HEAT TRANSFER

Module I

HEAT CONDUCTION

Course material Adapted from:

1. Warren. L, McCabe, Julian. C. Smith and Peter Harriott, "Unit Operations of Chemical Engineering", 7th Edn., McGraw Hill International Edition, NewYork 2005.
2. Holman. J.P., "Heat Transfer", 9th Edn., Tata McGraw Hill Book Co., New Delhi, 2008.
3. R.C.Sachdeva, "Fundamentals of Engineering Heat and Mass Transfer", 4th Edition,New Age International Publishers,2010
4. www.che.utexas.edu/course/che360/lecture_notes/chapter_2.ppt

CONTENTS

Introduction to various modes of heat transfer, Fourier's law of heat conduction, effect of temperature on thermal conductivity, steady-state conduction, compound resistances in series, heat flow through a cylinder, and critical radius of insulation in pipes. Introduction to unsteady state conduction.

Introduction

Practically all the operations that are carried out by the chemical engineers involve the production or absorption of energy in the form of heat. The study of temperature distribution and heat transfer is of great importance to engineers because of its almost universal occurrence in many branches of science and engineering. The first step in the optimal design of heat exchangers such as boilers, heaters, refrigerators and radiators is a detailed analysis of heat transfer. This is essential to determine the feasibility and cost of the undertaking, as well as the size of equipment required to transfer a specified amount of heat in a given time.

Difference between thermodynamics and heat transfer

Thermodynamic tells us

(i) How much heat is transferred

(ii) How much work is done

(iii) Final state of the system

Heat transfer tells us:

(i) How much heat is transferred(with what modes)

(ii) At what rate heat is transferred

(iii) Temperature distribution inside the body

1.1. INTRODUCTION TO VARIOUS MODES OF HEAT TRANSFER

The various modes of heat transfer are (i) conduction (ii) convection (iii) radiation.

Conduction

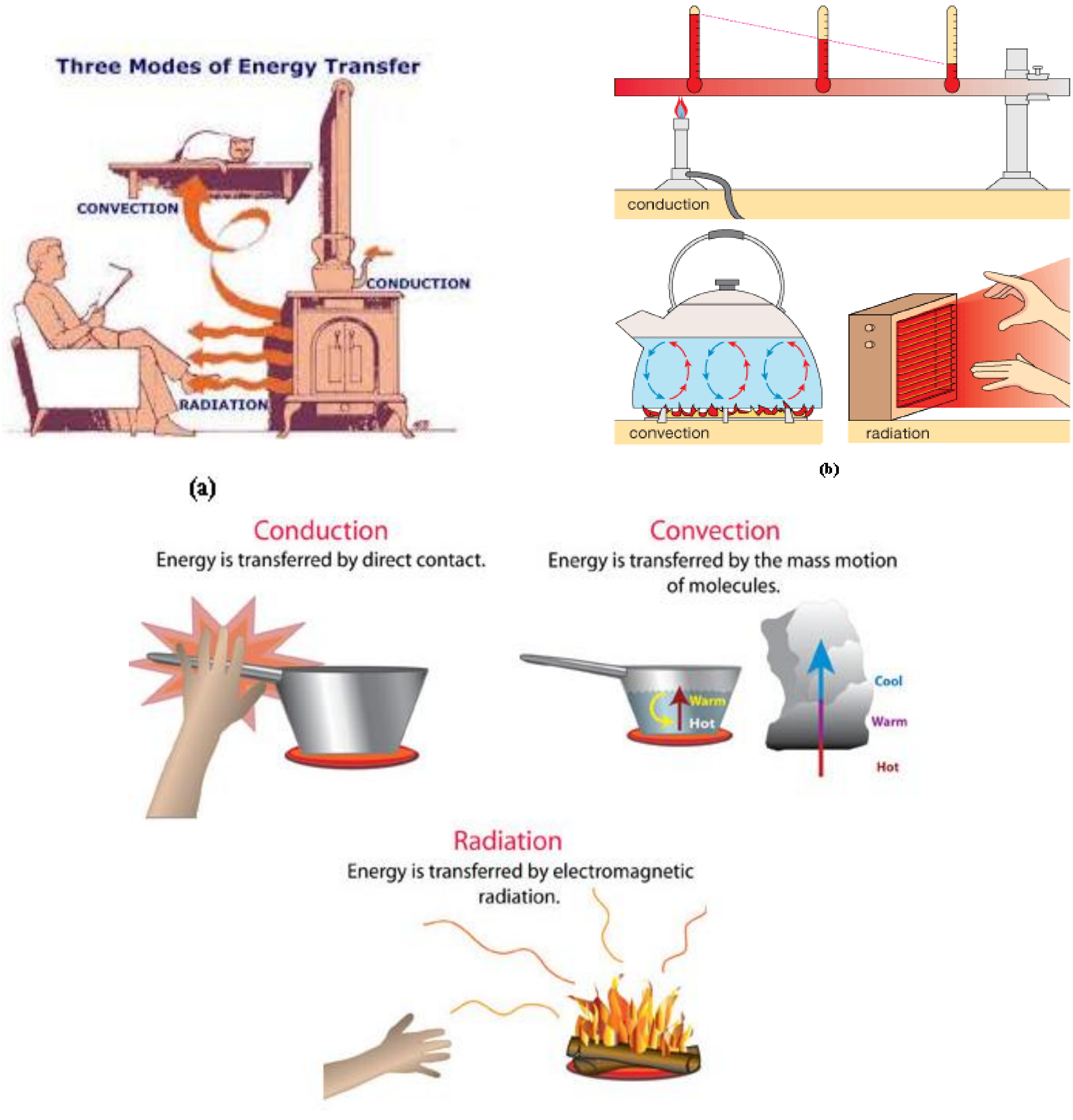
Heat transfer by the actual but invisible movement of molecules with in the continuous substance due to temperature gradient is known as conduction.

