UNIT I
CONDUCTION HEAT TRANSFER

1. Derive general heat conduction equation in Cartesian coordinates?

Consider a small rectangular element of sides dx, dy and dz as shown in figure.
The energy balance of this rectangular element is obtained from first law of thermodynamics

Net heat conducted into element from all the coordinate directions	+	**Heat generated within the element**	=	**Heat stored in the element -----1**

Net heat conducted into element from all the coordinate directions:

As per the Fourier law of heat conduction the rate of heat flow into the element in X, Y, Z directions through face ABCD, ABEF, ADHE are

$$\left.\begin{aligned} Q_x &= -k\,dy\,dz\,\frac{\partial T}{\partial x}dx \\ Q_y &= -k\,dx\,dz\,\frac{\partial T}{\partial y}dy \\ Q_z &= -k\,dy\,dx\,\frac{\partial T}{\partial z}dz \end{aligned}\right\} \text{------------------2}$$

The rate of heat flow out of the element in X direction through the face EFGH is

$$Q_{x+dx} = Q_x + \frac{\partial}{\partial x}(Qx)dx \quad \text{------3}$$

Sub Equ 2 in Equ 3

$$Q_x - Q_{x+dx} = Qx - \{Q_x + \frac{\partial}{\partial x}(Qx)dx\}$$

$$Q_x - Q_{x+dx} = \frac{\partial}{\partial x}\{kdydzdx \ \frac{\partial T}{\partial x}\}$$

$$Q_x - Q_{x+dx} = kdxdydx \ \frac{\partial^2 T}{\partial x^2}$$

$$Q_x - Q_{x+dx} = kdxdydx \ \frac{\partial^2 T}{\partial x^2} \quad \text{------4}$$

Similarly

$$Q_y - Q_{y+dy} = kdxdydx \ \frac{\partial^2 T}{\partial y^2} \quad \text{------5}$$

$$Q_z - Q_{z+dz} = k\,dx\,dy\,dx \frac{\partial^2 T}{\partial z^2} \text{ ------6}$$

$$Q = \{ (Q_x - Q_{x+dx}) + (Q_y - Q_{y+dy}) + (Q_z - Q_{z+dz}) \} \text{ ---- 7}$$

Sub Equ 4 , 5, 6 in Equ 7

$$k\,dx\,dy\,dz \left\{ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right\} \text{ ---8}$$

Heat generated internally : $Q_g = q\, dxdydz$ ------9

Heat stored in the element: $Q_{IE} = \rho\, C_p \frac{\partial T}{\partial t} dxdydz$ -----10

Sub Equ 8, 9, 10 in Equ 1

$$k\,dx\,dy\,dz \left\{ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right\} + q\, dxdydz = \rho\, C_p \frac{\partial T}{\partial t} dxdydz \text{ ---11}$$

Take dxdydz commonly and divide by k

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{k} = \frac{\rho C_p}{k} \frac{\partial T}{\partial t}$$

---- Three dimensional heat conduction equation for Cartesian coordinates

Case 1: No heat generation $\frac{q}{k} = 0$

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho C_p}{k} \frac{\partial T}{\partial t}$$

----- Fourier Equation

Case 2: Steady state condition $\frac{\partial T}{\partial t} = 0$

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{k} = 0$$

--- Poisson Equation

Case 3 : No heat generation and steady state : $\frac{q}{k} = 0 \quad \frac{\partial T}{\partial t} = 0$

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0$$

--- Laplace Equation

2. General heat conduction equation in Cylindrical coordinates:

While dealing with problems of conduction of heat through systems having cylindrical geometrics it is convenient to use cylindrical coordinates. Consider an elemental volume having the coordinates (r, φ, z) for three dimensional heat conduction analysis as shown in figure.

The volume of the element V = rdφ dr dz

Net heat conducted Heat generated Heat stored in the

into element from all the coordinate directions + within the element = element -----1

a. Net heat accumulated in the element due to conduction of heat from all the coordinate direction considered:

Heat flow in radial direction (r plane):

Heat influx $Qr = -krd\phi dz \frac{\partial T}{\partial r} dr$

Heat efflux $Qr + dr = Qr + \frac{\partial}{\partial r} Qrdr$

$$Qr - Qr + dr = Qr - \{Qr + \frac{\partial}{\partial r} Qrdr\}$$

$$= -\frac{\partial}{\partial r}\left\{-krd\phi dz \frac{\partial T}{\partial r} dr\right\}$$

$$= kd\phi drdz \frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)$$

$$= kd\phi drdz \left(r\frac{\partial^2 T}{\partial r^2} + \frac{\partial T}{\partial r}\right)$$

$$Qr - Qr + dr = kd\phi drdz\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \text{----2}$$

Heat flow in tangential direction (φ plane):

Heat influx: $Q_\phi = -kdrdz \frac{\partial T}{r\partial \phi}$

Heat efflux: $Q_{\phi+d\phi} = Q_\phi + \frac{\partial}{r\partial\phi} Q_\phi r d\phi$

$$Q_\phi - Q_{\phi+d\phi} = Q_\phi - \left[Q_\phi + \frac{\partial}{r\partial\phi}\left(-kdrdz \frac{\partial T}{r\partial\phi}\right) r d\phi\right]$$

$$Q_\phi - Q_{\phi+d\phi} = kdrrd\phi dz\left[\frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}\right] \text{---3}$$

Heat flow in axial direction (z plane):

Heat influx: $Q_z = -kdrrd\phi \frac{\partial T}{\partial z}$

Heat efflux: $Q_{z+dz} = Q_z + \frac{\partial}{\partial z} Q_z dz$

$$Q_z - Q_{z+dz} = kdrrd\phi dz\left[\frac{\partial^2 T}{\partial z^2}\right] \text{---4}$$

b. Heat generated within the element:

$$Qg = qrd\phi drdz \text{ ------------ } 5$$

c. Energy stored in the element:

$$Q_{IE} = \rho Cp \frac{\partial T}{\partial t} rd\phi drdz \text{ -----6}$$

Sub Equations 2, 3, 4, 5, 6 in Equation 1

$$krd\phi drdz \left[\frac{\partial^2 T}{dr^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2}\right] + qrd\phi drdz = \rho Cp \frac{\partial T}{\partial t} rd\phi drdz$$

$$\left[\frac{\partial^2 T}{dr^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2}\right] + \frac{q}{k} = \frac{\rho Cp}{k}\frac{\partial T}{\partial t}$$

Heat conduction equation for cylindrical coordinates

3. Explain the different modes of heat transfer with appropriate expressions?

Modes of Heat Transfer:

a. **Conduction:** Heat conduction is a mechanism of heat transfer from a region of high temperature to a region of low temperature within a medium or between different medium in direct physical contact. Examples: Heating a Rod.

$$\mathbf{Q = -k\ A}\ \frac{dT}{dx}$$

b. **Convection:** It is a process of heat transfer that will occur between a solid surface and a fluid medium when they are at different temperatures. It is possible only in the presence of fluid medium. Example: Cooling of Hot Plate by air.

$$\mathbf{Q = h\ A}\ (T_s - T_\infty)$$

c. **Radiation:** The heat transfer from one body to another without any transmitting medium. It is an electromagnetic wave phenomenon. Example: Radiation sun to earth.

$$\mathbf{Q} = \sigma\left[T_s^{\ 4} - T_\infty^{\ 4}\right]$$

4. What do you understand by critical radius of insulation, obtain the expression for the same?

The addition of insulation always increases the conductive thermal resistance. But when the total thermal resistance is made of conductive thermal resistance and convective thermal resistance, the addition of insulation in some cases may reduce the convective thermal resistance

due to increase in surface area as in case of a cylinder and sphere and the total thermal resistance may actually decrease resulting in increased heat flow. It may be shown that the thermal resistance actually decreases and then increases in some cases. The thickness up to which heat flow increases and after which heat flow decreases is termed as critical thickness. In case of cylinders and spheres it is called as Critical radius.

For Cylinders:

$$r_c = \frac{k}{h_o}$$

For Sphere:

$$r_c = \frac{2k}{h_o}$$

5. The inner surface at r = a and the outer surface at r = b of a hollow cylinder are maintained at uniform temperatures T1 and T2 respectively. The thermal conductivity of the solid is constant. Develop an expression for the one dimensional steady state temperature distribution in the cylinder and for the radial heat flow rate through the cylinder over a length H.

Consider a hollow cylinder of inner radius a, outer radius b, inner temperature T1, outer temperature T2 and thermal conductivity k.

From Fourier law of heat conduction

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

Area A = 2 π rH

$$Q = -k2\pi rH\frac{dT}{dr}$$

$$Q\int_a^b \frac{dr}{r} = -k2\pi H\int_{T1}^{T2} dT$$

$$Q\ln\left(\frac{b}{a}\right) = k2\pi H[T1 - T2]$$

$$\mathbf{Q} = \frac{T1 - T2}{\frac{1}{2\pi kH}\ln\left[\frac{b}{a}\right]}$$

6. What is Lumped capacity analysis and obtain the expression for temperature distribution of the same?

All solids have a finite thermal conductivity and there will be always a temperature gradient inside the solid whenever heat is added or removed. However for solids of large thermal conductivity with surface areas that are large in proportion to their volume like plates and thin metallic wires, the internal resistance {L/ kA} can be assumed to be small or negligible in comparison with the convective resistance {1/hA} at the surface. Typical examples of this type of heat flow are:

1. Heat treatment of metals
2. Time response of thermocouples and thermometers

The process in which the internal resistance is assumed negligible in comparison with its surface resistance is called the Newtonian heating or cooling process. The temperature, in this process is considered to be uniform at a given time. Such an analysis is called Lumped parameter analysis because the whole solid, whose energy at any time is a function of its temperature and total heat capacity is treated as one lump.

Let us consider a body whose initial temperature is t_i throughout and which is placed suddenly in ambient air or any liquid at a constant temperature t_o as shown in figure.

$$Q = -\rho V C p \frac{dT}{dt} = hA(T - Ta)$$

T – Temp pf body at any time

$$\int \frac{dT}{(T - Ta)} = -\frac{hA}{\rho V C p} \int dt$$

Ta – Ambient Temp

$$\ln(T - Ta) = -\frac{hA}{\rho V C p} t + C_1$$

The boundary conditions are t=0 T = Ti

$$C_1 = \ln(Ti - Ta)$$

Sub C_1 in the above equation

$$\ln(T - Ta) = -\frac{hA}{\rho V C p} t + \ln(Ti - Ta)$$

$$\frac{T - Ta}{Ti - Ta} = \exp\left[-\frac{hA}{\rho V C p} t\right]$$

1. Define heat transfer.

Heat transfer can be defined as the transmission of energy from one region to another due to temperature difference.

