5

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, microwave 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:

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

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.

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

$$= \frac{L}{k_m A} \qquad (2)$$

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:

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

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

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

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 5-1). The characteristics are as follows.

Area of the wall = A, m^2

Thickness of the wall = L, m

Face of the wall (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 A 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, A. For this section, Fourier's law may be applied as given below.

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

where Q = heat transferred, J
θ = time, s
k = proportionality constant, W/m·K
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:

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

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

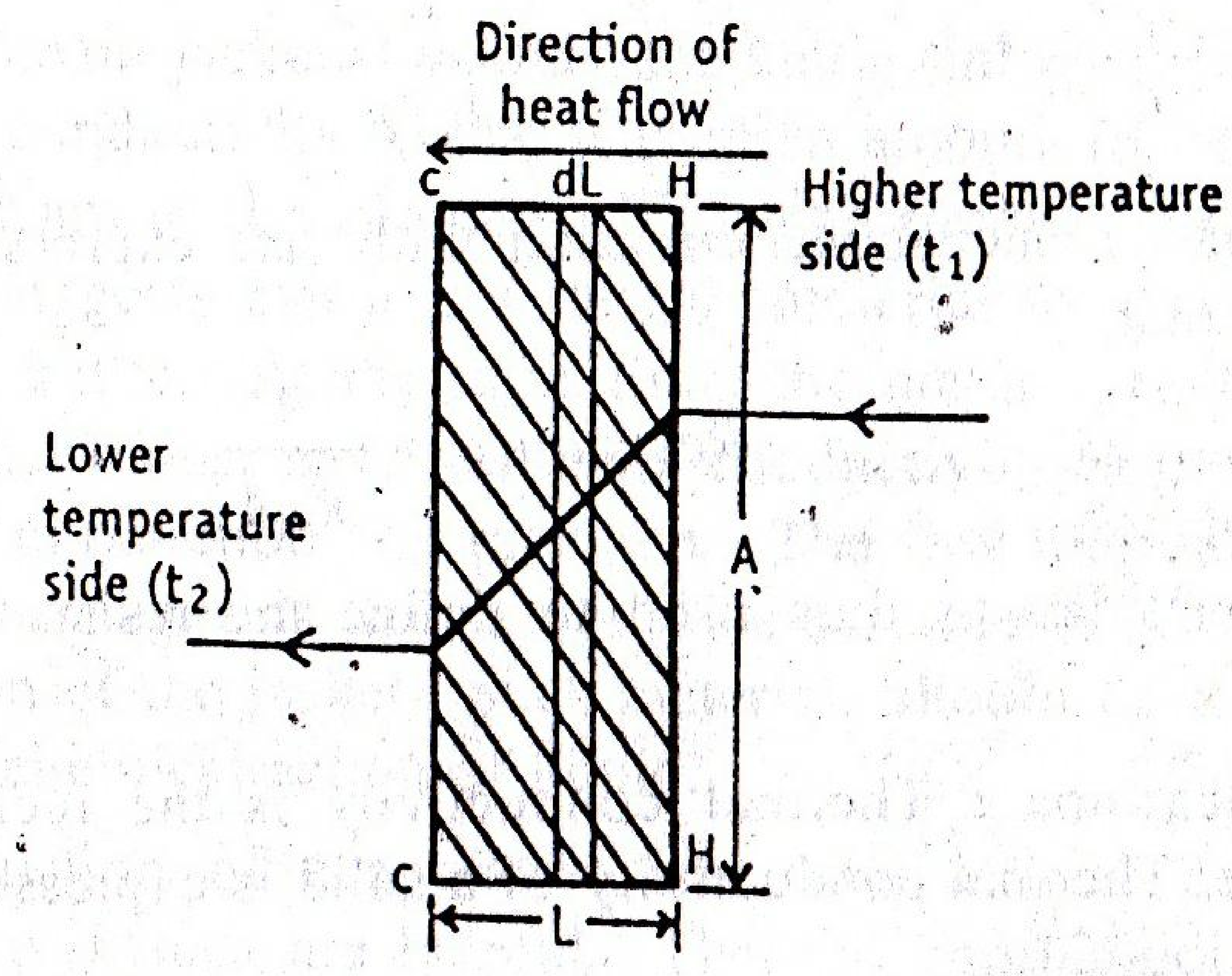


Figure 5-1. Heat transfer through a metal wall by conduction.