Convection

When a current or macroscopic particle of fluid crosses a specific surface, it carries with it a definite quantity of enthalpy. Such a flow of enthalpy is called convection. Convection is the mode of heat transfer in which the heat flow is associated with the movement of fluid.

Radiation

Transfer of energy through space by electromagnetic waves is known as radiation.



(c)

Fig.1. Modes of Heat Transfer

1.2. APPLICATIONS OF HEAT TRANSFER

Energy production and conversion	-steam power plant, solar energy conversion etc.
Refrigeration and air-conditioning	
Domestic applications	-ovens, stoves, toaster
	Cooling of electronic equipment
Manufacturing / materials processing	-welding, casting, soldering, laser machining
Automobiles / aircraft design	

1.3. Conduction

It is the transfer of internal energy by microscopic diffusion and collisions of particles or quasi-particles within a body due to a temperature gradient. The microscopically diffusing and colliding objects include molecules, electrons, atoms, and phonons. They transfer disorganized microscopic kinetic and potential energy, which are jointly known as internal energy. Conduction can only take place within an object or material, or between two objects that are in direct or indirect contact with each other. On a microscopic scale, heat conduction occurs as hot, rapidly moving or vibrating atoms and molecules interact with neighboring atoms and molecules, transferring some of their energy (heat) to these neighboring particles. In other words, heat is transferred by conduction when adjacent atoms vibrate against one another, or as electrons move from one atom to another.

1.4. FOURIER'S LAW OF HEAT CONDUCTION

According to Fourier's law of heat conduction, heat flux is proportional to temperature gradient.

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

Joseph Fourier

Where Q = Rate of heat transfer, W

k = Thermal conductivity, W/mK or W/m °C

A = Heat transfer area, m^2

$\frac{dT}{dx}$ = Temperature gradient, °C/m

EFFECT OF TEMPERATURE ON THERMAL CONDUCTIVITY

Thermal conductivity is the physical property of the substance. It depends upon temperature gradient. For pure metals thermal conductivity decreases with increase in temperature. For gases and insulators thermal conductivity increases with increase in temperature.

For small ranges of temperature, k may be considered constant. For larger temperature ranges, thermal conductivity can be approximated by an equation of the form k = a + bT, where a and b are empirical constants.

Steady-State Conduction

It is the form of conduction which happens when the temperature difference driving the conduction is constant so that after an equilibrium time, the spatial distribution of temperatures (temperature field) in the conducting object does not change any further. In steady state conduction, the amount of heat entering a section is equal to amount of heat coming out.

Unsteady state conduction

It is the form of conduction which happens when the temperature difference driving the conduction is not constant so that after an equilibrium time, the spatial distribution of temperatures (temperature field) in the conducting object changes as a function of time.

1.5. HEAT TRANSFER THROUGH A PLANE WALL

Let us consider a plane wall of thickness L, thermal conductivity k, inside surface temperature T_i, outside surface temperature T_o. Let Q be the rate of heat transferred through the plane wall.

By Fourier's law of heat conduction

$$Q = -kA \frac{dT}{dx} \qquad (1)$$

$$Q \int_0^L dx = -k\,A \int_{Ti}^{To} dT \qquad (2)$$

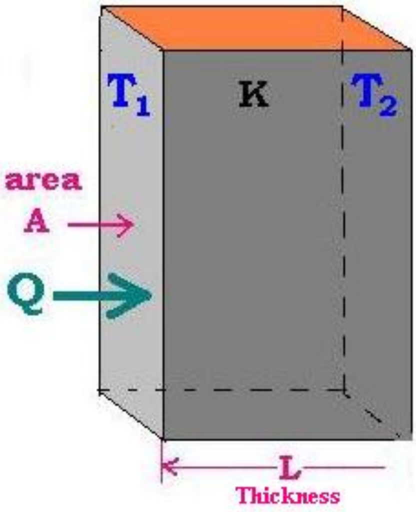


Fig. 2. Plane wall

Integrating eqn(2), we get

$$Q = \frac{k\;A\left(T_i - T_o\right)}{L} \qquad (3)$$

1.6. HEAT TRANSFER THROUGH A HOLLOW CYLINDER

Let us consider a hollow cylinder as shown in fig.3. The inside radius of the cylinder is r_1, the outside radius is r_2, and the length of the cylinder is L. The thermal conductivity of the material of which the cylinder is made is k. The temperature of the outside surface is T_2, and that of the inside surface is T_1.

By Fourier's law of heat conduction

$$Q = -kA \frac{dT}{dr} \qquad (1)$$

$$Q \int_{r1}^{r2} \frac{dr}{r} = -k\, 2\pi L \int_{T1}^{T2} dT \qquad (2)$$

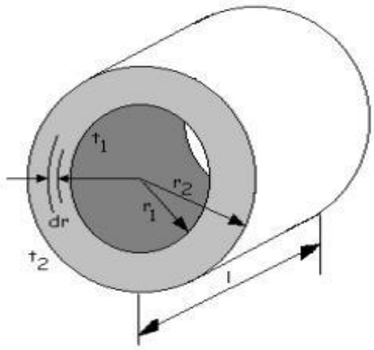


Fig.3. Hollow cylinder

Integrating eqn(2), we get

$$Q = \frac{2\pi k L \left(T_1 - T_2\right)}{\ln\left(\frac{r_2}{r_1}\right)} \qquad (3)$$