2. What are the modes of heat transfer?

1. Conduction.

2. Convection.

3. Radiation

3. What is conduction?

Heat conduction is a mechanism of heat transfer from a region of high temperature to a region of low temperature with in a medium (solid, liquid or gases) or different medium in directly physical contact. In conduction, energy exchange takes place by the kinematic motion or direct impact of molecules. Pure conduction is found only in solids.

4. Define Convection.

Convection is a process of heat transfer that will occur between a solid surface and a fluid medium when they are at different temperatures. Convection is possible only in the presence of fluid medium.

5. Define Radiation.

The heat transfer from one body to another without any transmitting medium is known as radiation. It is an electromagnetic wave phenomenon.

6. State Fourier's law of conduction.

The rate of heat conduction is proportional to the area measured normal to the direction of heat flow and to the temperature gradient in that direction.

$$Q \propto A \frac{dT}{dx}$$

$$Q = -K \; A \frac{dT}{dx}$$

Where, A – Area in m^2

$\frac{dT}{dx} - Temperature\ gradient\ , K/m$

K – Thermal conductivity, W/mk

7. Define Thermal conductivity.

Thermal conductivity is defined as the ability of a substance to conduct heat.

8. Write down the three dimensional heat conduction equations in Cartesian co-ordinate system.

The general three dimensional heat conduction equations in Cartesian co-ordinate is

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{K} = \frac{1}{\alpha} \frac{\partial T}{\partial \tau}$$

Where, q = heat generation, W/m^2

A – Thermal diffusivity, m^2/s

9. Write down the three dimensional heat conduction equations in cylindrical co-ordinate system.

The general three dimensional heat conduction equations in cylindrical co-ordinate is

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{K} = \frac{1}{\alpha} \frac{\partial T}{\partial \theta}$$

10. List down the three types of boundary conditions.

1. Prescribed temperature

2. Prescribed heat flux

3. Convection boundary conditions

11. Write down the equation for conduction of heat through a slab or plane wall

$$Heat\ Transfer\ Q = \frac{\Delta T_{overall}}{R}$$

Where, $\Delta T = T_1 - T_2$

$$R = \frac{L}{KA} - Thermal\ resistance\ of\ slab$$

12. Explain about Fourier equation.

This Fourier equation is used to find out the conduction heat transfer. According to this equation, heat transfer is directly proportional to surface area and temperature gradient. It is indirectly proportional to the thickness of the slab.

$$Q \alpha \frac{A\ \Delta T}{L}$$

$$Q = \frac{-K\ A\ \Delta T}{L}$$

13. Explain about Poisson's equation.

When the temperature is not varying with respect to time, then the conduction is called as steady state conduction.

$$\frac{\partial T}{\partial \tau} = 0$$

14. Explain about Laplace equation.

When the conduction is steady state conduction, and there is no heat generation, the general equation becomes,

$$\frac{\partial^2 T}{\partial^2 x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0$$

15. What is critical radius of insulation?

Critical radius (r_c): it is defined as outer radius of insulation for which the heat transfer rate is maximum.

Critical thickness: it is defined as the thickness of insulation for which the heat transfer rate is maximum.

16. Explain variation in thermal conductivity with temperature.

The thermal conductivity vary with temperature according to relation

$$k = k_o(1 + \beta T)$$

Where k_o= thermal conductivity at 0^oc

β= temperature co- efficient of thermal conductivity.

17. What are the factors affect thermal conductivity?

1. Material structure. 2. Moisture content. 3. Density of material. 4. Pressure and temperature.

18. What is super insulation and give its application.

Super insulation is a process which is used to keep the cryogenic liquids at very low temperature. The super insulation consists of multiple layers of highly reflective material separated by insulating spacers. The entire system is evacuated to minimize air conduction.

19. Where do you use Heisler's chart.

Heisler's charts are used to solve problems – Transient heat conduction in solids with finite conduction and convective resistances. i.e $0 < B_i < 100$.

20. Give some examples of heat generation application in heat conduction.

1. Fuel rod – nuclear reactor. 2. Electrical conductor. 3. Chemical and combustion process. 4. Drying and setting of concrete.

21. State Newton's law of cooling or convection law.

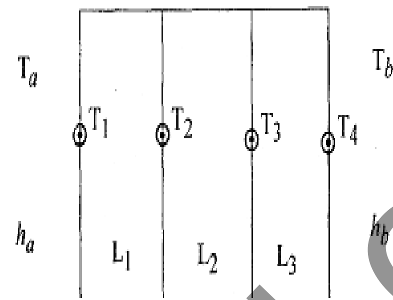
Heat transfer by convection is given by Newton's law of cooling

$$Q = hA(T_S - T_\alpha)$$

22. Write down the equation for heat transfer through a composite plane wall.

$$Heat\ Transfer\ \ Q = \frac{\Delta T_{overall}}{R}$$

$$Where \quad \Delta T = T_a - T_b$$



$$R = \frac{1}{h_a A} + \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{L_3}{k_3 A} + \frac{1}{h_b A}$$

L - Thickness of slab

A - Area

h_a - Heat transfer coefficient at inner diameter

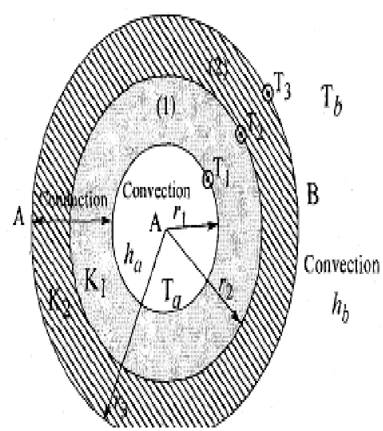
h_b - Heat transfer coefficient at outer side.

23.Write down the equation for heat transfer through composite pipes or cylinder.

$$Heat\ Transfer\ \ Q = \frac{\Delta T_{overall}}{R}$$

$$Where \quad \Delta T = T_a - T_b$$

$$R = \frac{1}{2\pi L}\frac{1}{h_a r_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_1} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_2} + \frac{1}{h_b r_3}$$



24. Write down one dimensional, steady state conduction equation without internal heat generation.

$$\frac{\partial^2 T}{\partial x^2} = 0$$

25. Write down steady state, two dimensional conduction equation without heat generation.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0$$

26. Write down the general equation for one dimensional steady state heat transfer in slab or plane wall without heat generation

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

27. Define overall heat transfer co-efficient.

The overall heat transfer is defined as amount of transmitted per unit area per unit time per degree temperature difference between the bulk fluids on each side of the metal. it is denoted by 'U'.

Heat transfer, $Q = UA\,\Delta T$.

28. Define fins or Extended surfaces.

It is possible to increase the heat transfer rate by increasing the surface of heat transfer. The surfaces used for increasing heat transfer are called extended surfaces or sometimes known as fins.

29. State the applications of fins.

The main applications of fins are

1. Cooling of electronic components
2. Cooling of motor cycle engines.
3. Cooling of transformers.
4. Cooling of small capacity compressors.

30. Define Fin efficiency.

The efficiency of a fin is defined as the ratio of actual heat transferred to the maximum possible heat transferred by the fin

$$\eta_{fin} = \frac{Q_{fin}}{Q_{\max}}$$

31. Define Fin effectiveness.

Fin effectiveness is the ratio of heat transfer with fin to that without fin

$$Fin\ effectiven\ ess = \frac{Q_{with\ fin}}{Q_{without}}$$

32. What is meant by steady stale heat conduction?

If the temperature of a body does not vary with time, it is said to be in a steady state and that type of conduction is known as steady state heat conduction.

33. What is meant by Transient heat conduction or unsteady state conduction?

If the temperature of a body varies with time, it is said to be in a transient state and that type of conduction is known as transient heat conduction or unsteady state conduction.

34. What is Periodic heat flow?

In periodic heat flow, the temperature varies on a regular basis.

Example:

1. Cylinder of an IC engine.

2. Surface of earth during a period of 24 hours.

35. What is non periodic heat flow?

In non periodic heat flow, the temperature at any point within the system varies non linearly with time.

Examples:

1. Heating of an ingot in a furnace.

2. Cooling of bars.

36. What is meant by Newtonian heating or cooling process?

The process in which the internal resistance is assumed as negligible in comparison with its surface resistance is known as Newtonian heating or cooling process.

37. What is meant by Lumped heat analysis?

In a Newtonian heating or cooling process the temperature throughout the solid is considered to be uniform at a given time. Such an analysis is called Lumped heat capacity analysis.

38. What is meant by Semi-infinite solids?

In a semi infinite solid, at any instant of time, there is always a point where the effect of heating or cooling at one of its boundaries is not felt at all. At this point the temperature remains unchanged. In semi infinite solids, the biot number value is ∞.

39. What is meant by infinite solid?

A solid which extends itself infinitely in all directions of space is known as infinite solid. In infinite solids, the biot number value is in between 0.1 and 100.

$$0.1 < B_i < 100 .$$

40. Define Biot number.

It is defined as the ratio of internal conductive resistance to the surface convective resistance.

$$B_i = \frac{Internal \quad conductive \quad resis\tan ce}{Surface \quad convective \quad resis\tan ce}$$

$$B_i = \frac{hL_c}{k}$$

41. What is the significance of Biot Number?

Biot number is used to find Lumped heat analysis, Semi infinite solids and Infinite solids

If $B_i < 0.1 \rightarrow$ Lumped heat analysis

$B_i = \infty \rightarrow$ Semi infinite solids

$0.1 < B_i < 100 \rightarrow$ Infinite solids.

42. Explain the significance of Fourier number.

It is defined as the ratio of characteristic body dimension to temperature wave penetration depth in time.

$$Fourier\ number = \frac{Characteristic\ body\ dimension}{Temperature\ wave\ penetration\ depth\ in\ time}$$

It signifies the degree of penetration of heating or cooling effect of a solid.