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:

$$q\int_0^L \frac{dL}{A} = -\int_{t_1}^{t_2} kdt = \int_{t_2}^{t_1} kdt$$

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

Rearranging equation (7) gives:

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

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:

$$q = \frac{\Delta t}{\dfrac{L}{k_m \cdot A}}$$

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

$$Resistance = \frac{L}{k_m A} \qquad (2)$$

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 5-1.

TABLE 5-1
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

From Table 5-1, the following conclusions can be drawn.

- Thermal conductivities of liquids and gases are very small compared 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.

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. The materials and their usefulness with respect to thermal conductivities are discussed in Chapter 17.

Compound Resistance in Series

Consider a flat wall constructed of a series of layers as in Figure 5-2. 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 = Δt_1, Δt_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:

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

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.

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

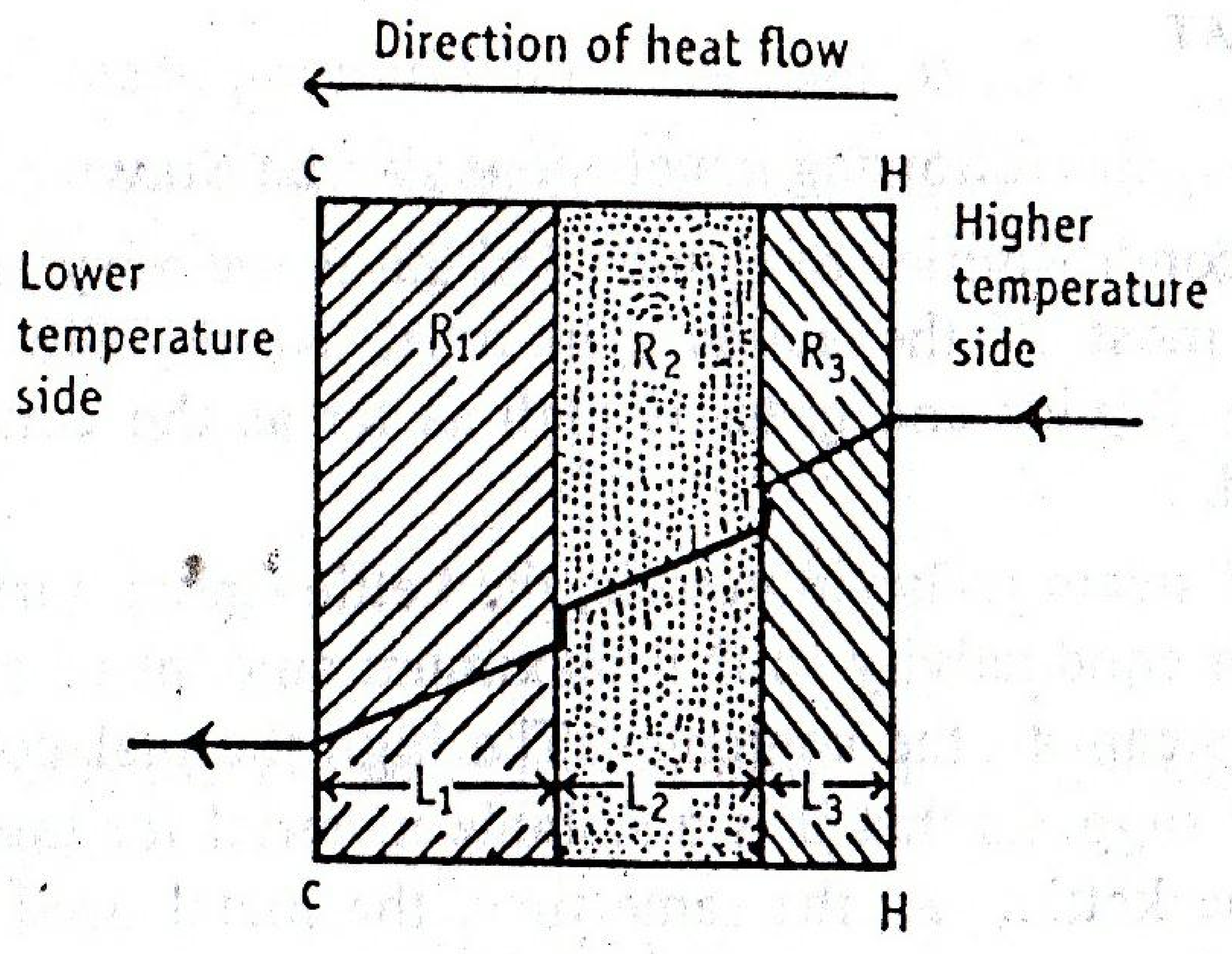


Figure 5-2. Flow of heat through several resistances arranged in series.

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

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

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

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

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

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

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

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

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 5-3. 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.

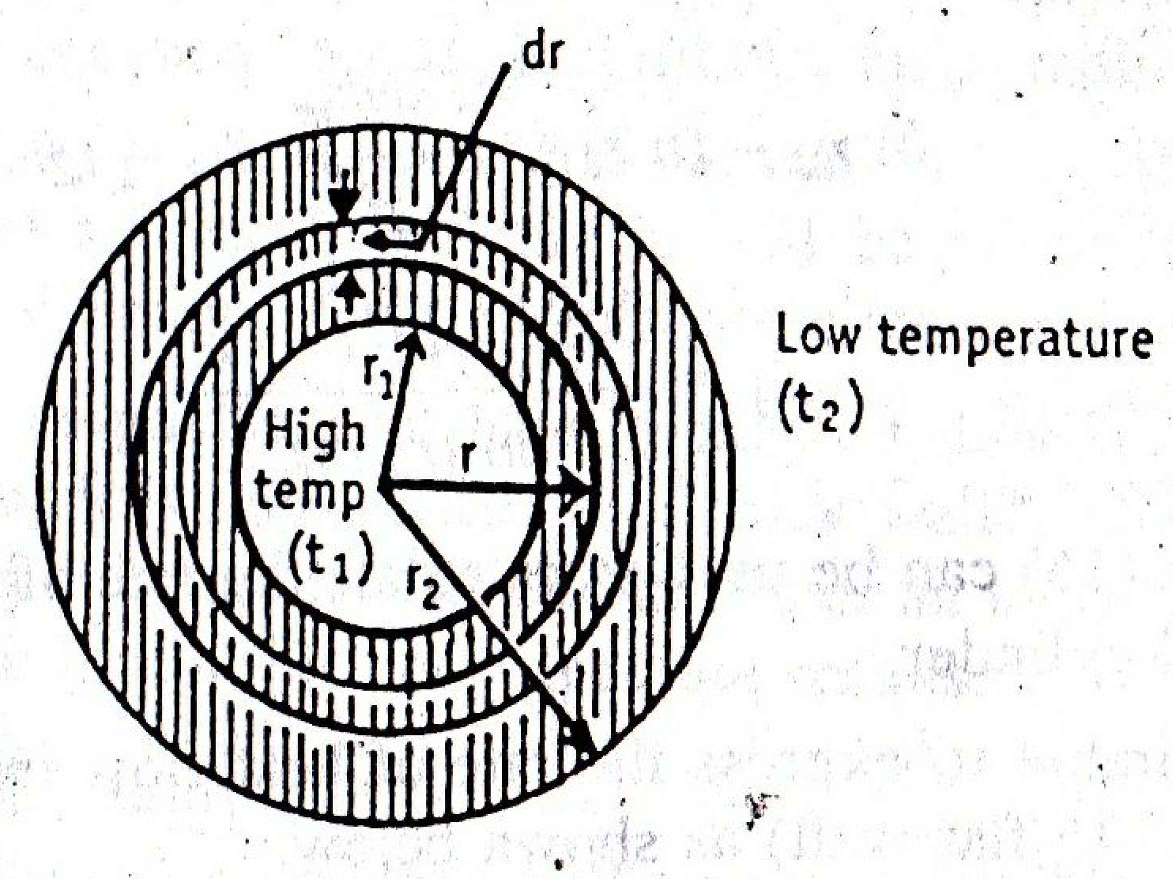


Figure 5-3. Flow of heat through thick-walled cylinder.