LOGARITHMIC MEAN RADIUS AND ARITHMETIC MEAN RADIUS

Logarithmic mean radius is the radius that when applied to the integrated equation for a flat wall, will give the correct rate of heat flow through a thick walled cylinder. It is given by the expression

$$\overline{r_L} = \frac{r_o - r_i}{\ln\left(\frac{r_o}{r_i}\right)}$$

Arithmetic mean radius is used for thin walled cylinder.

$$r_A = \frac{r_o + r_i}{2}$$

where, $\overline{r_L}$ = log mean radius

r_A = Arithmetic mean radius

r_o = outer radius

r_i = inner radius

1.7. COMPOUND RESISTANCES IN SERIES

(I) Heat Transfer Through A Composite Plane Wall

Let us consider a flat wall constructed of a series of 3 layers as shown in fig.4. Let the thickness of the layers be L_1, L_2, L_3 and the average thermal conductivities of the materials of which the layers are made be k_1, k_2, k_3 respectively. Let us consider a hot fluid at a temperature T_a and heat transfer coefficient h_a inside the wall and cold fluid at a temperature T_b and heat transfer coefficient h_b outside the wall. Let T_1, T_2, T_3 and T_4 be the interface temperatures. It is desired to derive an equation for calculating the rate of heat flow through the series of resistances.

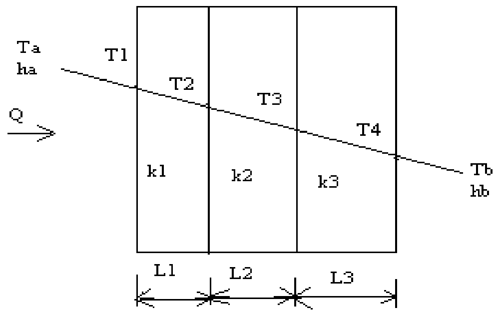


Fig.4.Composite wall

Rate of heat flow from the hot fluid to the inner surface of the wall

By Newton's law of cooling

$$Q = h_a A (T_a - T_1) \qquad (1)$$

By rearranging eqn(1),we get

$$Q = \frac{(T_a - T_1)}{\frac{1}{h_a A}}$$

Rate of the heat flow through the I layer

By Fourier's law of heat conduction

$$Q = \frac{k_1 \; A\left(T_1 - T_2\right)}{L_1} \qquad (2)$$

By rearranging eqn(2),we get

$$Q = \frac{\left(T_1 - T_2\right)}{\frac{L_1}{k_1 A}}$$

Rate of the heat flow through the II layer

By Fourier's law of heat conduction

$$Q = \frac{k_2 \; A\left(T_2 - T_3\right)}{L_2} \qquad (3)$$

By rearranging eqn(3),we get

$$Q = \frac{(T_2 - T_3)}{\frac{L_2}{k_2 A}}$$

Rate of the heat flow through the III layer

By Fourier's law of heat conduction

$$Q = \frac{k_3 \ A(T_3 - T_4)}{L_3} \qquad (4)$$

By rearranging eqn(4),we get

$$Q = \frac{(T_3 - T_4)}{\frac{L_3}{k_3 A}}$$

Rate of heat flow from the outer surface of the wall to the cold fluid

By Newton's law of cooling

$Q = h_b A (T_4 – T_b)$ (5)

By rearranging eqn(5),we get

$$Q = \frac{(T_4 - T_b)}{\frac{1}{h_b A}}$$

Overall rate of heat flow = $\frac{overall\ temperature\ drop}{overall\ thermal\ resis\tan ce}$

Overall rate of heat flow

$$Q = \frac{(T_a - T_b)}{\frac{1}{h_a A} + \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{L_3}{k_3 A} + \frac{1}{h_b A}} \qquad (6)$$

(ii) Heat Transfer Through Coaxial Cylinders

Let us consider coaxial cylinders constructed of a series of 3 layers as shown in fig.5. Let r_1, r_2, r_3 and r_4 be the radii of the cylinders and the average thermal conductivities of the materials of which the layers are made be k_1, k_2, k_3 respectively. Let us consider a hot fluid at a temperature T_a and heat transfer coefficient h_a inside the cylinder and cold fluid at a temperature T_b and heat transfer coefficient h_b outside the cylinder. Let T_1, T_2, T_3 and T_4 be the interface temperatures. It is desired to derive an equation for calculating the rate of heat flow through the series of resistances.

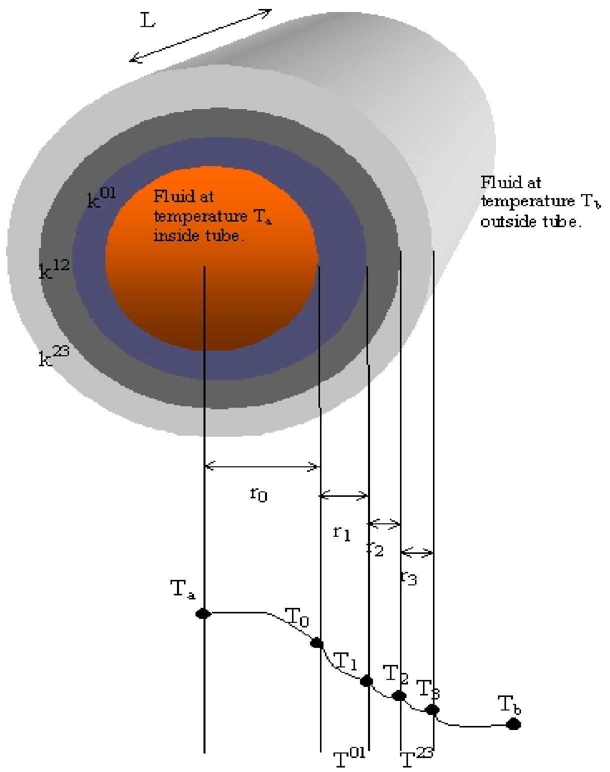


Fig.5.Coaxial cylinders

Rate of heat flow from the hot fluid to the inner surface of the wall

By Newton's law of cooling

$Q = h_a A (T_a – T_1)$ (1)