43. What are the factors affecting the thermal conductivity?

1. Moisture. 2. Density of material. 3. Pressure. 4. Temperature.

5. Structure of material.

44. Explain the significance of thermal diffusivity.

The physical significance of thermal diffusivity is that it tells us how fast heat is propagated or it diffuses through a material during changes of temperature with time.

PROBLEMS FOR PRACTICE:

1. A brick wall (k = 07W/mK) is 0.3m thick. If the temperatures of the inner and outer surface are maintained at 50C and 30C respectively. Calculate the heat loss through one square meter area. Find also the temperature at an interior point of the wall 24cm distance from the outer wall. **(Ans : 46.67w/m^2, 34C)**
2. A steam pipe 200mm OD is covered with 25mm thich layer of insulation material with an average thermal conductivity of 0.08W/mK. The temperature of the pipe surface is 400C and that of the outer surface of insulation is 50C. Find the loss of heat from a length of 10m of the pipe line. **(Ans: 7.88kW)**

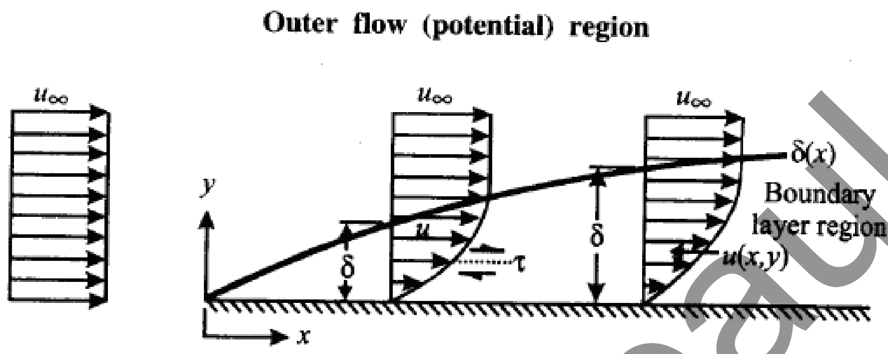
3. Compute the heat loss per square meter of the surface area of furnace wall 25cm thick. The inner and outer surface temperatures are 400C and 40C respectively. The variation of the thermal conductivity in W/mK with temperature in C is given by the following equation: $k = 0.002T - 10^{-6} T^2$ **(Ans: 575 W/ m²)**
4. The temperature distribution in a long cylindrical tube at a certain instant is given by $T= 800 + 1000r - 5000r^2$. Find (1) The rate of heat flow at the inside and outside surface per m length. (2) The rate of heat storage per m length. (3) The rate of change of temperature with time at the inner and outer surfaces. Take the following data ID = 60cm, OD = 1m, k = 58 W/mK, $\alpha = 0.004 m^2/h$. **(Ans: 219kW, 730kW, -511kW, -72C/h)**
5. An aluminium sphere weighing 7kg and initially at a temperature of 260C is suddenly immersed in a fluid at 10C. If h = 50W/m²K, compute the time required to cool the sphere to 90C. $\rho = 2707\ kg/m^3$, c = 9000 J/kgK, k = 204 W/mC. (Ans: 1580sec)

UNIT II
CONVECTION HEAT TRANSFER

Convection is the mode of heat transfer between a surface and a fluid moving over it. The energy transfer in convection is predominately due to the bulk motion of the fluid particles; through the molecular conduction within the fluid itself also contributes to some extent. If this motion is mainly due to the density variations associated with temperature gradients within the fluid, the mode of heat transfer is said to be due to **free or natural convection**. On the other hand if this fluid motion is principally produced by some superimposed velocity field like fan or blower, the energy transport is said to be due to **forced convection**.

Convection Boundary Layers:

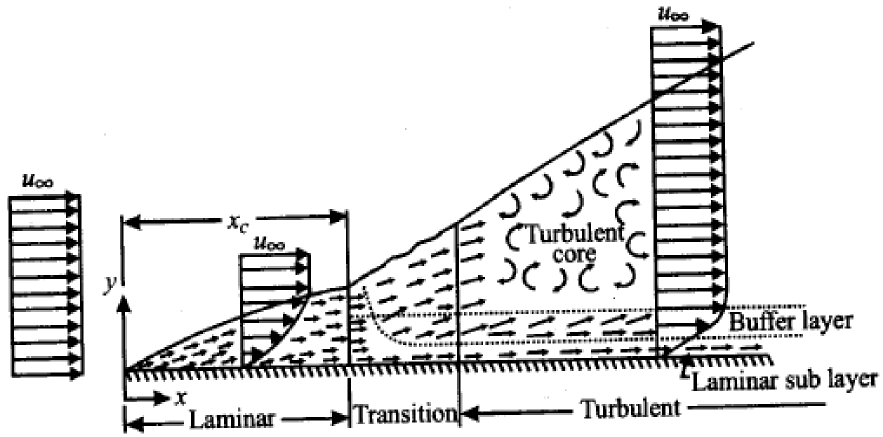
Velocity Boundary Layer: Consider the flow of fluid over a flat plate as shown in the figure. The fluid approaches the plate in x direction with uniform velocity u_∞. The fluid particles in the fluid layer adjacent to the surface get zero velocity. This motionless layer acts to retart the motion of particles in the adjoining fluid layer as a result of friction between the particles of these two adjoining fluid layers at two different velocities. This fluid layer then acts to retart the motion of particles of next fluid layer and so on, until a distance
$y = \delta$ from the surface reaches, where these effects become negligible and the fluid velocity u reaches the free stream velocity u_∞ as a result of frictional effects between the fluid layers, the local fluid velocity u will vary from x =0, y = 0 to $y = \delta$.



Velocity Boundary Layer on a Flat Plate

The region of the flow over the surface bounded by δ in which the effects of viscous shearing forces caused by fluid viscosity are observed, is called velocity boundary layer or hydro dynamic boundary layer. The thickness of boundary layer δ is generally defined as a distance from the surface at which local velocity u = 0.99 of free stream velocity u_∞. The retardation of fluid motion in the boundary layer is due to the shear stresses acting in opposite direction with increasing the distance y from the surface shear stress decreases, the local velocity u increases until approaches u_∞. With increasing the distance from the leading edge, the effect of viscosity penetrates further into the free stream and boundary layer thickness grows.

Thermal boundary Layer: If the fluid flowing on a surface has a different temperature than the surface, the thermal boundary layer developed is similar to the velocity boundary layer. Consider a fluid at a temperature T_∞ flows over a surface at a constant temperature Ts. The fluid particles in adjacent layer to the plate get the same temperature that of surface. The particles exchange heat energy with particles in adjoining fluid layers and so on. As a result, the temperature gradients are developed in the fluid layers and a temperature profile is developed in the fluid flow, which ranges from Ts at the surface to fluid temperature T_∞ sufficiently far from the surface in y direction.

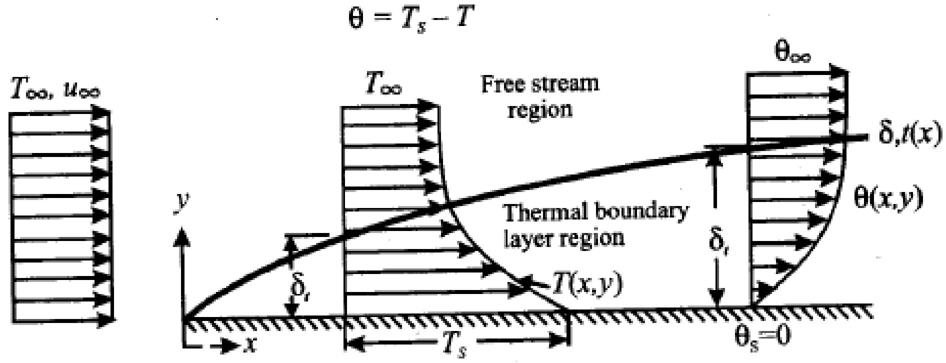


Development of Velocity Boundary Layer on a Flat Plate

The flow region over the surface in which the temperature variation in the direction, normal to surface is observed is called thermal boundary layer. The thickness of thermal boundary layer δ_{th} at any location along the length of flow is defined as a distance y from the surface at which the temperature difference (T-Ts) equal 0.99 of (T∞ - Ts). With increasing the distance from leading edge the effect of heat transfer penetrates further into the free stream and the thermal boundary layer grows as shown in the figure. The convection heat transfer rate any where along the surface is directly related to the temperature gradient at that location. Therefore, the shape of the temperature profile in the thermal boundary layer leads to the local convection heat transfer between surface and flowing fluid.

Development of velocity boundary layer on a flat plate:

It is most essential to distinguish between laminar and turbulent boundary layers. Initially, the boundary layer development is laminar as shown in figure for the flow over a flat plate. Depending upon the flow field and fluid properties, at some critical distance from the leading edge small disturbances in the flow begin to get amplified, a transition process takes place and the flow becomes turbulent. In laminar boundary layer, the fluid motion is highly ordered whereas the motion in the turbulent boundary layer is highly irregular with the fluid moving to and from in all directions. Due to fluid mixing resulting from these macroscopic motions, the turbulent boundary layer is thicker and the velocity profile in turbulent boundary layer is flatter than that in laminar flow.



Thermal Boundary Layer on a Flat Plate

The critical distance x_c beyond which the flow cannot retain its laminar character is usually specified in term of critical Reynolds number Re. Depending upon surface and turbulence level of free stream the critical Reynolds number varies between 10^5 and 3 X 10^6. In the turbulent boundary layer, as seen three distinct regimes exist. A laminar sub-layer, existing next to the wall, has a nearly linear velocity profile. The convective transport in this layer is mainly molecular. In the buffer layer adjacent to the sub-layer, the turbulent mixing and diffusion effects are comparable. Then there is the turbulent core with large scale turbulence.

1. What is dimensional analysis?

Dimensional analysis is a mathematical method which makes use of the study of the dimensions for solving several engineering problems. This method can be applied to all types of fluid resistances, heat flow problems in fluid mechanics and thermodynamics.

2. State Buckingham Π theorem.

Buckingham Π theorem states as follows: "If there are n variables in a dimensionally homogeneous equation and if these contain m fundamental dimensions, then the variables are arranged into (n - m) dimensionless terms. These dimensionless terms are called Π terms.

