UNIT: II **(EVAPORATION)**

CLASS:15

TOPIC: OBJECTIVES, APPLICATIONS AND FACTORS INFLUENCING EVAPORATION, DIFFERENCE BETWEEN EVAPORATION AND OTHER HEAT PROCESS

FLOW OF HEAT

Heat is a form of energy. According to the principles of thermodynamics, whenever a physical or chemical transformation occurs, heat flows into or leaves the system.

A number of sources of heat is used for industrial scale operations. Steam and electric power are the chief sources to transfer heat. It is essential to convey steam without any losses to the apparatus in which it is used. The study of heat transfer processes helps in designing the plant efficiently and economically.

Applications

A few areas of relevance to pharmaceutical engineering are enumerated here.

Evaporation: Heat is supplied in order to convert a liquid (vehicle) into a vapour, which is subsequently removed. This process is used for preparing vegetable extracts. A construction similar to shell-and-tube heat exchanger is employed in evaporators. The heat flow can be quantified so as to estimate the efficiency of the process.

Distillation: Heat is supplied to a liquid mixture for converting the liquid into vapour so that the individual vapour components are condensed at another place. In case of steam distillation, steam will be in direct contact with the material.

Drying: In the production of tablets, heat is passed through a carrier gas over a bed of wet solid mass for achieving drying. In case of spray drying, heat is supplied to the solutions and suspensions (as in case of production of milk products).

Crystallisation: Saturated solution is heated to bring about super-saturation, which promotes the crystallisation of drugs. On the other hand, removal of heat (cooling) from a saturated solution also facilitates crystallisation, as in case of purification of bulk drugs.

Sterilization: For the sterilization of pharmaceuticals. autoclaves are used with steam as a heating medium. Dry heat is used for the sterilization of glass apparatus and other containers. In addition, a number of other processes, such as boiling. exsiccation, sublimation and fusion, also use heat.

In a laboratory setup, number of equipment involving heat are used. A few examples are air-ovens, incubators, dryers, refrigerators etc. On industrial scale, equipment are used for applying heat, removing heat and preventing heat loss. The basic principles involved in heat transfer are understood properly for the maintenance and efficient working of the equipment.

MECHANISMS OF HEAT FLOW

Heat flows from a region of high temperature to a region of low temperature. Heat may flow by one or more of the three basic mechanisms.

Conduction

When heat flow in a body is achieved by the transfer of the momentum of individual atoms or molecules without mixing, such a process is known as conduction.

For example, flow of heat through the metal shell of a boiler takes place by conduction as far as solid wall or shell is considered. No mixing is involved. Conduction is limited to solids and fluids whose movement is restricted.

Convection

When heat flow is achieved by actual mixing of warmer portions with cooler portions of the same material, the process is known as convection.

For example, heating of water by a hot surface (coil type water heater) is mainly by convection. Convection is restricted to the flow of heat in fluids (i.e., liquids and gases). Convection currents of air are set up almost daily in the atmosphere. These are responsible for winds, land and sea breezes, ocean currents etc.

Radiation

When heat flows through space by means of electromagnetic waves. such energy transfer is known as radiation.

For example, a black surface absorbs most of the radiation received by it. Simultaneously the absorbed energy is quantitatively transferred into heat. Fused quartz transmits all the radiation that strikes it, while a polished opaque surface or mirror will reflect most of the radiation that strikes it. Solar water heaters, solar cookers, microwave ovens, micro- wave cookers, sonicator baths etc., are few examples in which radiation is utilized for producing heat.

In general. these mechanisms may operate simultaneously. For example, in ovens hot air is circulated by fan, so as to transfer heat by forced convection. Simultaneously, heat is transferred by conduction from the shelf to the material' in contact. Heat also radiates from hot walls of the oven.

CONDUCTION

Heat can flow only when there is a temperature gradient, i.e., heat flows from a hot surface to a cold surface. The rate of conduction through solids can be studied easily, since it is the sole phenomenon. The basic law of heat transfer by conduction can be written in the form of a rate equation as follows

$$\text{Rate}=\frac{driving\ force}{resistance} \qquad (1)$$

The driving force is the temperature drop across the solid surfaces. The greater the temperature drop. the greater will be the rate of heat flow.

