theta_o} = \frac{t - t_a}{t_o - t_a} = \frac{\cosh\{m(l - x)\}}{\cosh ml}$$

At x = 1, J = 1. this equation, reduces to

or, $$\frac{\theta_l}{\theta_o} = \frac{1}{\cosh ml}$$

Here, $\theta_l = 145 - 25 = 120°\text{C}$ and $\theta_o = t_o - t_a = 180 - 25 = 155°\text{C}$

∴ $$\frac{120}{155} = \frac{1}{\cosh ml}$$

or $$\cosh ml = \frac{155}{120} = 1.292 \text{ or } ml = 0.747$$

or $$m = \frac{0.747}{l}$$

But, $$m = \sqrt{\frac{hP}{kA}}$$

∴ $$\sqrt{\frac{hP}{kA_{cs}}} = \frac{0.747}{l}$$

or, $$\frac{hp}{kA_{cs}} = \frac{0.747^2}{l^2}$$

or, $$\frac{h}{k} \cdot \frac{\pi d}{\frac{\pi}{4} d^2} = \frac{0.747^2}{l^2} \text{ or } \frac{h}{k} \times \frac{4}{d} = \frac{0.558}{l^2}$$

or, $$k = \frac{4hl^2}{0.558d} = \frac{4 \times 65 \times 0.18^2}{0.558 \times 0.035} = 431.34 \text{ W/m°C}$$

(where l = 180 mm = 0.18 m (given)]

Example 7.15 **A steel tube carries steam at a temperature of 320°C. A thermometer pocket of iron (k = 52.3 W/m°C) of inside diameter 15 mm and 1 mm thick is used to measure the temperature. The error to be tolerated in 1.5% of maximum. Estimate the length of the pocket necessary to measure the temperature within this error. The diameter of steel tube is 95 mm. Assume h = 93 W/m^2°C and tube wall temperature is 120°C. Suggest a suitable method of locating the thermometer pocket.**

Solution :

Given : $t_f = 320$°C; $k = 52.3$ W/m°C; $d_i = 15$ mm = 0.015 m; $\delta = 1$ mm = 0.001 m; $h = 93$W/m^2°C; $t_o = 120$°C

$$d_0 = d_i + 2\delta = 15 + 2 \times 1 = 17 \text{ mm} = 0.017 \text{ m}$$

Length of the pocket, l :

The temperature recorded by the thermometer (t_l) is found from the relation

$$\frac{t_l - t_f}{t_o - t_f} = \frac{1}{\cosh(ml)}$$

where, t_o = Wall temperature, and

t_f = Steam temperature.

The error in measurement is indicated by $(t_f - t_l)$

Now, $$t_f - t_l = (1.5\%)\, t_f = \frac{1.5}{100} t_f$$

∴ $$t_l = t_f - \frac{1.5}{100} t_f = 0.985 t_f$$

∴ $$\frac{0.985 t_f - t_f}{t_o - t_f} = \frac{1}{\cosh(ml)} \qquad ...(1)$$

where, $$m = \sqrt{\frac{hP}{kA_{cs}}} = \sqrt{\frac{h}{k} \times \frac{\pi d_o}{\frac{\pi}{4}(d_o^2 - d_i^2)}}$$

$$= \sqrt{\frac{93}{52.3} \times \frac{4 d_o}{d_o^2 - d_i^2}} = \sqrt{\frac{93}{52.3} \times \frac{4 \times 0.017}{(0.017^2 - 0.015^2)}} = 43.5$$

Substituting the value in eqn. (1), we get

$$\frac{0.985 \times 320 - 320}{120 \times 320} = \frac{1}{\cosh(ml)} = \frac{1}{\cosh(43.5 l)}$$

or $$\cosh(43.5 l) = \frac{120 \times 320}{0.985 \times 320 - 320} = 41.67$$

or $$\cosh(43.5 l) = 4.423$$

or, $$l = 0.1016 \text{ or } 101.6 \text{ mm}$$

As $l > D$ (95 mm), the pocket should he fitted inclined.

Example 7.16 A 50 cm × 50 cm copper slab 6.25 mm thick has a uniform temperature of 300°C. Its temperature in suddenly lowered to 36°C. Calculate the time required for the plate to reach the temperature of 108°C.