$Q = h_a 2\pi r_1 L (T_a – T_1)$

By rearranging eqn(1),we get

$$Q = \frac{(T_a - T_1)}{\frac{1}{h_a 2\pi r_1 L}}$$

Rate of the heat flow through the I layer

By Fourier's law of heat conduction

$$Q = \frac{2\pi k_1 L (T_1 - T_2)}{\ln\left(\frac{r_2}{r_1}\right)} \quad (2)$$

By rearranging eqn(2),we get

$$Q = \frac{(T_1 - T_2)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_1 L}}$$

Rate of the heat flow through the II layer

By Fourier's law of heat conduction

$$Q = \frac{2\pi k_2 L\,(T_2 - T_3)}{\ln\left(\frac{r_3}{r_2}\right)} \qquad (3)$$

By rearranging eqn(3),we get

$$Q = \frac{(T_2 - T_3)}{\frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi k_2 L}}$$

Rate of the heat flow through the III layer

By Fourier's law of heat conduction

$$Q = \frac{2\pi k_3 L\,(T_3 - T_4)}{\ln\left(\frac{r_4}{r_3}\right)} \qquad (4)$$

By rearranging eqn(4),we get

$$Q = \frac{(T_3 - T_4)}{\frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi k_3 L}}$$

Rate of heat flow from the outer surface of the wall to the cold fluid

By Newton's law of cooling

$Q = h_b A (T_4 – T_b)$ (5)

$Q = h_b 2\pi r_4 L (T_4 – T_b)$

By rearranging eqn(5),we get

$$Q = \frac{(T_4 - T_b)}{\frac{1}{h_b 2\pi r_4 L}}$$

$$\text{Overall rate of heat flow} = \frac{overall\ temperature\ drop}{overall\ thermal\ resistance}$$

Overall rate of heat flow

$$Q = \frac{2\pi L\,(T_a - T_b)}{\frac{1}{h_a r_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_1} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_2} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{k_3} + \frac{1}{h_b r_4}} \qquad (6)$$

1.8. Insulation

The addition of insulation material on a surface reduces the amount of heat flow to the ambient. There are certain instances in which the addition of insulation to the outside surface of cylindrical of spherical walls does not reduce the heat loss. Under certain circumstances it actually increases the heat loss up to a certain thickness of insulation. It is well known fact that the rate of heat transfer will approach zero if an infinite amount of insulation are added. This means that there must be a value of radius for which rate of heat transfer is maximum.This value is known as the critical radius of insulation, r_c.

1.8.1. CRITICAL RADIUS OF INSULATION IN PIPES

Let us consider an insulating layer in the form of a hollow cylinder of length L. Let r_i and r_o be the inner and outer radii of insulation. The thermal conductivity of the material of which the layer is made be k. Let the inside surface of insulation be at a temperature T_i, and the outside surface at a temperature T_o be dissipating heat by convection to the surroundings at a temperature T_b with a heat transfer coefficient h. Then the rate of heat transfer Q through this insulation layer is

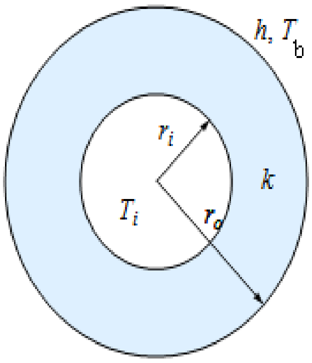


Fig.6. Insulation layer

$$Q = \frac{2\pi L\left(T_i - T_b\right)}{\frac{\ln\left(\frac{r_o}{r_i}\right)}{k} + \frac{1}{hr_o}} \qquad (1)$$

The value of critical radius r_c, that is r_o for which Q is a maximum may be obtained by equating dQ/dr_o to zero.

$$\frac{dQ}{dr_o} = \frac{0 - \left(T_i - T_b\right)\left[\frac{1}{2\pi kLr_o} - \frac{1}{2\pi hLr_o^2}\right]}{\left[\frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi kL} + \frac{1}{2\pi hLr_o}\right]^2} \qquad (2)$$

$\left(T_i - T_b\right) \neq 0$(Since it is the driving force)

$$\therefore \quad \frac{1}{2\pi kLr_o} - \frac{1}{2\pi hLr_o^2} = 0 \qquad (3)$$

$$r_0 = \frac{k}{h} = r_c$$

The radius at which the rate of heat transfer is maximum is known as the critical radius of insulation.

1.9.VARIABLE THERMAL CONDUCTIVITY

Let us a hollow cylinder. The inside radius of the cylinder is r_i, the outside radius is r_o, and the length of the cylinder is L. The thermal conductivity of the material of which the cylinder is varies with temperature as k= k_o (1 + βT). The temperature of the outside surface is T_o, and that of the inside surface is T_i.

By Fourier's law of heat conduction

$$Q = -kA \frac{dT}{dr} \qquad (1)$$

$$Q = - k_o (1 + \beta T) A \frac{dT}{dr}$$

$$Q \int_{ri}^{ro} \frac{dr}{r} = - k_o 2\pi L \int_{Ti}^{To} (1+\beta T)\ dT \qquad (2)$$

$$Q \ \ln \frac{r_o}{r_i} = k_0 2\pi L \left(1 + \beta \frac{[T_i + T_o]}{2} \right) (T_i - T_o)$$

$$Q = \frac{k_0 2\pi L \left(1 + \beta \frac{[T_i + T_o]}{2} \right) (T_i - T_o)}{\ln \frac{r_o}{r_i}} \qquad (3)$$

1.10. Introduction to Unsteady state heat transfer

A solid body is said to be in a steady state if its temperature does not vary with time. If however there is an abrupt change in its surface temperature or environment it takes some time before the body to attain an equilibrium temperature or steady state. During this interim period the temperature varies with time and the body is said to be in an unsteady or transient state.