The flow of heat will also depend on the conductivity of the materials through which it is flowing. For example, conduction of heat is faster through an iron rod than through a wooden log. This factor is represented by the term resistance, which can be quantitatively expressed by Fourier's law.

$$\text{Resistance} =\frac{thickness\ of\ the\ surface\ (m)}{mean\ proportionality\ constant\ (W/m.K)\times area\ of\ the\ surface\ (m^2)}$$

$$=\frac{L}{k_{mA}} \qquad (2)$$

Equation (2) for resistance can be obtained from the Fourier's law.

Fourier's Law Conduction of Heat through a Metal Wall

Fourier's law states that the rate of heat flow through a uniform material is proportional to the area and the temperature drop and inversely proportional to the length of the path of flow. The Fourier's law may be mathematically expressed as:

Rate of heat flow α $\frac{area\ (m^2) \times temperature\ difference\ (\Delta t)}{thickness\ (m)}$

$$q \ \alpha \ \frac{A.\Delta t}{L}$$

Or $$q = \frac{k_m . A . \Delta t}{L} \quad (3)$$

where $k_{m=}$ mean proportionality constant, W/m K.

Derivation: Fourier's law can be applied to a metal wall through which the conduction of heat is taking place (Figure). The characteristics are as follows.

Area of the wall = A, m²

Thickness of the wall = L, m

Face of the wail (HH) is maintained at a uniform definite and higher temperature = t_1, K

Face of the wall (CC) is maintained at a lower, but uniform temperature = t_2, K

The heat flow will be at right angles to the plane and is assumed to be in a steady state. Consider a thin section of thickness dL at an intermediate point in the wall. This section is parallel to the plane... For this section, Fourier's law may be applied as given below.

$$\frac{dQ}{d\theta} = \frac{-k\ .\ A\ .dt}{dL} \quad (4)$$

Where Q = heat transferred, J

Θ = time, s

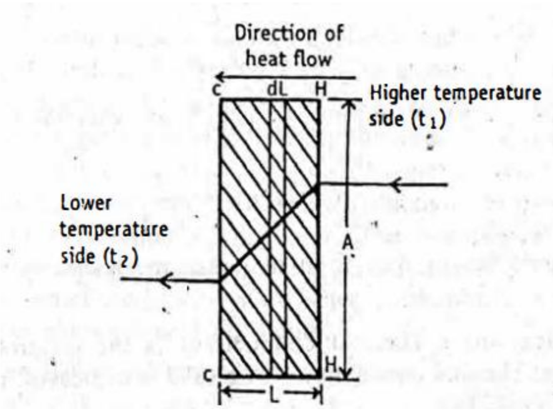
k = proportionality constant, W/mK

t = temperature, K

The constant, k, is a function of temperature, but independent of length. The minus' sign indicates the decrease in temperature in the direction of flow. In equation (4), (dt/dL) represents the temperature gradient. For a steady state heat transfer, equation (4) changes to:

$$\frac{dQ}{d\theta} = \text{Constant} = q = \frac{-k\ .\ A\ .dt}{dL} \quad (5)$$

where q = rate of heat transfer, J/s (or W)



Heat transfer through a metal wall by conduction

The temperature difference in the intermediate section is not known. But temperatures at the two faces of the wall are known. The area, A, may vary with L, but is independent of temperature. By separating the variables. equation (5) can be written as:

$$\frac{q\,.dL}{A} = -kdt \qquad (6)$$

Integrating equation (6) between the limits.

L=0 when t = t_1 and

L = L (total thickness) when t = t_2,

gives: $q\int_{O}^{L}\frac{dL}{A} = -\int_{t_1}^{t_2} kdt = -\int_{t_2}^{t_1} kdt$

$$\frac{qL}{A} = k_m(t_1 - t_2) = k_m\,\Delta t \qquad (7)$$

Rearranging equation (7) gives:

$$q = \frac{-k\,.\,A\,.dt}{dL} \qquad (3)$$

where k_m = mean proportionality constant, W/m.K

In steady state heat transfer, 'q' remains constant. In equation (3), the term Δt indicates the driving force. Equation (3) may be rearranged to obtain:

$$q = \frac{\frac{\Delta t}{L}}{k_{m\,.}\,A}$$

Comparing the above equation with rate expression [equation (1)] indicates that:

$$\text{Resistance} = \frac{L}{k_{m\,.}\,A} \qquad (2)$$

Fourier's law is thus used to define the resistance in quantitative terms.