Take ρ = 9000 kg/m^3; c = 0.38 kJ/kg°C, k = 370 W/m°C and h = 90 W/m^2°C

Solution :

Surface area of plate, $A_s = 2 \times 0.5 \times 0.5 = 0.5 \text{ m}^2$ (two sides)

Volume of plate, $V = 0.5 \times 0.5 \times 0.00625 = 0.0015625 \text{ m}^3$

Characteristic length, $$L_c = \frac{V}{A_s} = \frac{0.0015625}{0.5} = 0.003125 \text{ m}$$

Biot number, $$B_i = \frac{hL_c}{k} = \frac{90 \times 0.003125}{370} = 7.6 \times 10^{-4}$$

Since B_i is less than 0.1, hence lumped capacitance method (Newtonian heating or cooling) may be applied for the solution of the problem.

The temperature distribution is given by

$$\frac{t - t_a}{t_i - t_a} = \exp\left[\frac{-hA_x}{\rho Vc} \rho\right]$$

Substituting the values, we get

$$\frac{108 - 36}{300 - 36} = \exp\left[-\frac{90 \times 0.5}{9000 \times 0.0015625 \times (0.38 \times 1000)} \tau\right] = e^{-0.00842\tau}$$

$$0.2727 = e^{-0.002842\tau} = \frac{1}{e^{0.00842\tau}}$$

or $$e^{-0.00842\tau} = \frac{1}{0.2727} = 3.667$$

or $$0.00842\tau = \ln 3.667 = 1.2994$$

or $$\tau = \frac{1.2994}{0.00842} = 154.32 \text{ s}$$

Example 7.17 A solid copper sphere of 10 cm diameter [ρ = 8954 kg/m^3, c_p = 383 J/kg K, k = 386 W/m K], initially at a uniform temperature t_i = 250°C, is suddenly immersed in a well-stirred fluid which is maintained at a uniform temperature t_a = 50°C. The heat transfer coefficient between the sphere and the fluid is h = 200 W/m^2 K. Determine the temperature of the copper block at τ = 5 min. after the immersion.

Solution :

Given : D = 10 cm = 0.1 m; ρ = 8954 kg/m^3; c_p = 383 J/kg K; k = 386 W/m K; t_i = 250°C; t_a = 50°C; h = 200 W/m^2 K; τ = 5 min = 300s

Temperature of the copper block, t :

The characteristic length of the sphere is,

$$L_c = \frac{\text{Volume }(V)}{\text{Surface area }(A_s)} = \frac{\frac{4}{3}\pi R^3}{4\pi R^2} = \frac{R}{3} = \frac{D}{6} = \frac{0.1}{6} = 0.0167 \text{ m}$$

Biot number, $$B_i = \frac{hL_c}{k} = \frac{200\times 0.01667}{386} = 8.64 \times 10^{-3}$$

Since B_i is less than 0.1, hence lump capacitance method (Newtonian heating or cooling) may be applied for the solution of the problem.

The temperature distribution is given by

$$\frac{t-t_a}{t_i-t_a} = \exp\left[-\frac{hA_s}{\rho Vc}\cdot\tau\right]$$

Substituting the value, we get

$$\frac{t-50}{250-50} = \exp\left[-\frac{200}{8954\times 0.01667\times 383}\times 300\right] = 0.35$$

$$\left(\because \frac{A_s}{V} = \frac{L}{L_c} = \frac{1}{0.01667}\right)$$

$\therefore$ $$t = (250-50)\times 0.35 + 50 = 120°\text{C}$$

Example 7.18 An average convective heat transfer coefficient for flow of 90°C air over a flat plate is measured by observing the temperature time history of a 40 mm thick copper slab (ρ = 9000 kg/m^3, c = 0.38 kJ/kg°C, k = 370 W/m°C) exposed to 90°C air. In one test run, the initial temperature of the plate was 200°C, and in 4.5 minutes the temperature decreased by 35°C. Find the heat transfer coefficient for this case. Neglect internal thermal resistance.