3. What are all the advantages of dimensional analysis?

1. It expresses the functional relationship between the variables in dimensional terms.

2. It enables getting up a theoretical solution in a simplified dimensionless form.

3. The results of one series of tests can be applied to a large number of other similar problems with the help of dimensional analysis.

4. What are all the limitations of dimensiona1 analysis?

1. The complete information is not provided by dimensional analysis. It only indicates that there is some relationship between the parameters.
2. No information is given about the internal mechanism of physical phenomenon.
3. Dimensional analysis does not give any clue regarding the selection of variables.

5. Define Reynolds number (Re).

It is defined as the ratio of inertia force to viscous force.

$$R_e = \frac{Inertia \quad force}{Viscus \quad force}$$

6. Define Prandtl number (Pr).

It is the ratio of the momentum diffusivity to the thermal diffusivity.

$$\Pr = \frac{Momentum \quad diffusivit \ y}{Thermal \quad diffusivit \ y}$$

7. Define Nusselt Number (Nu).

It is defined as the ratio of the heat flow by convection process under a unit temperature gradient to the heat flow rate by conduction under a unit temperature gradient through a stationary thickness (L) of metre.

$$Nusselt \ \ Number(Nu) = \frac{q_{con}}{q_{conc}}$$

8. Define Grashof number (Gr).

It is defined as the ratio of product of inertia force and buoyancy force to the square of viscous force.

$$Gr = \frac{Inertia \quad force \times Buoyancy \quad force}{(Viscus \quad force)^2}$$

9. Define Stanton number (St).

It is the ratio of Nusselt number to the product of Reynolds number and Prandtl number.

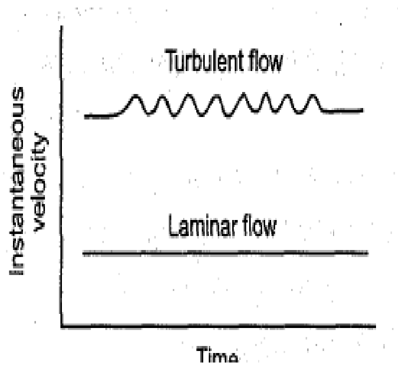
$$St = \frac{Nu}{\mathrm{Re} \times \Pr}$$

10. What is meant by Newtonian and non-Newtonian fluids?

The fluids which obey the Newton's law of viscosity are called Newtonian fluids and those which do not obey are called non Newtonian fluids.

11. What is meant by laminar flow and turbulent flow?

Laminar flow: Laminar flow is sometimes called stream line flow. In this type of flow, the fluid moves in layers and each fluid particle follows a smooth continuous path. The fluid particles in each layer remain in an orderly sequence without mixing with each other.



Turbulent flow: In addition to the laminar type of flow, a distinct irregular flow is frequently observed in nature. This type of flow is called turbulent flow. The path of any individual particle is zigzag and irregular. Fig. shows the instantaneous velocity in laminar and turbulent flow.

12. What is hydrodynamic boundary layer?

In hydrodynamic boundary layer, velocity of the fluid is less than 99% of free stream velocity.

13. What is thermal boundary layer?

In thermal boundary layer, temperature of the fluid is less than 99% of free stream temperature.

14. Define convection.

Convection is a process of heat transfer that will occur between a solid surface and a fluid medium when they are at different temperatures.

15. State Newton's law of convection.

Heat transfer from the moving fluid to solid surface is given by the equation

$$Q = hA(T_W - T\alpha)$$

16. What is meant by free or natural convection?

If the fluid motion is produced due to change in density resulting from temperature gradients, the mode of heat transfer is said to be free or natural convection.

17. What is forced convection?

If the fluid motion is artificially created by means of an external force like a blower or fan, that type of heat transfer is known as forced convection.

18. According to Newton's law of cooling the amount of heat transfer from a solid surface of area A, at a temperature T, to a fluid at a temperature T, is given by---------

$$Q = hA(T_W - T\alpha)$$

19. What are the dimensionless parameters used in forced convection?

1. Reynolds number (Re).2. Nusselt number (Nu).3. Prandtl number (Pr).

20. Define boundary layer thickness.

The thickness of the boundary layer has been defined as the distance from the surface at which the local velocity or temperature reaches 99% of the external velocity or temperature.

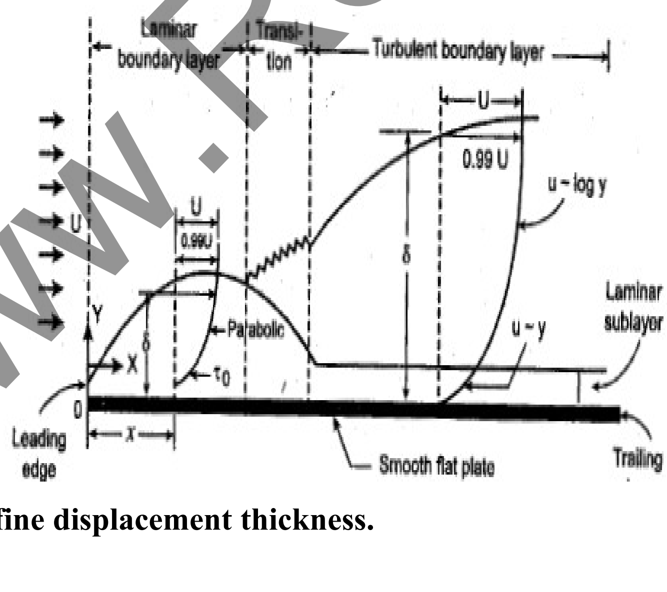
21. Indicate the concept or significance of boundary layer.

In the boundary layer concept the flow field over a body is divided into two regions:

1. A thin region near the body called the boundary layer where the velocity and the temperature gradients are large.

2. The region outside the boundary layer where the velocity and the temperature gradients are very nearly equal to their free stream values.

22. Sketch the boundary development of a flow.



23. Define displacement thickness.

The displacement thickness is the distance, measured perpendicular to the boundary, by which the free stream is displaced on account of formation of boundary layer.

24. Define momentum thickness.

The momentum thickness is defined as the distance through which the total loss of momentum per second is equal to if it were passing a stationary plate.

25. Define energy thickness.

The energy thickness can be defined as the distance, measured perpendicular to the boundary of the solid body, by which the boundary should be displaced to compensate for the reduction in kinetic energy of the flowing fluid on account of boundary layer formation.

1. A very long 1 cm diameter copper rod (k=377 W/mK) is exposed to an environment at 22℃. The base temperature of the rod is maintained at 150℃. The heat transfer coefficient between the rod and the surrounding air is 11 W/m^2K. Estimate the heat transfer rate from the rod to the surrounding air.
2. Compare the temperature distribution in a fin having a diameter of 2cm and length 10cm and exposed to an convection environment with h= 25W/m^2K for three materials Copper (k=385W/mK), Stainless steel (k= 17W/mK) and Glass (k= 0.8W/mK). Also compare the relative heat flows and fin efficiencies with respect to the copper fin.
3. A Copper wire 0.8mm diameter at 150℃ is suddenly dipped into water at 35℃. If h= 85.5W/m^2K, estimate the time required to cool the wire to 95℃. If the same wire were placed in air instead of water what would have been the time required to cool it to 95℃ h_{air}=11.65W/m^2K. For Copper ρ = 2707 Kg/m^3, c=9000j/KgK, k=204 W/m℃
4. A slab of aluminum 5cm thick initially at 200℃ is suddenly immersed in a liquid at 70℃ for which the convective heat transfer coefficient is 525 W/m^2K. Determine the temperature at the depth of 12.5mm from one of the faces 1 min after immersion. Also calculate the energy removed per unit area from the plate during 1 min of immersion. Take ρ = 2700Kg/m3, c= 09 Kj/KgK, k= 215 W/mK, α = 8.4x 10-5 m2/s.
5. Air flows over a thin plate with a velocity of 2.5m/s. The width of the plate is 1m and its length is also 1m. Calculate the boundary layer thickness at the end of the

plate and the force necessary to hold the plate in the stream of air. The properties of air are $\rho = 1.12 Kg/m^3$, $\mu = 0.86 \times 10^{-5} Ns/m^2$.

6. Air at 20℃ and 1 atm flows over a flat plate at 35m/s. The plate is 75cm long and is maintained at 60℃. calculate the heat transfer from the plate per unit width of the plate. Also calculate the turbulent boundary layer thickness at the end of the plate assuming it to develop from the leading edge of the plate. The physical properties of air at 40℃ are Pr = 0.7, k=0.02723 W/mK, Cp = 1007 j/Kg℃.
7. Air at a temperature of 26.2℃ flows over a heated cylinder of 12.7mm diameter and 94mm length at a velocity of 10m/s. if the surface of the cylinder is maintained at 128.4℃. Calculate the convective heat transfer coefficient.
8. A Copper sphere 10mm diameter initially at a uniform temperature of 75℃ is suddenly subjected to an air stream at 23℃ having a velocity of 10m/s. It produces 40W. Estimate the heat transfer coefficient and compute the percentage of power lost due to convection.
9. In a pressurized water space heater, heated water is passed through a staggered tube arrangement for which the tube outside diameter is 16.4mm and S_L = 34.3mm and S_T = 31.3mm. There are 7 rows of tubes in the air flow direction. If the upstream temperature and velocity of air are 15℃ and 6m/s respectively and the tube surface temperature is 70℃, Determine the air side convection coefficient and exit temperature of air.
10. An instant water heater consists of a 4 mm I. D. Tube through which water flows at the rate of 3.6 kg/h at a temperature of 25°C. A nichrome heating element wound over the tube provides a constant heat flux of 200 W per metre length into the water. Find the length of the tube to raise the temperature to 75°C and also the maximum temperature at the exit.
11. Ethylene glycol enters a 5 m length of 100 mm diameter copper tube in a cooling system at a velocity of 5 *mls*. Estimate the heat transfer rate if the average bulk temperature is 20°C and the tube wall is maintained at 100°C. The properties of Ethylene glycol at 20°C are $\nu = 1.92 \times 10^{-5} m^2/s$, *k=0.249·W/m.K, Pr* = 204
12. Hot air at 103°C flows through a duct of 15 cm diameter with a mass flow rate of 0.05 kg/s. The temperature of air at a distance of 5 m from entry has been measured to be 77°C. The duct is losing heat at O°C with a heat transfer coefficient of 6 W/m2K. Neglecting the duct wall resistance calculate the heat loss from the duct over the 5 m length. Also estimate the heat flux and the surface temperature at *x=5* m.
13. In a double pipe-heat exchanger steam flows through the inner pipe and the air through the annular space. The outer diameter of the inner pipe is 25 cm and the inner diameter of the outer pipe which is insulated is 38 cm. The air flows with a velocity of 6 m/s at an average temperature of 40°C. If the steam is condensing at 160°C on the inner surface of the inner tube, estimate the heat transfer coefficient on the air side.
14. A vertical plate 0.25m high is maintained at a temperature of 70℃ in a still atmosphere of air at 25℃. Compute the boundary layer thickness and the average heat transfer coefficient at the trailing edge of the plate. If this plate were placed

in a air stream flowing with a velocity of 5m/s over the plate. Compute the boundary layer thickness and the average heat transfer coefficient at the trailing edge of the plate.