The analysis of unsteady state heat transfer is of great interest to engineers because of its widespread occurrence such as in boiler tubes, rocket nozzles, automobile engines, cooling of IC engines, cooling and freezing of food, heat treatment of metals by quenching, etc. For practical purposes it is necessary to know the time taken to attain a certain temperature when the environment suddenly changes. The solution of an unsteady sate problem will be more complex than that of steady state one because of the presence of another variable time, t.

Transient heat conduction problems can be divided into periodic heat flow and non periodic heat flow problems. Periodic heat flow problems are those in which the temperature varies on a regular basis, eg., the variation of temperature of the surface of the earth during a twenty four hour period.. In the non periodic type, the temperature at any point within the system varies non linearly with time.

1.10.1. Systems with negligible internal resistance – Lumped Heat Analysis

Heat transfer in heating and cooling of a body is dependent upon both the internal and surface resistances. The simplest unsteady state problem is one in which the internal resistance is negligible, that is, the convective resistance at the surface boundary is very large when compared to the internal resistance due to conduction. In other words, the solid has an infinite thermal conductivity so that there is no variation of temperature inside the solid and temperature is a function of time only. This situation cannot exist in reality because all the solids have a finite thermal conductivity and there will always be a temperature gradient inside whenever heat is added or removed. Problems such as heat treatment of metals by quenching, time response of thermocouples and thermometers, etc can be analysed by this idealization of negligible internal resistance. The process in which the internal resistance is ignored being negligible in comparison with its surface resistance is called the Newtonian heating and cooling process. In Newtonian heating and cooling process the temperature throughout the solid is considered to be uniform at a given time. Such an analysis is called the lumped heat capacity analysis.

1.10.2. Systems with negligible surface resistance

Another class of transient problems met with in practice is one in which the surface resistance is negligible compared to the overall resistance. This amounts to saying that the convective heat transfer coefficient at the surface is infinity. For such a process the surface temperature remains constant for all the time and its value is equal to that of ambient temperature.

P.No. 1. A furnace wall consists of two layers, 22.5cm of fire brick(k=1.2kcal/hr m ^oC)and 12.5cm of insulating brick (k=0.15kcal/hr m ^oC) . The temperature inside the furnace is 1650 ^oC and the inside heat transfer coefficient is 60kcal/hr m ^oC . The temperature of the surrounding atmosphere is 27°C and the outside heat transfer coefficient is 10kcal/hr m^2 °C . Determine the rate of heat of loss per square meter of the wall.

Solution:

L_1 - 22.5 x 10^{-2} m

L_2 - 12.5 x 10^{-2} m

k_1 - 1.2 kcal/hr m ^oC

k_2 - 0.15 kcal/hr m ^oC

h_a - 60 kcal/hr m^2 ^oC

h_b - 10kcal/hr m^2 °C

T_a – 1650 °C

T_b – 27 °C

$$Q = \frac{(T_a - T_b)}{\frac{1}{h_a A} + \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{1}{h_b A}}$$

Q / A = 1426.8 W / m^2

P.No.2. A pipe carrying steam at 220 °C has an I.D. of 15cm. The convection coefficient on the inside wall is 60W/m^2K . The pipe wall thickness is 15mm and the thermal conductivity is 35W/mK . The outside is exposed to a chemical at 130°C with a convection coefficient of 15W/m^2K . If the pipe wall is covered with two insulation layers, the first 3cm thickness with k=0.12W/mK and the second 4cm thickness with k= 0.35W/m K. Determine the rate of heat transfer.

Solution :

r_1 - 75 x 10^{-3} m

r_2 - 90 x 10^{-3} m

r_3 - 120 x 10^{-3} m

r_4 - 160 x 10^{-3} m

k_1 - 35 W / m K

k_2 - 0.12 W / m K

k_2 - 0.35 W / m K

$h_{a\,-}$ 60 W / m^2 K

h_b – 15 W / m^2 K

$$Q = \frac{2\pi L\left(T_a - T_b\right)}{\frac{1}{h_a r_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_1} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_2} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{k_3} + \frac{1}{h_b r_4}}$$

Q = 146.32 W

ASSIGNMENT:

Composite Wall

1. A composite wall consists of a 17cm thick firebrick layer (k = 1.1 W/m ^{o}C) and a 13cm thick ordinary brick layer (k = 0.70 W/m ^{o}C). The inside and outside surface temperatures of the walls are 400 ^{o}C and 45 ^{o}C respectively. Calculate the heat loss per unit area of the wall. Also calculate the temperature between the ordinary brick and the firebrick layers.
2. A steam boiler furnace is made of a layer of fireclay (k = 0.533 W/m K)12.5cm thick and a layer of red brick(k = 0.7 W/mK) 50cm thick. If the wall temperature inside the boiler furnace is 1100°C and that on the outside wall is 50 ^{o}C, determine the amount of heat loss per square meter of the furnace wall.
3. The wall of a cold storage consists of three layers, an outer layer of ordinary brick of 25cm thick, a middle layer of cork,10cm thick, and inner layer of cement,6cm thick. The thermal conductivities of the materials are: k_{brick} = 0.7 W/m ^{o}C, k_{cork} = 0.043 W/m ^{o}C, k_{cement} = 0.72 W/m^{o}C. The temperature of the outer surface of the wall is 30^{o}C, and the inner is -15 ^{o}C. Calculate rate of heat transfer per unit area of the wall and interface temperatures.
4. A furnace wall consists of 23cm of refractory fire clay brick (k=1W/m ^{o}C) 11.5 cm of the silica brick (k=0.188W/m ^{o}C) and 6mm of iron plate (k=45W/m ^{o}C) .The fire side of the refractory is at 1150 ^{o}C and outside surface of steel is 32 ^{o}C. Determine the heat loss.
5. A furnace wall is made of inside silica brick (k=1.858W/m^{o}C) and outside magnetite brick (k=5.8W/m^{o}C). The thickness of the silica brick is 12cm and that of magnetite brick is 20^{o}C. The temperature of silica brick surface inside the furnace is 300^{o}C and at the outside surface of magnetite is 130^{o}C. Find the heat loss per square meter of the furnace wall.
6. The composite wall of a furnace consists of an inner layer of silica brick,15cm thick (k=1.04 W/m ^{o}C), and an outer layer of insulating brick,20cm thick (k=0.2 W/m ^{o}C). The inside temperature of the furnace is 800^{o}C and the interface temperature is 705^{o}C. Calculate the rate of heat loss per unit area of the furnace wall.
7. A wall of 0.5m thickness is to be constructed from a material which has an average thermal conductivity of 1.4W/mK. The wall is to be insulated with a material having an average thermal conducting of 0.35W/mK, so that the heat loss per square meter will not exceed 1450W. Assuming that the inner and outer surface temperatures are 1200^{o}C and 15^{o}C respectively, calculate the thickness of insulation required.
8. A wall 2cm thick is to be constructed from a material which has an average thermal conductivity of 1.3 W/m°C. The wall is to be insulated with a material having an average thermal conductivity of 0.35W/m°C, so that the heat loss per square meter will not exceed 1830W. Assuming that the inner and outer surface temperatures of the insulated wall are 1300 and 30°C, calculate the thickness of the insulation required.
9. A composite wall is made of two layers of 0.30m and 0.15m thickness with surfaces held at 600^{o}C and 20^{o}C respectively. If the conductivities are 20 and 50W/mK determine the heat conducted. In order to restrict the heat loss to 5kW/m^{2} another layer of 0.15m thickness. Determine the thermal conductivity required.

10. A furnace wall consists of 200mm of refractory fireclay brick, 100mm of kaolin brick, and 6 mm of steel plate. The fire side of the refractory is at 1150°C, and the outside of the steel is at 30°C. (a) Calculate the heat loss per square meter cross section of the wall. (b) Determine the interface temperatures. $k_{fireclay}$ = 1.520 W/m °C; $k_{kaolin\ brick}$ = 0.138 W/m°C ; k_{steel} = 45 W/m °C .
11. An exterior wall of a house may be approximated by a 10cm layer of common brick(k=0.7W/m°C) followed by a 3.75cm layer of gypsum plaster (k=0.48W/m°C).What thickness of loosely packed rock-wool insulation (k=0.065W/m°C) should be added to reduce the heat loss through the wall by 80%?
12. The door of a cold storage plant is made from two 6mm thick glass sheets(k = 0.75W/mK) separated by a uniform air gap(k = 0.02W/mK) of 2mm. The temperature of the air inside the room is -20°C and the ambient air temperature is 30^oC. Assuming the heat transfer coefficient between glass and air to be 23.26 W/m^2K, determine the rate of heat loss into the room per unit area of the door. Neglect convection effect in the air gap.

Coaxial cylinders

1. A thickwalled tube of stainless steel (k= 19 W/m°C)with 2cm ID and 4cm OD is covered with a 3cm layer of asbestos insulation(k= 0.2 W/m°C).If the inside wall temperature of the pipe is maintained at 600°C and outside wall temperature is maintained at 100°C, calculate the heat loss per meter length. Also calculate the tube insulation interface temperature.
2. A hot steam pipe having an inside surface temperature of 250°C has an inside diameter of 8cm and a wall thickness of 5.5mm. It is covered with a 9cm layer of insulation having k=0.5 W/m °C, followed by a 4cm layer of insulation having k = 0.25 W/m°C. The outside temperature of insulation is 20°C. Calculate the heat lost per meter of length. Assume k=47 W/m°C for the pipe.
3. A cylindrical hot gas duct, 0.5m inside radius,has an inner layer of fireclay brick(k = 1.3 W/m °C) of 0.27m thickness. The outer layer, 0.14m thick is made of a special brick(k=0.92 W/m °C). The brickwork is enclosed by an outer steel cover which has a temperature of 65 °C. The inside temperature of the composite cylindrical wall of the duct is 400°C. Neglecting the thermal resistance of the steel cover, calculate the rate of heat loss per meter of the duct and also the interface temperature between the ceramic layers.
4. A 10cm O.D steam pipe carrying saturated steam at temperature 195°C is lagged to 20cm diameter with magnesia (k= 0.07 W/mK) and further lagged with laminated asbestos (k=0.08 W/mK) to 25cm diameter. The whole pipe is further protected by a layer of canvas. If the temperature under the canvas is 20°C, calculate the rate of heat loss on 150m length of pipe.
5. A pipe of I.D 15.4cm and O.D 16.8cm carries saturated steam at temperature 190°C. The thermal conductivity of the pipe wall is 51 W/mK. The pipe is insulated with a 10cm thick fibre glass blanket (k=0.072 W/mK). If the outer surface temperature is 41 °C, calculate the rate of heat loss over a 10 m section of the pipe.
6. A steel pipe 33.4mm outer diameter ,3.38mm wall thickness carries saturated steam at 121^oC. Pipe is insulted with 50mm layer of magnesia pipe covering and outside this magnesia is 75 mm layer of cork. Inside temperature of cork is at 32^oC. Calculate the heat loss per meter length of the pipe and the temperature at

the boundaries between metal and magnesia and between magnesia and cork. Data: steel k=45W/m ^oC ; Mg, k=0.0588W/m ^oC , Cork, k= 0.0519W/m ^oC .