Mean thermal conductivity of material of cylinder = k_m, 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:

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

where $2\pi rN$ 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:

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

Integrating equation (15) within the limits of

$r = r_1$, when $t = t_1$ and
$r = r_2$, when $t = t_2$,

gives:

$$\int_{r_1}^{r_2} \frac{dr}{r} = \frac{-2\pi N}{q} \int_{t_1}^{t_2} k dt = \frac{2\pi N}{q} \int_{t_2}^{t_1} k dt$$

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

$$q = \frac{2\pi N\, k_m\, (t_1 - t_2)}{\ln (r_2/r_1)} \qquad (16)$$

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.

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

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

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 value $r_1/r_2 < 3.20$ reflects that the wall is thick. If arithmetic mean radius is used, the result will be within 10 % of that obtained by equation 16 (i.e., logarithmic mean radius is used).
- The value $r_1/r_2 < 1.5$, reflects that the wall is thin. If arithmetic mean diameter is used, the results will be within 1% of that obtained by equation 16 (i.e., logarithmic mean radius is used).

For most cases in practice, arithmetic mean radius is sufficiently accurate, if the cylinder is thin-walled. For thick walled tube, logarithmic mean radius has 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.

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.*

The heat transfer in fluid occurs on account of actual mixing of its layers.

Forced convection : Mixing of fluid may be obtained by the use of a stirrer or agitator or pumping the fluid for recirculation. Such a process in heat transfer is designated as *forced convection*. For example, in some types of tube evaporators, the evaporating liquid is forced through the tubes under pressure. Therefore forced convection is observed.

Natural convection : Mixing of fluid may be accomplished by the currents set up when body of fluid is heated. Such a process is known as *natural convection*. For example, in pan evaporator, convection currents are set up in the evaporating liquid.

In general, fluid flow may be described as either laminar or turbulent. These create problems in the estimations. Some of them are as follows. When heat is passed through the tube, stagnant films are important in determining the rate of heat transfer.

- When fluid exhibits viscous flow, the velocity is zero at the actual surface of the wall. It means that the layer of fluid adjacent to the wall acts as a stagnant film.
- A comparatively stagnant film can be observed even in turbulent flow. At the centre, the fluid is in turbulent flow, while at the surface the fluid exhibits viscous flow. A film of buffer layer oscillates between these types of flow.
- Sometimes, scales are deposited on the surface of the metal wall and heat must be conducted through the scales.
- When steam gives up latent heat, water will condense on the surface of the vessel (or tube). Again the heat must be conducted through this water film.

For heat transfer in a tube, heat must pass through the stagnant film by conduction. Hence, conductivity of these films is important. Normally, thermal conductivities of fluids are low. The conductivity of the stagnant film will be still less. For example, the thermal conductivity of water is less. A film of water has a resistance of about 500 times and that of air film is about 13,000 times greater than a copper sheet of the same thickness. Thus, the resistance offered by these films (though it is thin) is large for the heat flow. Beyond these films, the turbulence brings about rapid equalization of temperature.

Therefore, the resistance offered by the boundary film is of importance in the flow of heat, particularly in the evaporation process.

Forced Convection–Temperature Variation–Individual Heat Transfer Coefficients

Mixing of a fluid may be obtained by the use of a stirrer or agitator or pumping the fluid for recirculation. Such a process in heat transfer is designated as *forced convection*.

Forced convection is obtained in some types of tube evaporators, wherein the evaporating liquid is forced through the tubes under pressure.

In a heat transfer process, the overall coefficient depends upon many variables. It is necessary to break them into individual parts. The

temperature distribution across a column of fluid that is being heated (or cooled) is related to the velocity distribution across the same column of fluid.

Consider a case of heat flowing from a hot fluid through a metal wall into a cold fluid. At a specific point, the variation of temperature on each side of the metal wall is depicted in Figure 5-4. Several important facts are evident from Figure 5-4, as listed below.