Applications: Thermal conductivity is the reciprocal of thermal resistance. Thermal conductivity of a solid is expressed in terms of ***k*** as per equation (3).

The *coefficient of thermal conductivity* is the quantity of heat that flows across a unit surface area in unit time, when the temperature drop is unity.

The coefficient of thermal conductivity depends upon the material with which the body is made and upon its temperature. Thermal conductivities of some substances are given in Table

From Table the following conclusions can be drawn. –

Thermal conductivities of liquids and gases are very small com- pared to most of the solids. In other words, the resistance offered by liquids and gases is high as 'far as the conduction is concerned.

In case of steam jacketed vessels, the kettle (inner surface) must have good conductivity so that maximum amount of heat passes from the steam to the contents. The high thermal conductivity of copper suggests that it is a suitable material for the construction of the kettle. At the same time, the metal used for jacket (outer surface) must have minimum conductivity to prevent loss of heat by conduction and radiation. The low thermal conductivity of iron suggests that it would be suitable material for the construction of the jacket. Such materials should be resistant to solvent or chemical action of liquid.

Thermal Conductivities of Some Metals

Materials	*Thermal conductivity*, W/m·K
Copper	379.0
Silver	57.0
Steel	43.0
Aluminium	24.2
Stainless steel	17.0
Glass (borosilicate)	1.0
Building bricks	0.69
Water	0.62
Air	0.03

For the construction of evaporators and tubular heat exchangers thermal conductivity values are helpful. Thermal conductivity is very sensitive to changes in chemical composition and temperature and, therefore, the above values cannot be applied to all situations.

Compound Resistance in Series

Consider a flat wall constructed of a series of layers as in Figure

The characteristics are:

Thicknesses of the three layers = L_1, L_2 and L_3, m

Conductivities of materials of which layers are made = k_1, k_2 and k_3 .W/m.K

Area of the entire wall = A, m^2

Temperature drops across three layers = $\Delta t_1, \Delta t_2$ *and* Δt_3, K

Resistances of the three layers R_1, R_2 and R_3

For the above descriptions. The total temperature drop may be written as:

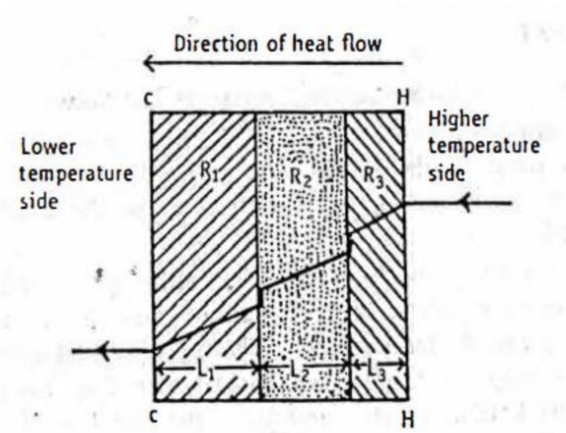
Driving force, $\Delta t = \Delta t_1 + \Delta t_2 + \Delta t_3$ (8)

The rate of flow of heat through several resistances in series is exactly analogous to the current flowing through several electrical resistances in series. Therefore, the overall resistance (R) is equal to the sum of individual resistances.

$$R = R_1 + R_2 + R_3 \qquad (9)$$

According to Fourier's law, individual resistances, are described by equation (2). These are incorporated in equation (9) to get:

$$R = \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{L_3}{k_3 A} \qquad (10)$$



Flow of heat through. several resistances arranged in series.