7. A multilayer cylindrical wall of a furnace is constructed of 4.5cm layer of insulating brick with thermal conductivity of 0.081W/mK followed by a 9cm layer of common brick with thermal conductivity of 0.0812W/mK . The inner wall temperature is 2500^oC and outer wall temperature is 70^oC .What is the heat loss through the wall, when the inner diameter of the furnace is 1.2m and the length of the wall is 1m?
8. A steel pipe (I.D. 4.14cm and O.D. 4.74cm) carries steam at 450^oC. The steel pipe is covered with a 2.5cm layer of an insulating material (k=0.09kcal/hr m^oC) .This is covered with a 5cm layer of another insulating material (k=0.06kcal/hr m^oC) . If the temperature of the outermost insulation layer is 60^oC, calculate the heat loss in kcal/hr per meter length of pipe and the layer contact temperatures. Neglect resistance of the steam film and assume k for the steel pipe as 36kcal/hr m ^oC.
9. A steel pipe line (k=50W/mK) of 100mm and O.D.110mm is to be covered with two layers of insulation each having a thickness of 50mm .The thermal conductivity of the first insulation material is 0.06W/mK , and that of the second is 0.12W/mK . Calculate the loss of heat per meter length of pipe and the interface temperature between the two layers of insulation when the temperature of the inside tube surface is 250^oC and that of the outside surface of the insulation is 50^oC.

<u>Combined Heat Transfer</u>

1. A furnace wall consists of two layers, 22.5cm of fire brick (k=1.2kcal/hr m ^oC) and 12.5cm of insulating brick (k=0.15kcal/hr m^oC) . The temperature inside the furnace is 1650^oC and the inside heat transfer coefficient is 60Kcal/hr m^{2o}C. The temperature of the surrounding atmosphere is 27^oC and the outside heat transfer coefficient is 10kcal/hr m^2 ^oC .Neglecting the thermal resistance of the mortar joints determine the rate of heat of loss per square meter of the wall.
2. The inner dimensions of a freezer cabinet are 60cm x 60cm x 50cm(height). The cabinet walls consist of two 2mm thick enameled sheet steel (k= 40W/mK) walls separated by a 4cm layer of fiberglass(k=0.049W/mK) insulation. The inside temperature is to be maintained at -15^oC and the outside temperature on a hot summer day is 45^oC.Calculate the rate of heat transfer assuming heat transfer coefficient of 10 W/m^{2}K both on the inside and outside of the cabinet. Also calculate the outer surface temperature of the cabinet.
3. A steel tube having k=46 W/m°C has an inside diameter of 3cm and wall thickness of 2mm. A fluid flows on the inside of the tube producing a convection coefficient of 1500 W/m2°C on the inside surface, while a second fluid flows across the outside of the tube producing a convection coefficient of 197 W/m^{2}°C on the outside tube surface. The inside fluid temperature is 223° C while the outside fluid temperature is 57°C. Calculate the heat lost by the tube per meter of length.
4. A steam pipe is covered with two layers of insulation, the first layer being 3cm thick and second 5cm. The pipe is made of steel(k=58W/mK) having an I.D of 160mm and O.D of 170mm. The inside and outside film coefficients are 30 and 5.8W/m^{2}K respectively. Calculate the heat lost per metre of pipe if the steam temperature is 300^oC and the air temperature is 50^oC. The thermal conductivity of the two insulating materials are 0.17 and 0.093 W/mK respectively.
5. A steel tube (k = 43.26 W/mK) of 5.08cm ID and 7.62 OD is covered with a 2.54cm layer of asbestos insulation(k= 0.208W/mK). The inside surface of the tube receives heat by convection from a hot gas at a temperature of 316^oC with the heat transfer coefficient 284W/m^{2}K,while the outer surface of the insulation is

exposed to the ambient air at 38 ^oC with the heat transfer coefficient of 17 W/m^2K.Calculate the loss of heat to ambient air for 3m length of the tube and also the interface temperatures.