Solution :

Given : t_a = 90°C; L = 40 mm = 0.04 m; ρ = 9000 kg/m^3; c = 0.38 kJ/kg°C; t_i = 200°C; t = 200 – 35 = 165°C; τ = 4.5 min = 270 s

Characteristic length, $$L_c = \frac{L}{2} = \frac{0.04}{2} = 0.02 \text{ m}$$

$$\frac{hA_s}{\rho Vc} = \frac{h}{\rho(V/A_s)c} = \frac{h}{\rho c L_c} = \frac{h}{9000\times(0.38\times1000)\times0.02} = 1.462 \times 10^{-5}\, h$$

Now,
$$\frac{t-t_a}{t_i-t_a} = \exp\left[-\frac{hA_s}{\rho Vc}\tau\right]$$

or,
$$\frac{165-90}{200-90} = e^{-(1.462\times10^{-5}h)\times(270)} = e^{-0.003947h} = \frac{1}{e^{0.003947h}}$$

or,
$$0.003947h = \ln 1.466 = 0.3825$$

∴
$$h = \frac{0.3825}{0.003947} = 96.9 \text{ W/m}^2\text{°C}$$

7.7 Convective Heat Transfer

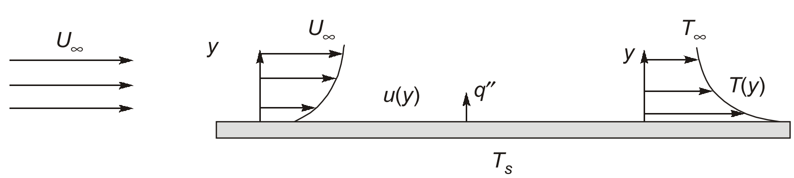
Main purpose of convective heat transfer analysis is to determine :

- Flow field
- Temperature field in fluid
- Heat transfer coefficient, (h)

7.7.1 Determination of Heat Transfer Coefficient (*h*)

Consider the process of convective cooling, as we pass a cool fluid past a heated wall. This process is described by Newton's law of cooling :

$$q = h.A.(T_s - T_\infty)$$



Near any wall a fluid is subject to the no slip condition; that is, there is a stagnant sub layer. Since there is no fluid motion in this layer, heat transfer is by conduction in this region. Above the sub layer is a region where viscous forces retard fluid motion; in this region some convection may occur, but conduction may well predominate. A careful analysis of this region allows us to use our conductive analysis in analyzing heat transfer. This is the basis of our convective theory.

At the wall, the convective heat transfer rate can be expressed as the heat flux.

$$q^*_{conv} = -k_f\left(\frac{\partial T}{\partial y}\right)_{y=0} = h(T_s - T_\infty)$$

Hence,
$$h = \frac{-k_f \left.\frac{\partial T}{\partial y}\right)_{y=0}}{(T_s - T_\infty)}$$

But $\left(\frac{\partial T}{\partial y}\right)_{y=0}$ depends on the whole fluid motion, and both fluid flow and heat transfer equations are needed.

The expression shows that in order to determine h, we must first determine the temperature distribution in the thin fluid layer that coats the wall.

Student's Assignments 1

Q.1 The wavelength at which the black body emissive power reaches its maximum value at 1000 K

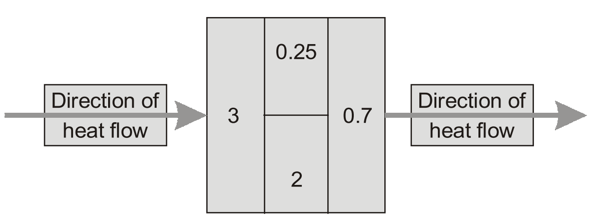
(a) 5.1 μm (b) 2.9 μm
(c) 15.5 μm (d) 38.0 μm

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 W/mK). The outside surface convection coefficient is 15 W/m^{2}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 °C. If thermal conductivity of the fluid is 1.0 W/m-K, the local convective heat transfer coefficient at that location will be _____ W/m^2-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) $\eta = \frac{1}{L}\sqrt{\frac{kd}{h}}$ (b) $\eta = \frac{1}{L}\sqrt{\frac{h}{kd}}$

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

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 _______ W/m^{2}K.

Q.9 Water at 10°C flows over a flate plate (at 90°C) with a velocity of 3 m/s Properties of water at 50°C are :
ρ = 988.1 kg/m^3, $\nu = 0.56 \times 10^{-6}$ m^2/s, Pr = 3.54, k = 0.648 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 W/m^{2}k (b) 108 kW/m^{2}k
(c) 108 MW/m^{2}k (d) 10.8 MW/m^{2}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.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/m^{2}K. Taking emissivity of the pipe surface as 0.8, the combined heat transfer coefficient due to convection and radiation is ________ W/m^{2}K. (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