15. An un-insulated duct of width 0.75m and height 0.3m is exposed to air at 15℃ on its outer surface. If the surface temperature of the duct is maintained at 45℃, compute the loss of heat from the duct per meter length.
16. A cylindrical heating element 25.4mm diameter and 4570mm long is inserted vertically into the tank of water at 21.1℃. The surface of the heating element is maintained at a uniform temperature of 54.4℃. Calculate the mean heat transfer coefficient and the rate of heat loss by the free convection from the entire surface of the element to the water.
17. A steam pipe of 100mm outer diameter is placed horizontally in a room at 23℃. The outside surface temperature of the pipe is 165℃ and its emissivity is 0.85. Determine the rate of heat loss per unit length of the pipe.
18. 1000 kg of cheese at 15°C is pumped through a tube of 75 mm diameter .The temperature of the tube is maintained at 90°C and the length of the tube is 120 cm. Calculate the heat transfer coefficient using Hausen'scorrelation. Also find the mean temperature of cheese leaving the heated section. The properties of cheese are ρ = 1100 Kg/m^3 , μ = 24 Kg/ ms, Cp = 2850 J/Kg K, k = 0.43 W/mK.
19. Water flows through a tube of 22 mm diameter with a velocity of 2 m/s, Steam at 150°C is being condensed 011 the outer surface of the tube thereby raising temperature of water flowing inside the tube from 15°C to 60°C. Find the heat transfer coefficient and the length of the tube required to meet the above requirement of heat. The resistances of tube and film may be neglected.
20. Water flows in a 50 mm diameter tube 3 m long at an average temperature ,of 30°C. The tube wall temperature is maintained at 70°C and the flow velocity is 0.8 *mls.* Estimate the heat transfer coefficient using the Dittus-Boelter correlation,
21. A horizontal steam pipe of 0.1m diameter is placed horizontally in a room at 20°C. The outside surface temperature is 80°C and the emissivity of the pipe material is 0.93. Estimate the total heat loss from the pipe per metre length due to free convection and radiation.
22. One surface of a panel 2m X 2m is insulated and the other surface is kept at a uniform temperature of 95°C. Calculate the mean heat transfer coefficient due to free convection between the heated surface of the panel and the atmospheric air at 10°C when
    - Heated surface is vertical
    - Panel is horizontal with hot surface facing up
    - Panel is horizontal with hot surface facing down.

UNIT III
BOILING AND CONDENSATION

Boiling Heat Transfer Phenomena

Boiling is a convection process involving a change in phase from liquid to vapor. Boiling may occur when a liquid is in contact with a surface maintained at a temperature higher than the saturation temperature of the liquid. If heat is added to a liquid from a submerged solid surface, the boiling process is referred to as ***pool boiling***. In this process the vapor produced may form bubbles, which grow and subsequently detach themselves from the surface, rising to the free surface due to buoyancy effects. A common example of pool boiling is the boiling of water in a vessel on a stove. In contrast, ***flow boiling or forced convection boiling*** occurs in a flowing stream and the boiling surface may itself be apportion of the flow passage. This phenomenon is generally associated with two phase flows through confined passages.

A necessary condition for the occurrence of pool boiling is that the temperature of the heating surface exceeds the saturation temperature of the liquid. The type of boiling is determined by the temperature of the liquid. If the temperature of the liquid is below the saturation temperature, the process is called sub cooled or local boiling. In local boiling, the bubbles formed at the surface eventually condense in the liquid. If the liquid is maintained at saturation temperature, the process is called saturated or bulk boiling.

There are various distinct regimes of pool boiling in which the heat transfer mechanism differs radically. The temperature distribution in saturated pool boiling with a liquid vapor interface is shown in the Figure1.

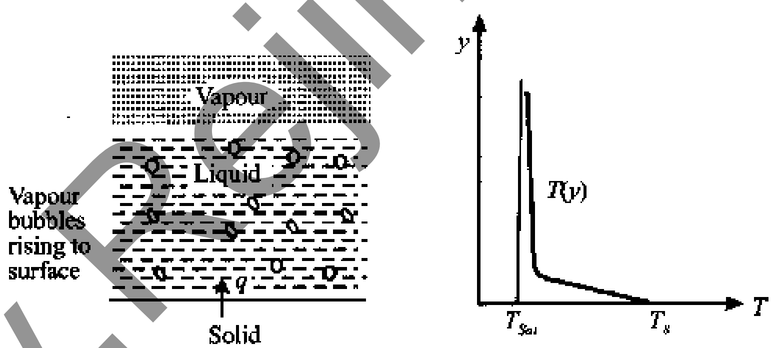


Fig. 1 Pool Boiling with Liquid-Vapour Interface

The different regimes of boiling are indicated in Figure 2. This specific curve has been obtained from an electrically heated platinum wire submerged in water b y varying its surface temperature and measuring the surface heat flux q_s. The six regimes of Figure 2 will now be described briefly.

In region I, called the ***free convection zo*****ne**, the excess temperature, ΔT is very small and ≤ 5°C. Here the liquid near the surface is superheated slightly, the convection currents circulate the liquid and evaporation takes place at the liquid surface.

Nucleate boiling exists in regions II and III. As the excess temperature, ΔT is increased, bubbles begin to form on the surface of the wire at certain localized spots. The bubbles condense in the liquid without reaching the liquid surface. Region II is in fact the beginning of nucleate boiling. As the excess temperating is further increased bubbles are formed more rapidly and rise to the surface of the liquid resulting in rapid evaporation.
This is indicated in region III. Nucleate boiling exists up to ΔT ≤ 50° C. The maximum heat flux, known as the *critical heat flux,* occurs at point *A* and is of the order of 1M*W/m2.*

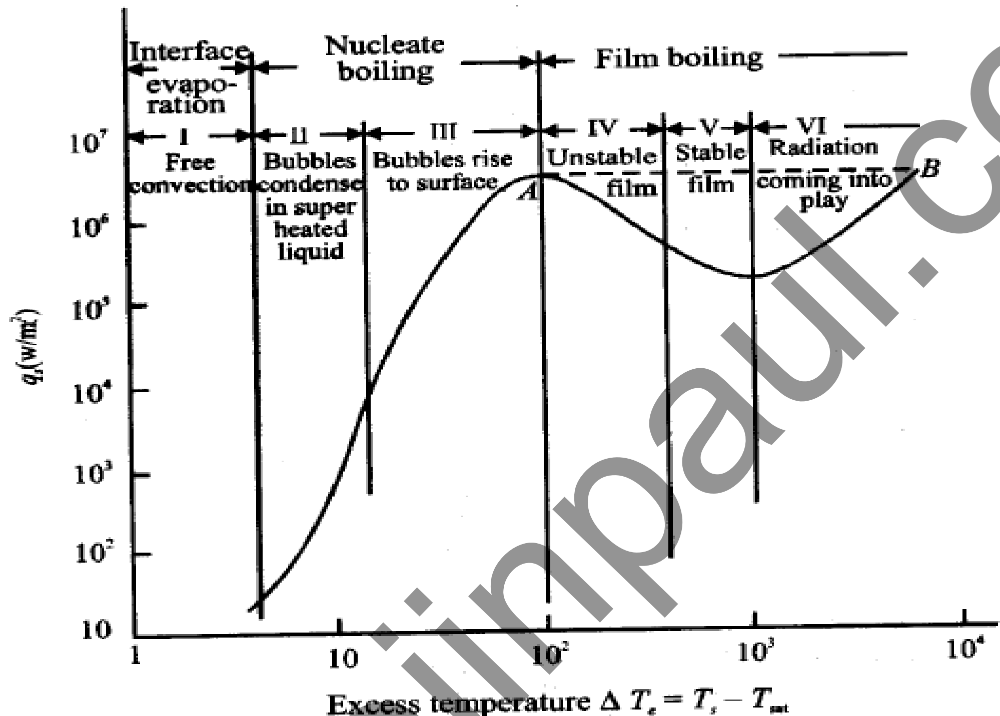


Fig. 2 Pool Boiling Curve for Water

The trend of increase of heat flux with increase in excess temperature observed up to region III is reversed in region IV, called the ***film boiling region***. This is due to the fact that bubbles now form so rapidly that they blanket the heating surface with a vapor film preventing the inflow of fresh liquid from taking their place. Now the heat must be transferred through this vapor film (by conduction) to the liquid to effect any further boiling. Since the thermal conductivity of the vapor film is much less than that of the liquid, the value of *q.* must then decrease with increase of ΔT. In region IV the vapor film is not stable and collapses and reforms rapidly. With further increase in ΔT the vapor film is stabilized and the heating surface is completely covered by a vapor blanket and the heat flux is the lowest as shown in region V. The surface temperatures required to maintain a stable film are high and under these conditions a sizeable amount of heat is lost by the surface due to radiation, as indicated in region VI.

The phenomenon of stable film boiling can be observed when a drop of water falls on a red hot stove. The drop does not evaporate immediately but dances a few times

on the stove. This is due to the formation of a stable steam film at the interface between the hot surface and the liquid droplet. From Fig.2 it is clear that high heat transfer rates are associated with small values of the excess temperature in the nucleate boiling regime. The equipment used for boiling should be designed to operate in this region only. The critical heat flux point *A* in Fig.2 is also called the *boiling crisis* because the boiling process beyond that point is unstable unless of course, point *B* is reached. The temperature at point *B* is extremely high and normally above the melting point of the solid. So if the heating of the metallic surface is not limited to point *A,* the metal may be damaged or it may even melt. That is why the peak heat flux point is called the *burnout point* and an accurate knowledge of this point is very important. Our aim should be to operate the equipment close to this value but never beyond it.