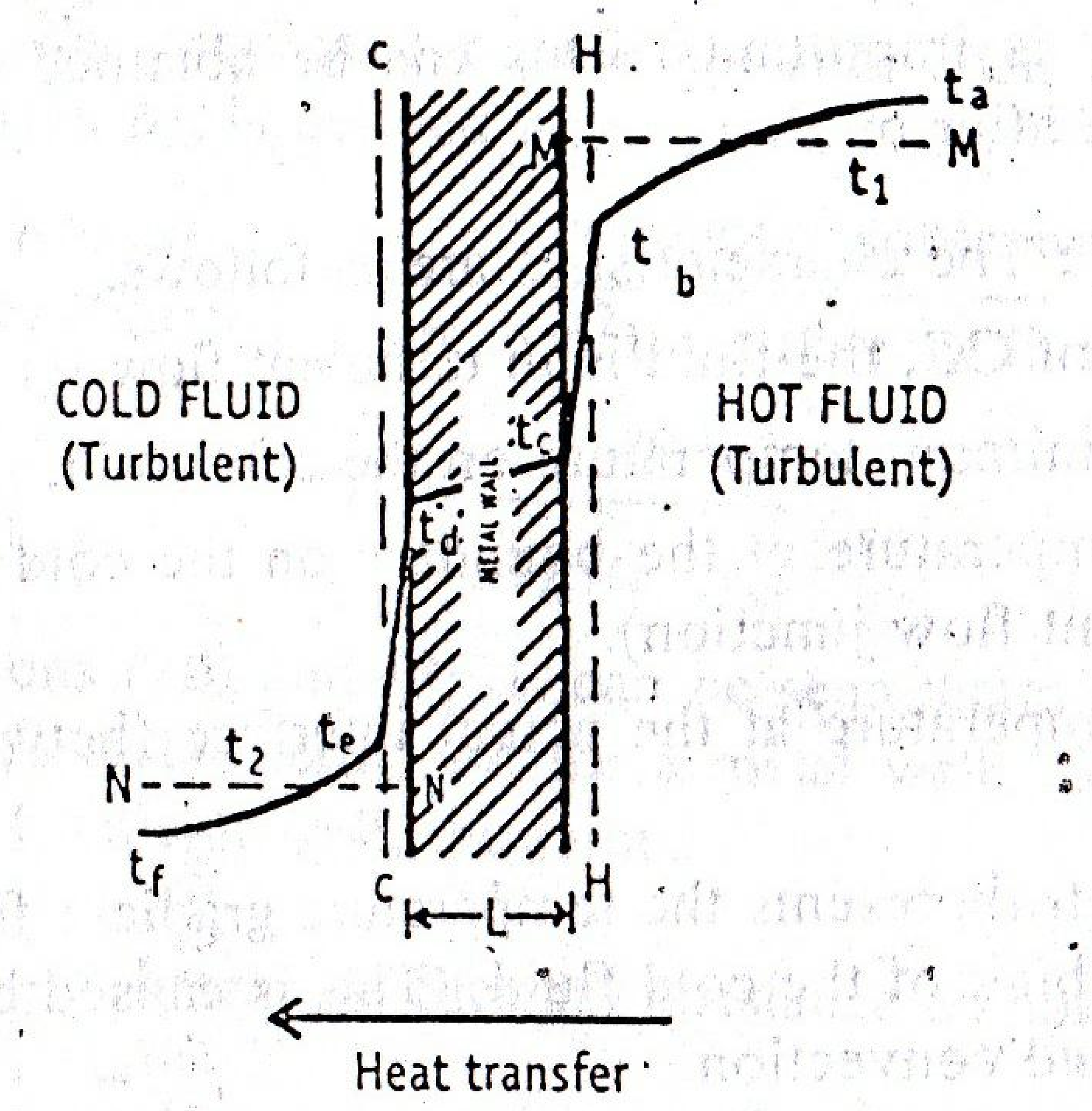


Figure 5-4. Temperature gradients in forced convection, while heat is flowing from a hot fluid to a cold fluid through a metal wall.

Metal wall : The characteristics are as follows.