Since entire heat must pass through the resistances in series, heat q can be written as:

$$q = q_1 + q_2 + q_3 \qquad (11)$$

Using the principles of conduction, the rate of heat transfer, q, may be expressed as:

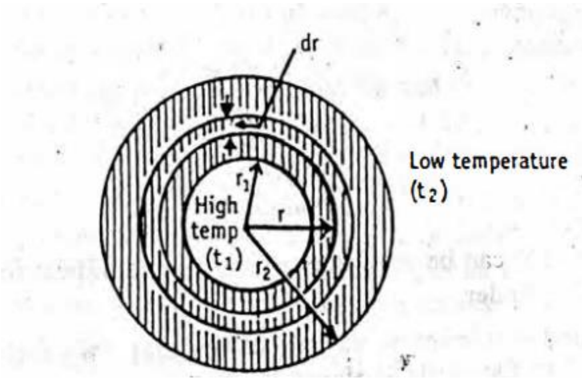
$$q = \frac{\Delta t}{R_1 + R_2 + R_3} \qquad (12)$$

The contributions of temperature drops to the total temperature and individual resistances to the total resistance can be expressed mathematically as:

$$\Delta t : \Delta t_1 : \Delta t_2 : \Delta t_3 \;::\; R : R_1 : R_2 : R_3 \qquad (13)$$

Heat Flow through A Cylinder-Conduction

In a heat exchanger, hot fluid or steam is passed through the circular pipe. The hot fluid transfers the heat to the inner surface of the pipe wall. Further heat transfer takes place by conduction through the pipe wall. The rate of heat transfer by conduction through a cylinder may be obtained as follows, Consider a hollow cylinder as shown in Figure. The heat is flowing from inside to outside the cylinder. Consider a very thin cylinder at the centre of the pipe. The following characteristics may be enumerated.



Flow of heat through thick-walled cylinder.

Mean thermal conductivity of material of cylinder = k, W/m.K

Temperature of the inside surface (higher) = t_1, K

Temperature of the outside surface (lower) = t_2, K

Radius of the thin cylinder = r, m

Thickness of the thin section dr, m

Radius of the inner wall = r_1, m

Radius of the outer wall =r_2, m

Length of the hollow cylinder = N, m

The heat flow (in watts) is considered as parallel and the rate of heat transfer (q) can be written as:

$$q = -k \frac{dt}{dr}(2\pi rN) \qquad (14)$$

where 2πrN is the area of the heating surface, i.e., the interior of the cylinder. The mean surface area (A_m) may be written as circumference multiplied by length of cylinder.

Considering the variables such as radius and temperature, equation (14) is rearranged to obtain:

$$\frac{dr}{r} = \frac{-2\pi Nk}{q}\, dt \qquad (15)$$

Integrating equation (15) within the limits of

r = r_1, when t = t_1 and

r = r_2, when t = t_2 ,

gives: $$\int_{r_1}^{r_2} \frac{dr}{r} = \frac{-2\pi N}{q} \int_{t_1}^{t_2} kdt = \frac{2\pi N}{q} \int_{t_2}^{t_1} kdt$$

$$\ln r_2 - \ln r_1 = \frac{2\pi N k_m}{q} (t_1 - t_2)$$

$$q = \frac{2\pi N k_{m}(t_{1}-t_{2})}{\ln(r_2/r_1)} \qquad (16)$$

Equation (16) can be used to calculate the rate of heat flow through a thick walled cylinder.

It is desirable to express the rate of heat flow in a more convenient form (similar to flat wall) as shown below.

$$q = \frac{\text{coefficient} \times \text{area} \times \text{temperature difference}}{\textit{length of the metal layer.}}$$

$$q = \frac{k_m \cdot A_m \cdot (t_1 - t_2)}{L} \qquad (17)$$

By equating the right hand-side terms in equations (16) and (17), the area (of surface) term may be obtained as:

$$\frac{A_m}{L} = \frac{2\pi N}{\ln(r_2/r_1)}$$

Since L is the thickness, it is related to thickness of the tube, i.e., (r_2 - r_1) of the cylinder. This value is substituted for L and rearranged to obtain A_m (mean area of a cylinder).

$$A_m = \frac{2\pi N\,(r_2 - r_1)}{\ln(r_2/r_1)} \qquad (18)$$

A_m, area may be considered as $2\pi r_m N$. From equation (18), mean radius, r_m may be written as:

$$r_m = \frac{((r_2 - r_1))}{\ln(r_2/r_1)} = \frac{(r_2 - r_1)}{2.303\ log(r_2/r_1)} \qquad (19)$$

In equation (19), the term, r_m. is called *logarithmic mean radius*. Logarithmic mean is less convenient than the arithmetic mean. The arithmetic mean is sufficiently accurate, if the tube is thin walled. This relationship is explained below.