Flow Boiling:

Flow or forced convection boiling may occur when a liquid is forced through a channel or over a surface which is maintained at a temperature higher than the saturation temperature of the liquid. There are numerous applications of flow boiling in the design of steam generators for nuclear power plants and space power plants. The mechanism and hydronamics of flow boiling are much more complex than in pool boiling because the bubble growth and separation are strongly affected by the flow velocity. The flow is a two-phase mixture of the liquid and its vapor.

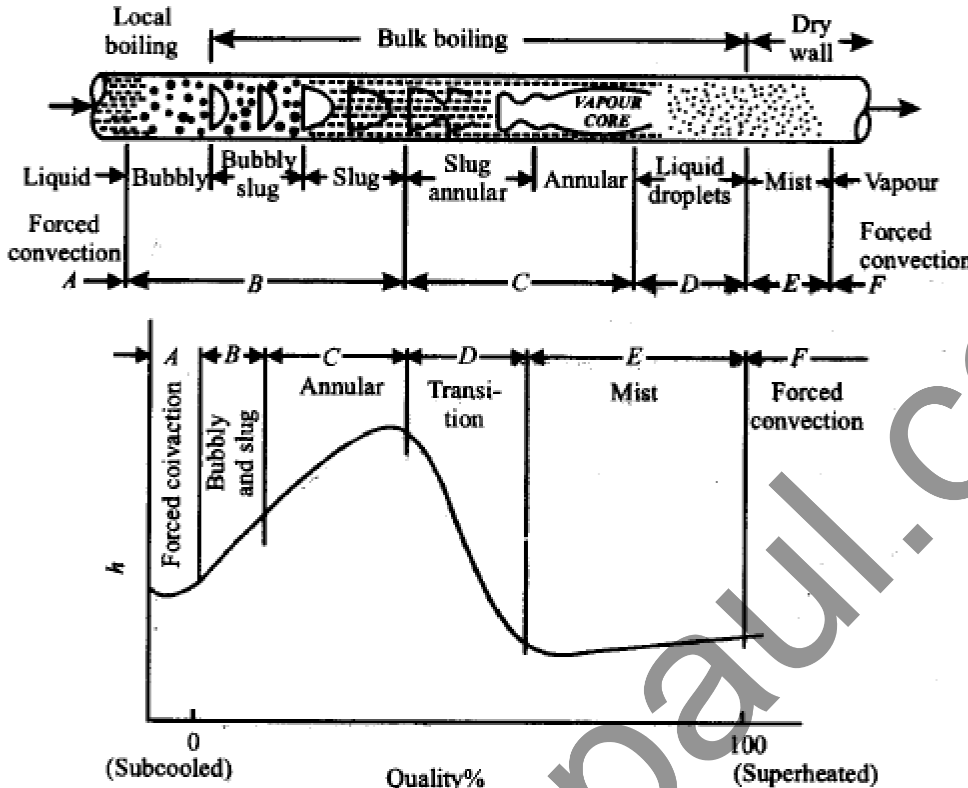


Fig. 3 Fow Regimes for Flow Boiling Inside a Tube

Fig 3 shows the various flow regimes inside a uniformly heated tube. Heat transfer to the sub cooled liquid at entry is by forced convection. This regime continues until boiling starts. The heat transfer coefficient in the boiling regime is suddenly increased. In this boiling regime, the bubbles appear on the heated surface, grow and are carried into the mainstream of the liquid, so that a ***bubbly flow regime*** prevails for some length of the tube. As the volume fraction of the vapor increases, the individual bubbles coalesce and plugs or slugs of vapor are formed. This regime is called the ***slug flow*** regime. As the vapor quality is increased, the flow becomes annular with a thin liquid layer on the wall and a vapor core. The vapor velocity is much higher than that of the liquid. The heat transfer coefficient remains high as long as the liquid film wets the wall. Eventually, dry spots appear on the wall and the heat transfer coefficient drops sharply. This is called the ***transition region****,* from the annular flow to the ***mist*** **or** ***fog flow*** Burnout sometimes occurs at this transition because a liquid film of high thermal conductivity is replaced by a low thermal conductivity vapor at the wall. The dry spots continue to expand until all the remaining liquid is in the form of fine droplets in the water. This is called the ***mist flow regime***. There is little change in the heat transfer coefficient through the mist flow regime which persists until the vapor quality reaches 100%. Beyond this point the vapor is superheated by forced convection from the surface.

CONDENSATION HEAT TRANSFER:

The process of condensation is the reverse of boiling. Whenever a saturated vapor comes in contact with a surface at a lower temperature, condensation occurs. There are two modes of condensation; ***film wise,*** in which the condensate wets the surface forming a continuous, film which covers the entire surface and ***drop wise*** in which the vapor condenses into small liquid droplets of various sizes which fall down the surface in a random fashion. Film wise condensation generally occurs on clean uncontaminated surfaces. In this type of condensation the film covering the entire surface grows in thickness as it moves down the surface by gravity. There exists a thermal gradient in the film and so it acts as a resistance to heat transfer. In drop wise condensation a large portion of the area of the plate is directly exposed to the vapor, making heat transfer rates much larger (5 to 10 times) than those in film wise condensation. Although drop wise condensation would be preferred to film wise condensation yet it is extremely difficult to achieve or maintain. This is because most surfaces become 'wetted' after being exposed to condensing vapors over a period of time. Drop wise condensation can be obtained under controlled conditions with the help of certain additives to the condensate and various surface coatings but its commercial viability has not yet been proved. For this reason the condensing equipment in use in designed on the basis of film wise condensation.

LAMINAR FILM WISE CONDENSATION ON A VERTICAL PLATE: (Nusselt's Analysis Of Film Condensation)

Film wise condensation on a vertical plate can be analyzed on lines proposed by Nusselt (1916). Unless the velocity of the vapor is very high or the liquid film very thick, the motion of the condensate would be laminar. The thickness of the condensate film will be a function of the rate of condensation of vapor and the rate at which the condensate is removed from the surface. On a vertical surface the film thickness will increase gradually from top to bottom as shown in Fig. 4. Nusselt's analysis of film condensation makes the following simplifying assumptions:

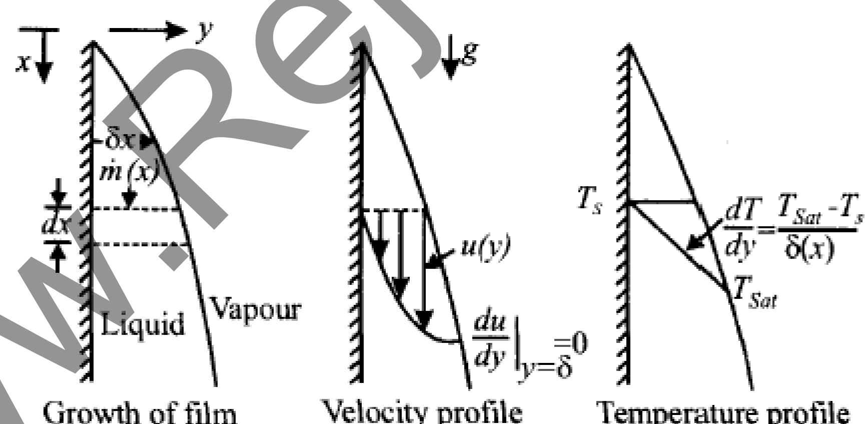


Fig. 4 Filmwise Condensation on a Vertical Plate

1. The plate is maintained at a uniform temperature, T_s which is less than the saturation temperature, T_{sat} of the vapor.
2. The condensate flow is laminar

3. The fluid properties are constant
4. The shear stress at the liquid vapor interface is negligible
5. The acceleration of fluid within the condensate layer is neglected.
6. The heat transfer across the condensate layer is by pure conduction and the temperature distribution is linear.

HEAT EXCHANGERS:

The device used for exchange of heat between the two fluids that are at different temperatures, is called the ***heat exchanger***. The heat exchangers are commonly used in wide range of applications, for example, in a car as radiator, where hot water from the engine is cooled by atmospheric air. In a refrigerator, the hot refrigerant from the compressor is cooled by natural convection into atmosphere by passing it through finned tubes. In a steam condenser, the latent heat of condensation is removed by circulating water through the tubes. The heat exchangers are also used in space heating and air-conditioning, waste heat recovery and chemical processing. Therefore, the different types of heat exchangers are needed for different applications.

The heat transfer in a heat exchanger usually involves convection on each side of fluids and conduction through the wall separating the two fluids. Thus for analysis of a heat exchanger, it is very convenient to work with an ***overall heat transfer coefficient*** **U**, that accounts for the contribution of all these effects on heat transfer. The rate of heat transfer between two fluids at any location in a heat exchanger depends on the magnitude of temperature difference at that location and this temperature difference varies along the length of heat exchanger. Therefore, it is also convenient to work with ***logarithmic mean temperature difference LMTD****,* which is an equivalent temperature difference between two fluids for entire length of heat exchanger.

CLASSIFICATION OF HEAT EXCHANGER:

Heat exchangers are designed in so many sizes, types, configurations and flow arrangements and used for so many purposes. These are classified according to heat transfer process, flow arrangement and type of construction.

According to Heat Transfer Process:

(i) **Direct contact type.** In this type of heat exchanger, the two immiscible fluids at different temperatures are come in direct contact. For the heat exchange between two fluids, one fluid is sprayed through the other. Cooling towers, jet condensers, desuperheaters, open feed water heaters and -scrubbers are the best examples of such heat exchangers. It cannot be used for transferring heat between two gases or between two miscible liquids. A direct contact type heat exchanger (cooling tower) is shown in Fig. 5

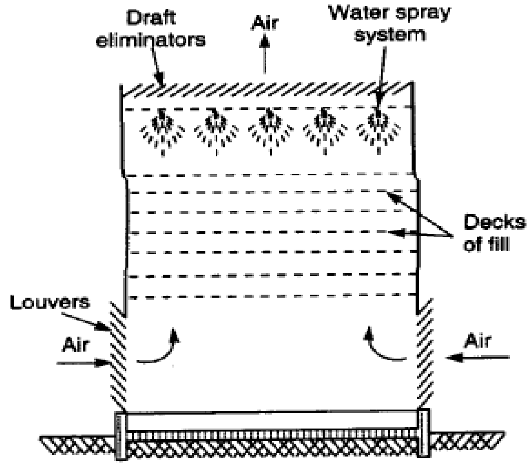


Fig. 5 Direct contact type heat exchanger (cooling tower)

***(ii)* Transfer type heat exchangers or recuperators:** In this type of heat exchanger, the cold and hot fluids flow simultaneously through the device and the heat is transferred through the wall separating them. These types of heat exchangers are most commonly used in almost all fields of engineering.