(1) Dotted lines HH and CC represent the boundaries of the films in viscous flow on the hot and cold sides, respectively, on each side of the metal wall.

(2) The temperature gradient through the line $t_c t_d$ is caused by the flow of heat purely by conduction through the metal whose thermal conductivity is known.

(3) Metal wall thickness is *L*.

Hot fluid side : The characteristics are as follows.

(1) To the right of HH, the fluid is in turbulent flow on the hot side.

(2) t_a is the maximum temperature in the hot fluid.

(3) t_b is the temperature at the boundary on the hot side (turbulent and viscous flow junction).

(4) t_c is the temperature at the actual interface (between fluid and solid surface).

(5) Curve t_a t_b t_c represents the temperature gradient from the bulk of the hot fluid to the metal wall. This is caused by the flow of heat in forced convection.

(6) t_1 is the average temperature on the hot fluid side represented by the line MM. In general, for heat transfer calculation, average temperature is important. This can be obtained by taking its temperature after mixing.

Cold fluid side : The characteristics are as follows.

(1) To the left of CC, the fluid is in turbulent flow on the cold side.

(2) t_f is the minimum temperature on the cold fluid.

(3) t_e is the temperature at the boundary on the cold side (viscous and turbulent flow junction).

(4) t_d is the temperature at the actual interface (between fluid and solid).

(5) Curve t_d t_e t_f represents the temperature gradient from the metal wall to the bulk of the cold fluid. This is caused by the flow of heat in forced convection.

(6) t_2 is the average temperature on the cold fluid side represented by the line NN. In general, for heat transfer calculation average temperature is important. This can be obtained by taking its temperature after mixing.

Surface or film coefficients : In forced convection, the stagnant films (HH and CC) are of great importance in determining the rate of heat transfer. Though these films are thin, the resistance offered by them is large. Beyond these films, the turbulence brings about rapid equalization of temperature.

Film coefficient is the quantity of heat flowing through unit area of the film for unit drop in temperature.

It is the conductive capacity of the stagnant film for the transfer of heat.

It is difficult to determine the thermal resistances of fluid films, since thicknesses of the films cannot be known precisely. The thickness of the film depends not only on viscosity of the fluid, but also on the fluid circulation level (forced convection). Hence, the resistance offered by these films cannot be individually calculated. Therefore, indirect method of computation of surface coefficients is employed.

Let q watt (joules per second) of heat is flowing from hot fluid to cold one. Same heat must pass through stagnant fluid film on the hot side, through the metal wall and through the stagnant film on the cold side. Let the following be the characteristics.

Area of the metal wall on the hot side = A_1, m^2
Area of the metal wall on the cold side = A_2, m^2
Average area of the metal wall = A_m, m^2

Surface or film coefficient on the hot side : On the hot side, the surface coefficient, h_1, is defined as:

$$\text{Film coefficient on the hot side } (W/m^2 \cdot K) = \frac{\text{amount of heat flowing (W)}}{\text{area } (m^2) \times \text{difference in temperature (K)}}$$

$$h_1 = \frac{q}{A_1 (t_1 - t_c)} \qquad (20)$$

From equations (20) and (7), it can be seen that surface coefficient (h_1) is analogous to the term, k/L for a metal wall. Since L/kA is the resistance term for metal wall, the term:

$\frac{1}{h_1 A_1}$ is known as thermal resistance on hot side.

The thermal resistance is due to the combined effect of the viscous film HH and the turbulent core. This resistance caused the difference in temperature, $t_a - t_b$.

Surface or film coefficient on the cold side : Film coefficient on the cold side can be written on similar lines as:

$$\text{Film coefficient on the cold side} = \frac{\text{amoun of heat flowing}}{\text{area} \times \text{difference in temperature}}$$

$$h_2 = \frac{q}{A_2 (t_d - t_2)} \qquad (21)$$

And,

$\frac{1}{h_2 A_2}$ is known as thermal resistance on cold side.

Overall coefficient : In the over all heat transfer, three resistance terms are involved in series.

$\frac{1}{h_1 A_1}$ is the resistance on the hot fluid side.

$\frac{L}{k A_m}$ is the resistance of the metal wall.