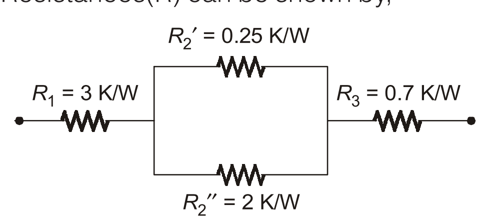
$$= \frac{k}{h_0} = \frac{0.18}{15}$$

$$= 0.012\ \text{m} = 12\ \text{mm}$$

Critical thickness = 12 – 10 = 2 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)

$$= R_1 + R_2 + R_3$$

$$= 3 + 0.222 + 0.7$$

$$= 3.922\ \text{K/W}$$

5. (2)

$$hA\Delta T = -k_f A \frac{\partial T}{\partial y}\bigg|_{y=0}$$

$$\Rightarrow \quad h(T_s - T_f) = -1\frac{\partial}{\partial y}\left[30 + 160e^{-y}\right]_{y=0}$$

$$\Rightarrow \quad h(110 - 30) = [0 + 160(-1)e^{-y}]$$

$$\Rightarrow \quad h = \frac{160}{80} = 2\ \text{W/m}^2\text{-K}$$

6. (d)

$$\eta = \frac{Q_{actual}}{Q_{ideal}} = \frac{\sqrt{hPkA}(T_b - T_\infty)}{hA_{fin}(T_b - T_\infty)}$$

$$= \frac{\sqrt{hPkA}}{hPL} = \frac{1}{L}\sqrt{\frac{kA}{hP}}$$

For circular fin

$$A = \frac{\pi}{4}d^2$$

$$P = \pi d$$

$$\eta = \frac{1}{L}\sqrt{\frac{kd}{4h}} = \frac{1}{2L}\sqrt{\frac{kd}{h}}$$

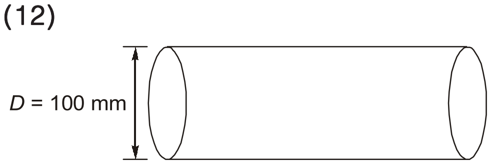
7. (c)

For maximum rate of heat transfer by radiation, surface must be blackbody (i.e., $\varepsilon = 1$)

Emissive power,

$$E_b = \sigma T_1^4$$
$$= 5.67 \times 10^{-8} \times (150 + 273)^4$$
$$= 1815.28\ \text{W/m}^2$$

8. (12)



Diameter of steel pipe, $D = 100$ mm

Nusselt number, Nu = 20

Thermal conductivity, $k = 0.06$ W/mK

For horizontal pipe, $\text{Nu} = \frac{hD}{k}$

$$\Rightarrow \quad 20 = \frac{h \times 0.1}{0.06}$$

Heat transfer coefficient, $h = 12$ W/m²K

9. (b)

For flow to be laminar,

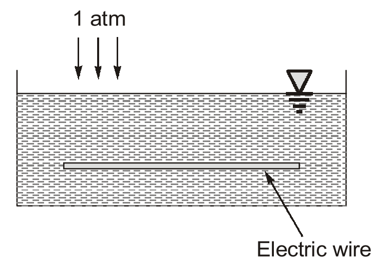
$$Re \le 500000$$

$$\frac{V \times x}{\nu} \le 500000$$

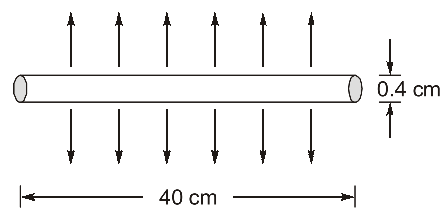
$$x = \frac{500000 \times 0.56 \times 10^{-6}}{3}$$
$$= 0.0933\ \text{m} = 9.33\ \text{cm}$$

10. (b)

Pressure is 1 atm i.e. water will boil at 100°C.



Now wire will loose heat from its curved surfaces.