(iii) **Regenerators or storage type heat exchangers.** In these types of heat exchangers, the hot and cold fluids flow alternatively on the same surface. When hot fluid flows in an interval of time, it gives its heat to the surface, which stores it in the form of an increase in its internal energy. This stored energy is transferred to cold fluid as it flows over the surface in next interval of time. Thus the same surface is subjected to periodic heating and cooling. In many applications, a rotating disc type matrix is used, the continuous flow of both the hot and cold fluids are maintained. These are preheaters for steam power plants, blast furnaces, oxygen producers etc. A stationary and rotating matrix shown in Fig. 6 are examples of storage type of heat exchangers.

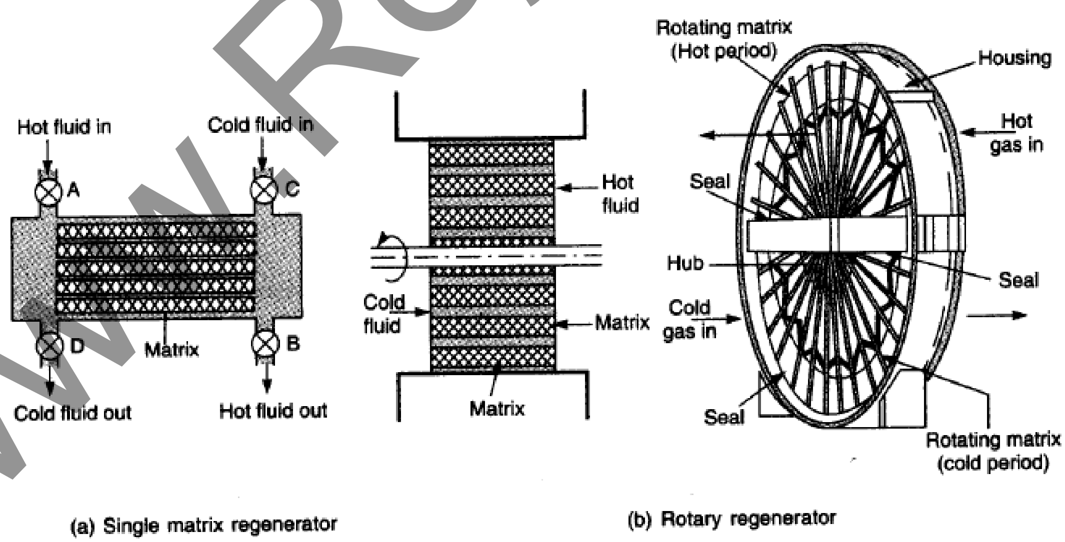


Fig. 6 Storage type heat exchangers

The storage type of heat exchangers is more compact than the transfer type of heat exchangers with more surface area per unit volume. However, some mixing of hot and cold fluids is always there.

According to Constructional Features:

(i) **Tubular heat exchanger.** These are also called *tube in tube* or *concentric tube* or *double pipe heat exchanger* as shown in Fig.7. These are widely used in many sizes and different flow arrangements and type.

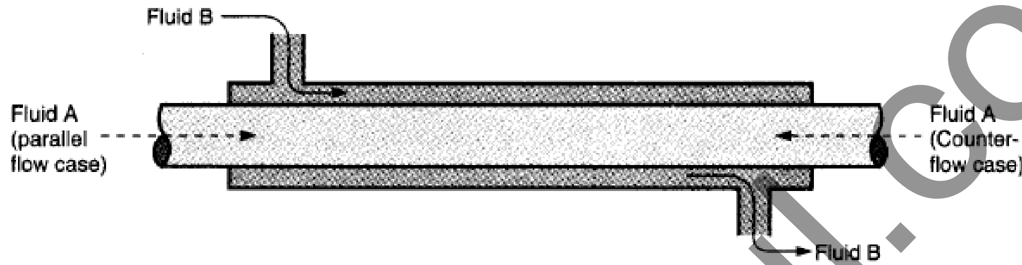


Fig. 7 Tubular heat exchanger

(ii) **Shell and tube type heat exchanger.** These are also called *surface condensers* and are most commonly used for heating, cooling, condensation or evaporation applications. It consists of a shell and a large number of parallel tubes housing in it. The heat transfer takes place as one fluid flows through the tubes and other fluid flows outside the tubes through the shell. The baffles are commonly used on the shell to create turbulence and to keep the uniform spacing between the tubes and thus to enhance the heat transfer rate. They are having large surface area in small volume. A typical shell and tube type heat exchanger is shown in Fig.8

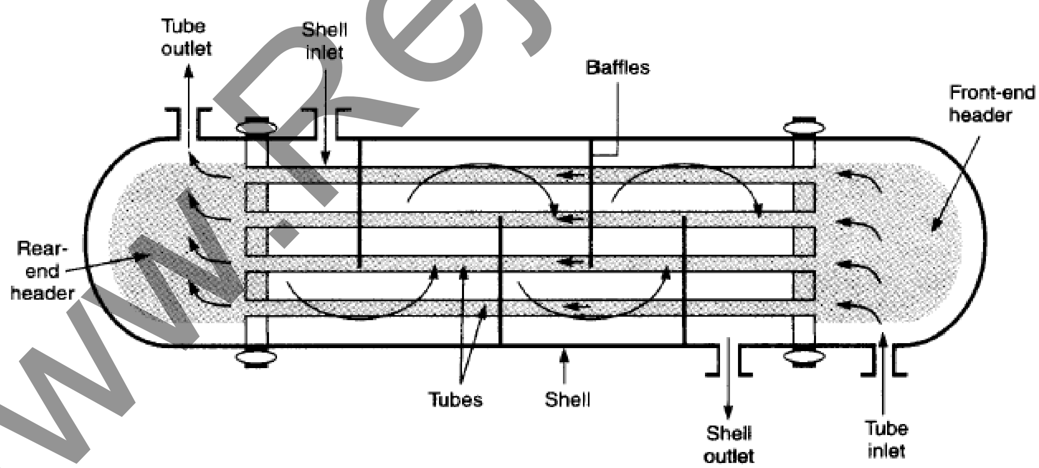
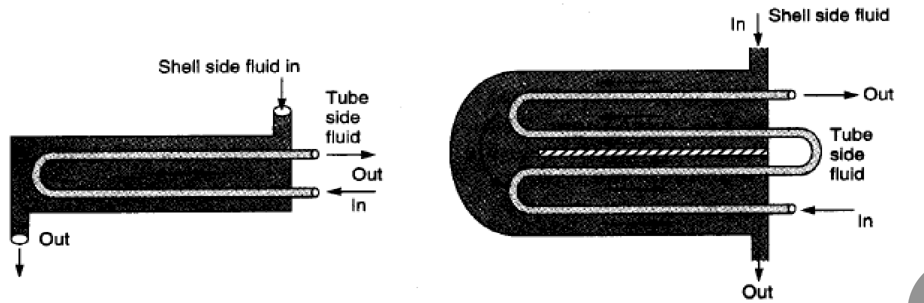


Fig. 8 Shell and tube type heat exchanger : One shell and one tube pass

The shell and tube type heat exchangers are further classified according to number of shell and tube passes involved. A heat exchanger with all tubes make one U turn in a shell is

called *one shell pass and two tube pass* heat exchanger. Similarly, a heat exchanger that involves two passes in the shell and four passes in the tubes is called a *two shell pass and four tube pass* heat exchanger as shown in Fig.9



(a) One shell pass and two tube pass heat exchanger

(b) Two shell pass and four tube pass heat exchanger

Fig. 9 Multipass flow arrangement in shell and tube type heat exchangers

(iii) **Finned tube** type. When a high operating pressure or an enhanced heat transfer rate is required, the extended surfaces are used on one side of the heat exchanger. These heat exchangers are used for liquid to gas heat exchange. Fins are always added on gas side. The finned tubes are used in gas turbines, automobiles, aero planes, heat pumps, refrigeration, electronics, cryogenics, air-conditioning systems etc. The radiator of an automobile is an example of such heat exchanger.

(iv) **Compact heat exchanger.** These are special class of heat exchangers in which the heat transfer surface area per unit volume is very large. The ratio of heat transfer surface area to the volume is called *area density.* A heat exchanger with an area density greater than 700 m^2/m^3 is called *compact heat exchanger.* The compact heat exchangers are usually cross flow, in which the two fluids usually flow perpendicular to each other. These heat exchangers have dense arrays of finned tubes or plates, where at least one of the fluid used is gas. For example, automobile radiators have an area density in order of 1100 m^2/m^3.

According to Flow Arrangement:

(i) **Parallel flow:** The hot and cold fluids enter at same end of the heat exchanger, flow through in same direction and leave at other end. It is also called the *concurrent heat exchanger Fig 10.*

(ii) **Counter flow**: The hot and cold fluids enter at the opposite ends of heat exchangers, flow through in opposite direction and leave at opposite ends Fig 10.