$\frac{1}{h_2 A_2}$ is the resistance on the cold fluid side.

Applying the principle of compound resistance in series, the overall heat transfer may be written as:

$$q = \frac{\Delta t}{\frac{1}{h_1 A_1} + \frac{L}{k A_m} + \frac{1}{h_2 A_2}} \qquad (22)$$

If both numerator and denominator of the right side of equation (22) are multiplied by A_1, equation (23) is obtained.

$$q = \frac{A_1 \Delta t}{\frac{1}{h_1} + \frac{L A_1}{k A_m} + \frac{A_1}{h_2 A_2}} \qquad (23)$$

Then, the overall heat transfer coefficient U_1 (W/m²·K) is defined by equation (24)

$$U_1 = \frac{1}{\frac{1}{h_1} + \frac{L A_1}{k A_m} + \frac{A_1}{h_2 A_2}} \qquad (24)$$

If equation (24) is compared with equation (23), it is apparent that:

$$q = U_1 \Delta t A_1 \qquad (25)$$

Equation (25) states that

Rate of heat transfer = overall heat transfer coefficient × area of the heating surface × temperature drop (26)

For a tubular wall : The above derivation (equation (24)) is based on the metal wall of thickness, L. This relationship may be extended to a tubular metal wall. The heat coefficients may be written in terms of diameter (metre), since area is proportional to the corresponding tube

diameter. The overall heat transfer coefficient for a tubular metal wall may be written as:

$$U_1 = \frac{1}{\frac{1}{h_1} + \frac{L D_1}{k D_m} + \frac{D_1}{h_2 D_2}} \qquad (27)$$

In some cases, one particular area is more convenient than the other. Suppose $h_2 >> h_1$, the $(D_1/D_2 h_2)$ becomes small in comparison to $(1/h_1)$. Similarly, resistance of the tube wall is also small in comparison with $(1/h_1)$. Hence, ratios (D_1/D_m) and (D_1/D_2) have very little significance and can be disregarded. Then, equation (27) becomes:

$$U_1 = \frac{1}{\frac{1}{h_1} + \frac{L}{k} + \frac{1}{h_2}} \qquad (28)$$

Equation (28) can be used in cases of:

(a) thin walled tubes with larger diameter
(b) thin walled plates

In these cases, area A can be used for A_1, A_m and A_2, since errors will be negligible. In such cases,

$$U_1 = U_m = U_2 \qquad (29)$$

When h_1 is very small compared to h_2 and (L/k), $(1/h_1)$ will be larger. Therefore these two terms in the denominator are disregarded. Then

$$U_1 = h_1 \qquad (30)$$

Thus, rate of heat flow from one fluid to another through the retaining wall can be simplified. Hence, numerical value of surface coefficients can be predicted easily.

Factors influencing film coefficients : Several factors influence the surface film coefficients. However, the factors that are widely applied in practice are a few with reference to the processing conditions. These are:

- Thermal conductivity of the liquid
- Specific heat of the film
- Density of the liquid
- Turbulence of the fluid
- Thickness of the film

If the films are thin, their resistances will be reduced. This can be achieved by increasing the speed of the steam on one side and the speed of liquid on other side.

Fluids in Natural Convection

When a fluid is heated, the currents set up may cause mixing of fluid. Such a heat transfer process is known as *natural convection.*

The mechanism of natural convection is depicted in Figure 5-5. Consider a case of single horizontal cylinder. A large volume of fluid is present surrounding the cylinder. When a fluid is in contact with a hot surface, the fluid that is immediately adjacent to the tube absorbs heat. The temperature of this part of the fluid increases, which in turn decreases the density. As a result, the fluid rises from the surface and is replaced by the cold fluid. This process continues thereby effecting the mixing of hot and cold fluids.

Fluid circulation caused by changes in the densities due to temperature differences in the fluid is termed as *natural convection.*

Fluid circulation also changes with:

- geometry of the system, i.e., size, shape and arrangement of heating surface.
- shape of the vessel in which the fluid is enclosed.