Heat lost by wire $= hA\Delta T$

$$7.6 \times 10^3 = h \times \pi \times (0.4 \times 10^{-2}) \times (40 \times 10^{-2}) \times (114 - 100)$$

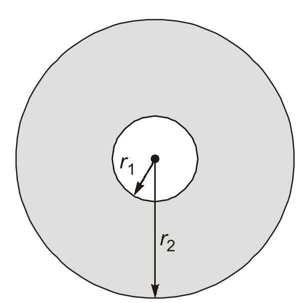
$$h = 107.99 \times 10^3\ \text{W/m}^2\text{K}$$

or $\quad h \approx 108$ kW/m²K

11. (b)

Since, $\quad Q = \frac{\Delta T}{R_{th}}$

for sphere, $\quad R_{th} = \left(\frac{r_2 - r_1}{4\pi r_1 r_2 k}\right)$



$$\Delta T = Q \cdot \frac{r_2 - r_1}{4\pi r_1 r_2 k} = \frac{Q}{4\pi k}\left[\frac{1}{r_1} - \frac{1}{r_2}\right]$$

Since, $\quad \Delta T \propto \frac{1}{r}$

∴ Hyperbolic function

12. (c)

Time constant, $\tau^* = \frac{\rho VC}{hA}$

21. (c)

Wall thickness, δ = 10 mm = 0.01 m

As given in question, Thermal conductivity,

$$k = ax + b$$

$$\text{Heat flux, } q'' = -k\frac{dT}{dx}$$

$$q'' = -(ax+b)\frac{dT}{dx}$$

$$\frac{q''}{ax+b}dx = -dT$$

On integrating,

$$q''\int_0^{\delta}\frac{dx}{ax+b} = -\int_{T_1}^{T_2} dT$$

$$\Rightarrow \frac{q''}{a}[\ln|ax+b|]_0^{\delta} = -(T_2 - T_1)$$

$$\Rightarrow \frac{q''}{a}\ln\left|\frac{a\delta+b}{a\times 0+b}\right| = (T_1 - T_2)$$

$$\Rightarrow \frac{q''}{a}\ln\left|\frac{a\delta+b}{b}\right| = (T_1 - T_2)$$

$$\frac{3.723\times10^6}{7\times10^4}\ln\left|\frac{7\times10^4\times0.01+200}{200}\right| = (100 - T_2)$$

$$T_2 = 20.0046°\text{C}$$

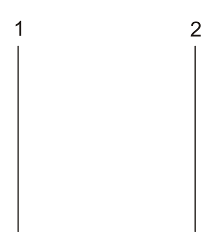
$$T_2 \simeq 20°\text{C}$$

23. (b)

Without shield :

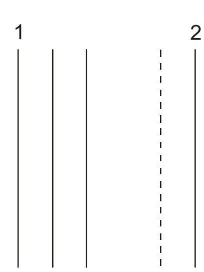
Radiation heat transfer rate,

$$q = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}$$



Let number of shields be N.

With shield : Radiation heat transfer rate,



Shields

$$q' = \frac{\sigma(T_1^4 - T_2^4)}{\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1\right)+N\left(\frac{2}{\varepsilon}-1\right)}$$

As per the conditions,

$$q' = (1-0.9)q$$

$$\frac{q}{q'} = \frac{1}{0.1} = 10$$

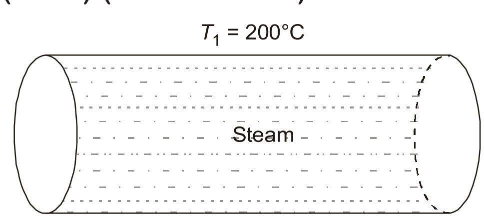
$$\frac{\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1\right)+N\left(\frac{2}{\varepsilon}-1\right)}{\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1\right)} = 10$$

$$\frac{\left(\frac{1}{0.8}+\frac{1}{0.6}-1\right)+N\left(\frac{2}{0.29}-1\right)}{\left(\frac{1}{0.8}+\frac{1}{0.6}-1\right)} = 10$$

Number of shields, $N = 2.925$

$$N \simeq 3$$

24. (16.93) (16.88 to 16.98)



Heat transfer rate due to radiation,

$q = \varepsilon\sigma(T_1^4 - T_2^4)$

$= 0.8 \times 5.67 \times 10^{-8} \times [(200 + 273)^4 - (25 + 273)^4]$

$= 1912.7638 \text{ W/m}^2$

$= h_r(T_1 - T_2)$

where, h_r = Radiation heat transfer coefficient

$\Rightarrow \quad 1912.7638 = h_r \times (200 - 25)$

$h_r = 10.93 \text{ W/m}^2\text{K}$

Convection heat transfer coefficient

$h_c = 6 \text{ W/m}^2\text{-K}$

So, combined heat transfer coefficient

$= h_r + h_c$

$= 10.93 + 6 = 16.93 \text{ W/m}^2\text{-K}$

25. (c)

Both conduction and convection resistance increases.

■■■■