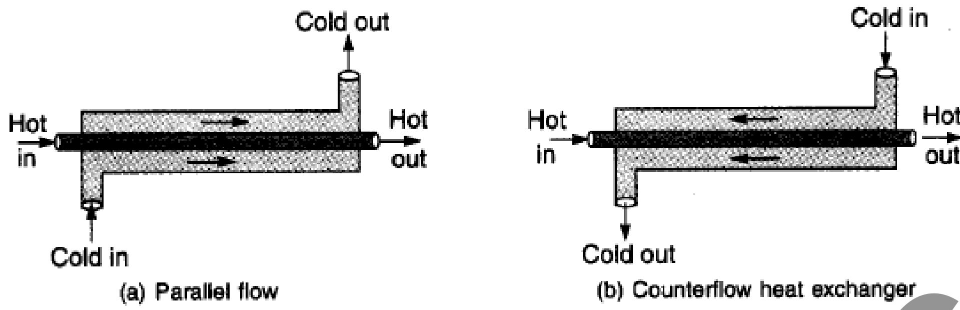


Fig 10 Concentric tube heat exchanger

(iii) **Cross flow:** The two fluids flow at right angle to each other. The cross flow heat exchanger is further classified as unmixed flow and mixed flow depending on the flow configuration. If both the fluids flow through individual channels and are not free to move in transverse direction, the arrangement is called unmixed as shown in Fig 11a. if any fluid flows on the surface and free to move in transverse direction, then this fluid stream is said to be mixed as shown in Fig 11b.

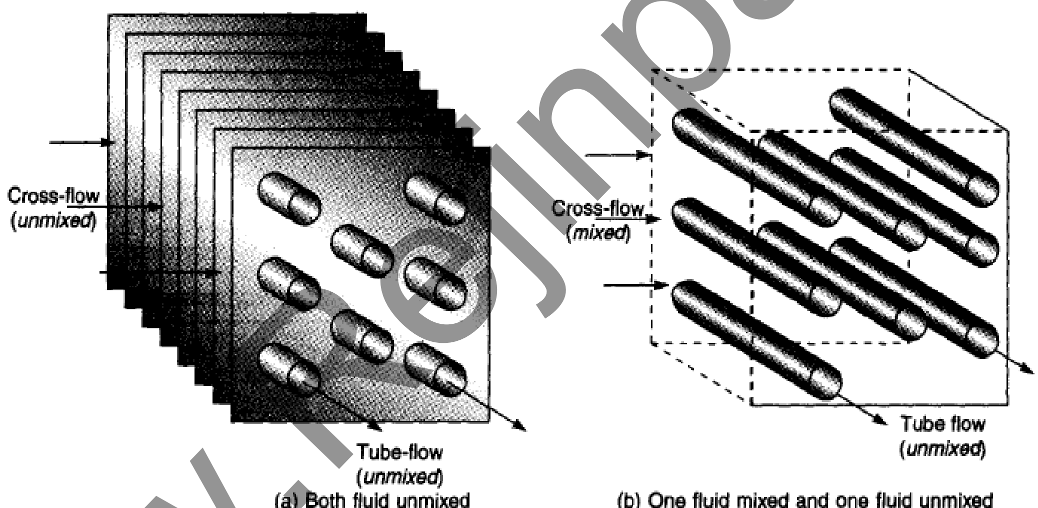
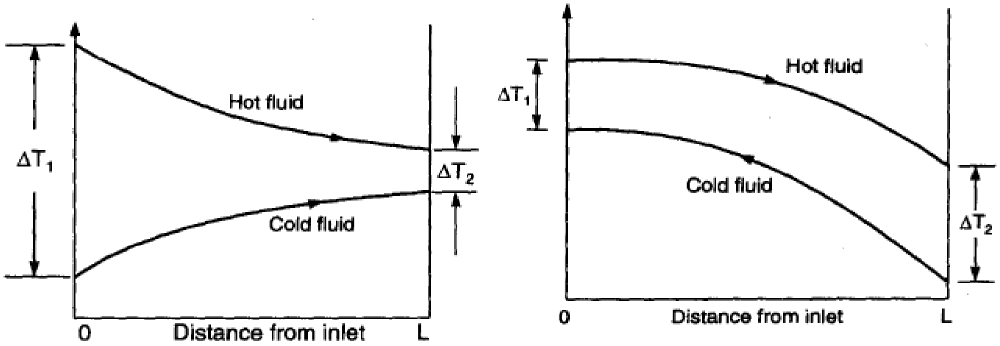


Fig 11 Different flow configurations in cross-flow heat exchangers

TEMPERATURE DISTRIBUTION:

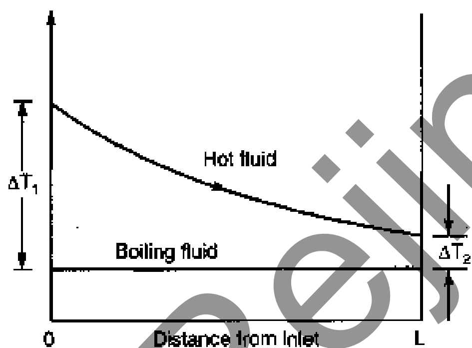
The heat transfer from the hot to the cold fluid causes a change in temperature of one or both fluids flowing through the heat exchanger. In some common cases, the temperature is plotted against the distance from the cold fluid inlet



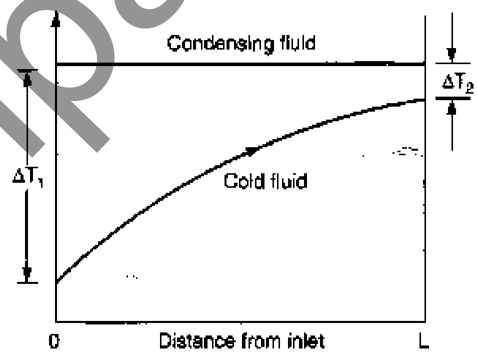
(a) Parallel flow heat exchanger (b) Counter flow heat exchanger

Condensers and Evaporators:

Two special forms of heat exchangers, namely condensers and evaporators, are employed in many industrial applications. One of the fluids flowing through these exchangers changes phase. The temperature distributions in these exchangers are shown in Fig. In the case of a condenser, the hot fluid will remain at a constant temperature, provided its pressure does not change, while the temperature of the cold fluid increases.



Temperature distribution for evaporator



Temperature distribution for condenser

<u>TWO MARKS:</u>

1. Define boiling

The change of phase from liquid to vapour state is known as boiling.

2. What is meant by condensation?

The change of phase from vapour to liquid state is known as condensation.

3. Give the application of boiling and condensation.

Boiling and condensation process finds wide applications as mentioned below

1. Thermal and nuclear power plant
2. Refrigerating systems
3. Process of heating and cooling
4. Air conditioning systems

4. What is meant by pool boiling?

If heat is added to a liquid from a submerged solid surface, the boiling process is referred to as pool boiling. In this case the liquid above the hot surface is essentially stagnant and its motion near the surface is due to free convection and mixing induced by bubble growth and detachment.

5. What are the modes of condensation?

There are two modes of condensation

1. Film wise condensation 2. Drop wise condensation

6. What is meant by Film wise condensation?

The liquid condensate wets the solid surface, spreads out and forms a continuous film over the entire surface is known as film wise condensation.

7. What is meant by Drop wise condensation?

In drop wise condensation, the vapour condenses into small liquid droplets of various sizes which fall down the surface in a random fashion.

8. Give the merits of drop wise condensation.

In drop wise condensation, a large portion of the area of the plate is directly exposed to vapour. The heat transfer rate in drop wise condensation is 10 times higher than in film condensation.

9. Write the force balance equation on a volume element for film wise condensation on a vertical plane surface.

$$\frac{\partial^2 U}{\partial y^2} = \frac{1}{\mu_l}\frac{\partial p}{\partial x} - \frac{Bx}{\mu_l}$$

Where,

Bx – Body force in x direction

$\frac{\partial p}{\partial x}$ – Pressure gradient

11. What is heat exchanger?

A heat exchanger is defined as equipment which transfers the heat from a hot fluid to a cold fluid.

12. What are the types of heat exchangers?

The types of heat exchangers are as follows

1. Direct contact heat exchangers. 2. Indirect contact heat exchangers 3. Surface heat exchangers. 4. Parallel flow heat exchangers 5. Counter flow heat exchangers. 6. Cross flow heat exchangers 7. Shell and tube heat exchangers. 8. Compact heat exchangers

13. What is meant by direct heat exchanger (or) open heat exchanger?

In direct contact heat exchanger, the heat exchange takes place by direct mixing of hot and cold fluids.

14. What is meant by indirect contact heat exchanger?

In this type of heat exchangers, the transfer of heat between two fluids could be carried out by transmission through a wall which separates the two fluids.

15. What is meant by Regenerators?

In this type of heat exchangers, hot and cold fluids flow alternately through the same space.

Examples: IC engines, gas turbines.

16. What is meant by Recuperators (or) Surface heat exchangers?

This is the most common type of heat exchangers in which the hot and cold fluid do not come into direct contact with each other but are separated by a tube wall or a surface.

Examples: Automobile radiators, Air preheaters, Economisers etc,

17. What is meant by parallel flow heat exchanger?

In this type of heat exchanger, hot and cold fluids move in the same direction.

18. What is meant by counter flow heat exchanger?

In this type of heat exchanger, hot and cold fluids move in parallel but opposite directions.

19. What is meant by cross flow heat exchanger?

In this type of heat exchanger, hot and cold fluids move at right angles to each other.

20. What is meant by Shell and tube heat exchanger?

In this type of heat exchanger, one of the fluids moves through a bundle of tubes enclosed by a shell. The other fluid is forced through the shell and it moves over the outside surface of the tubes.

21. What is meant by compact heat exchangers?

There are many special purpose heat exchangers called compact heat exchangers. They are generally employed when convective heat transfer co-efficient associated with one of the fluids is much smaller than that associated with the other fluid.

22. What is meant by LMTD?

We know that the temperature difference between the hot and cold fluids in the heat exchanger varies from point to point. In addition various modes of heat transfer are involved. Therefore based on concept of appropriate mean

temperature difference, also called logarithmic mean temperature difference, the total heat transfer rate in the heat exchanger is expressed as

$$Q = U\,A(\Delta T)_m$$

Where

U = over all heat transfer co efficient W/m^2K

A = Area , m^2

$(\Delta T)_m$ = Logarithmic mean temperature difference

23. What is meant by Fouling factor?

We know, the surfaces of heat exchangers do not remain clean after it has been in use for some time. The surfaces become fouled with scaling or deposits. The effect of these deposits affecting the value of overall heat transfer co-efficient. This effect is taken care of by introducing an additional thermal resistance called the fouling resistance.

24. What is meant by Effectiveness?

The heat exchanger effectiveness is defined as the ratio of actual heat transfer to the maximum possible heat transfer.

$$\text{Effectiveness } \varepsilon = \frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}}$$

$$= \frac{Q}{Q_{\max}}$$