- The arithmetic mean radius gives the result within 10 % of that obtained by equation 16. logarithmic mean radius is used if the value of r_2/r_1< 3.20 (thick wall).
- The arithmetic mean radius gives the result within 1 % of that obtained by equation 16. logarithmic mean radius is used if the value of r_2/r_1< 1.5 (thin wall).

For most cases in practice, arithmetic mean radius is sufficiently accurate. if the cylinder is thin-walled. For thick walled tube, logarithmic mean radius is to be used. The use of either an inner radius or an outer radius does not give sufficiently accurate results.

Conduction through Fluids

Conduction in liquids is usually small and this presents a considerable obstacle for heat transfer. Conductance in fluids is because of eddies setup by the changes in density, with temperature, which is observed in the boiling of liquids (as in case of evaporation and distillation of liquids).

Conduction through fluids rarely occurs in practice, except when heat. flows through thin films. In these cases, the thickness of the film is not exactly known. Therefore, equations described earlier cannot be applied. This difficulty can be overcome by the use of surface coefficient, which will be discussed later. If a body of fluid is large, both convection and conduction may prevail. This complicates the data analysis and fails to provide accurate predictions.

MCQ Each carry 1 mark

1. The general equation for heat transfer rate, q, is expressed as:
    a. AΔt/U
    b. U/AΔt
    c. UAΔt
    d. UA/Δt
2. Fourier's law is applicable to one of the following types of heat flow.
    a. **Conduction**
    b. Convection
    c. Radiation
    d. Emission
3. The flow of heat is NOT applicable generally in one of the following unit operations
    a. Centrifugation
    b. Crystallization
    c. Drying
    d. Refrigeration
1. What is heat transfer?
    a) Flow of thermal energy from low-temperature reservoir to high-temperature reservoir
    b) Flow of energy in the form of heat from high-temperature reservoir to low-temperature reservoir
    c) Flow of thermal energy irrespective of reservoir temperature
    d) None of the above
4. Heat transfer takes place according to which of the following law?
    a) Newton's second law of motion
    b) First law of thermodynamics
    c) Newton's law of cooling
    d) Second law of thermodynamics
5. For conduction heat transfer, the heat energy propagation will be minimal for ___________
    a) Copper
    b) Air
    c) Water
    d) Lead
6. Which of the following is having the lowest value of overall heat transfer coefficient?
    a) Feed water heaters
    b) Air condensers
    c) Air to low viscosity liquids
    d) Steam condensers
7. Which of the following statement is incorrect according to heat transfer?
    a) Heat flow doesn't depend on temperature
    b) A material medium is not necessary for heat transmission
    c) The process of heat transfer is an irreversible process
    d) For heat exchange, a temperature gradient must exist
8. Which of the following is the rate of heat transfer unit?
    a) Watt
    b) Pascal
    c) Joule

d) Newton

Each carry 2 marks

1. Give characteristics of drop-wise and film types condensation
2. Drop-wise or film type condensation gives. superior value of overall heat transfer coefficient and why?
3. What are "overall heat transfer coefficient' and 'individual film coefficient.
4. State the relationship between individual film coefficients and overall heat. Differentiate between them.
5. Define conductivity with a suitable example.
6. State and explain Fourier's law of heat transmission with equation.
7. Write the final equation for heat transfer by conduction through resistances in parallel and explain the terms.
8. What is meant. by overall heat transfer coefficient? What is its significance

Each carry 5 marks

1. Derive an equation for heat transfer by conduction through compound resistances in series
2. Describe the conduction of heat through a circular pipe. Give suitable equations for rate of heat transfer and explain terms.
3. Describe the conduction of heat through compound resistances in series.
4. Derive an expression for the logarithmic mean temperature difference

Each carry 10 marks

1. Derive an equation for heat transmission through a circular pipe from Fourier's law.

RCP