6. A multilayer cylindrical wall of a furnace is constructed of 4.5cm layer of insulating brick with thermal conductivity of 0.081W/mK followed by a 9cm layer of common brick with thermal conductivity of 0.0812W/m K. The inner wall temperature is 2500°C and outer wall temperature is 70°C.(a) Calculate the heat loss through the wall, when the inner diameter of the furnace is 1.2m and the length of the wall is 1m.(b) Determine the interface temperatures.
7. A steel pipe having an I.D.52.50mm and an O.D.60.33mm and k=39.7kcal/hr m^oC carries steam at 150^oC . It is lagged with 12.7mm thick rock wool of thermal conductivity 0.049kcal/hr m ^oC and the surrounding air is at 20^oC .If the heat transfer coefficient from the insulated pipe to the surrounding air is 6kcal/hr $m^{2o}C$, what will be the (a) heat loss per meter length of pipe (b) temperature at the boundaries between the pipe wall and rock wool and (c) between the rock wool and surrounding air.
8. A pipe carrying steam at 230°C has an internal diameter of 12cm and the pipe thickness is 7.5 mm. The conductivity of the pipe material is 49 W/m K. The convective heat transfer coefficient on the inside is 85 W/m^2 K. The pipe is insulated by one layer of insulation of 5 cm thickness having conductivity of 0.15 W/m K. The outside is exposed to air at 25°C with a convection coefficient of 18 W/m^2K. Determine the heat loss for 5m length and the interface temperatures.
9. A 5cm diameter steel pipe is covered with a 1cm layer of insulating material having k = 0.22 W/m°C followed by a 3 cm thick layer of another insulating material having k = 0.06 W/m°C. The entire assembly is exposed to a convection surrounding condition of h = $60W/m^{2\circ}C$ and T = 15°C. The outside surface temperature of steel is 400°C. calculate the heat lost by the pipe insulation assembly for a pipe length of 20m.
9. A steel pipe (k= 44W/mK) of 5.08cm I.D and 7.62cm O.D is covered with a 2.54cm layer of asbestos insulation (k=0.208W/mK).The inside surface of the pipe receives heat from the hot gas at a temperature of 316^oC with the heat transfer coefficient $284W/m^2K$,while the outer surface of the insulation is exposed to the ambient air at 38^oC with the heat transfer coefficient of $17W/m^2K$. Calculate the heat loss to ambient air for 3m length of the pipe and also calculate the interface temperatures.
10. A pipe carrying steam at 220^oC has an I.D. of 15cm. The convection coefficient on the inside wall is $60W/m^2K$.The pipe wall thickness is 15mm and the thermal conductivity is 35W/mK. The outside is exposed to a chemical at 130^oC with a convection coefficient of $15W/m^2K$. If the pipe wall is covered with insulation layers, the first 3cm thickness with k=0.12W/mK and the second 4cm thickness with k= 0.35W/mK, determine the rate of heat transfer and interface temperature
11. A pipe carrying steam at 230°C has an internal diameter of 12cm and the pipe thickness is 7.5 mm. The conductivity of the pipe material is 49 W/m K. The convective heat transfer coefficient on the inside is 85 W/m^2 K. The pipe is insulated by one layer of insulation of 5 cm thickness having conductivity of 0.15 W/m K. The outside is exposed to air at 25°C with a convection coefficient of 18 W/m^2K. Determine the heat loss for 5m length and the interface temperatures.

Critical radius of insulation

1. A tube of O.D. 2.5 cm is to be insulated with a layer of asbestos of thermal conductivity k= 0.2 w/m^{2o}C. The conduction heat transfer coefficient from the surface of the asbestos to the ambient air is h_α=12 W/m°C. Calculate the critical radius of insulation.
2. A steam pipe 10 cm I.D. and 11 cm O.D. is covered with an insulating substance (k=1w/mk). The steam temperature and the ambient temperature are 200^{o}C and 20^{o}C respectively. If the convective heat transfer coefficient between the insulation surface and air is 8W/m^{2}k, find the critical radius of insulation. For this value, calculate the heat loss per meter length of pipe and the outer surface temp. Neglect the resistance of the pipe material.
3. Calculate the critical radius of insulation for asbestos (k=0.17 W/m^{o}c) surrounding a pipe and exposed to room air at 20^{o}C with h=3.0 W/m^{2o}C. Calculate the heat loss from a 200^{o}C, 50 mm dia pipe covered with the critical radius of insulation and without insulation.
4. Evaluate the thickness of rubber insulation necessary in the case of a 10mm dia copper conductor to ensure max. heat transfer to the atmosphere , given the thermal conductivity of rubber as 0.155 W/mK and the surface coefficient as 8.5 W/m^{2}K. Estimate the max heat transfer rate per meter length of conductor if the temperature of rubber is not to exceed 65^{0}C while the atmosphere is at 30^{o}C.

Variable thermal conductivity

1. A plane wall of fireclay brick of thickness 25cm is having temperatures 1350^{o}C and 50^{o}C on its two sides. The thermal conductivity of the fireclay brick is a function of temperature. k(W/mK) = 0.838 (1+0.0007T). Calculate the rate of heat transfer.
2. A fire clay wall 20cm thick has its two surfaces maintained at 1000^{o}C and 200^{o}C. The thermal conductivity varies with temp. as k(W/mk) = 0.813 + 0.000582T. Calculate the rate of heat flow.
3. Calculate the heat loss per square metre of the surface area of a furnace wall 25cm thick. The inner and outer surface temperatures are 400^{o}C and 40^{o}C respectively. The variation of the thermal conductivity in W/mK with temperature in ^{o}C is given by the following equation: $K = 0.002T – 10^{-6}T^2$.
4. Compute the heat loss per square meter surface area of a 40cm thick furnace wall having surface temp. of 300^{o}C and 50^{o}C, if the thermal conductivity k of the wall material is given by k = 0.005T - 5×10-6 T^2, T is in ^{o}C.
5. The two faces of a slab at x = 0 and x = L are kept at t_1 and t_2^{o}C respectively. The 'k' of the material is given by as a temperature dependent value by $k = k_o(t^2 - t_o^2)$ where t_o and k_o are constants. Deduce the expression for heat flow/unit area.
6. Calculate the rate of heat transfer in a slab of thickness 20 cm and area 4.5 cm^2 when the two faces are maintained at 200°C and 50°C. The thermal conductivity, k can be expressed by the relation, k= 6.8+7.2×10^{-3}T W/mk.
7. Derive an expression for one dimensional heat transfer in a hollow cylinder. The thermal conductivity varies with temperature as $k= k_o (1 + \beta T)$
8. Derive an expression for one dimensional heat transfer in a hollow cylinder. The thermal conductivity varies with temperature as $k= k_o (1 + \alpha T + \beta T^2)$
9. A thick wall copper cylinder has an inside radius of 1cm and the outer radius of 2cm. The inner and outer surfaces are held at 310^{o}C and 290^{o}C

respectively. Assume k varies with temperature as k(W/mK) =317.9[1-9.25×10^{-5}(T-150)]. Determine the heat loss per unit length.