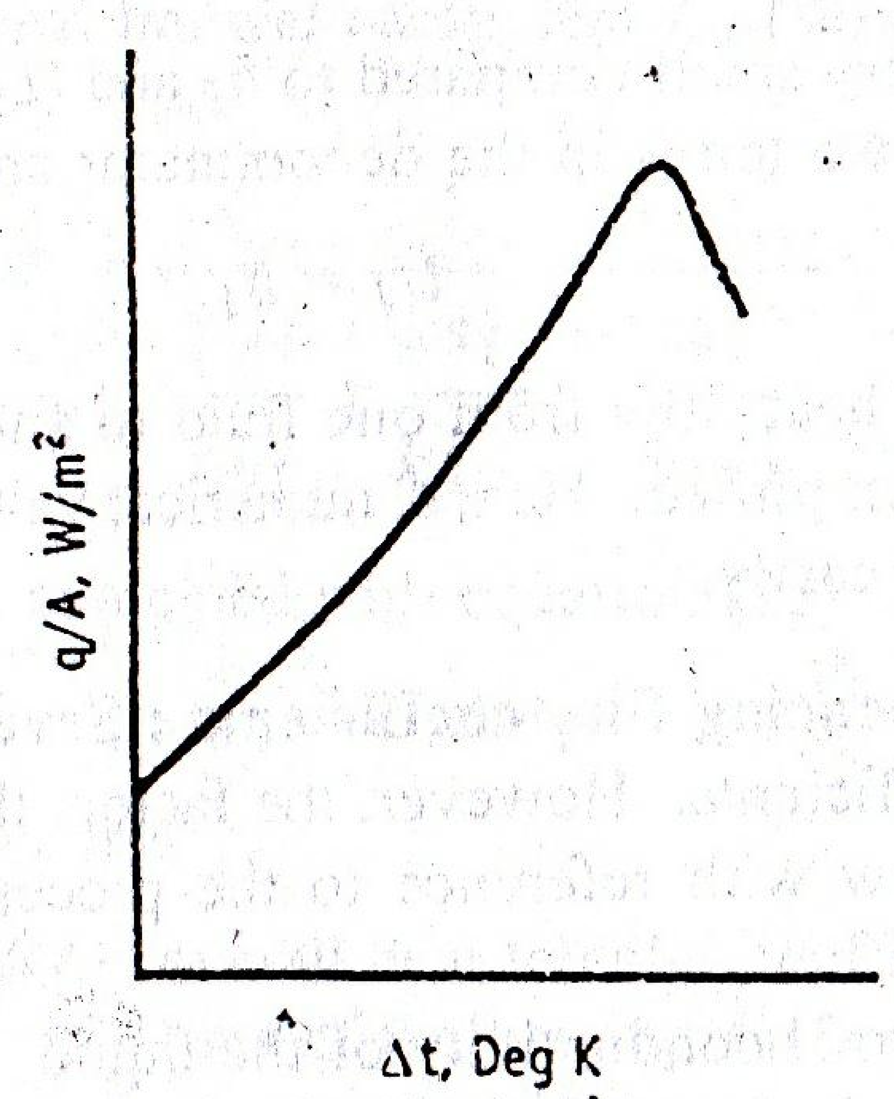


Figure 5-5. Mechanism of heat transfer in natural convection.

The physical properties of the system are individually evaluated at the mean film temperature. Generally, hot bodies lose heat to their

surroundings both by radiation and by convection. At lower temperature ranges, convection is more predominant, while radiation is important at higher temperature ranges. In practice, liquid film coefficients may vary from 10 to 200 depending on the arrangement of apparatus and the viscosity of the liquids.

Application : Natural convection is observed when extracts are evaporated in open pans.

Changes in Fluids during Heat Transfer

In heat transfer by convection, two liquids are involved. The hot liquid gives heat, while the cold liquid receives it. Each liquid undergoes changes during heat transfer. Steam condenses to give heat, while the cold liquid boils.

Hot liquid–Steam boiler : Steam is generated in a central boiler house at high pressure. The following are the advantages.

(1) High pressure steam can be used to drive a turbine for generating electric power.

(2) Low pressure exhaust steam is used for process heating.

(3) Central generation is more economical.

(4) More steam is stored in a boiler if high pressure is applied.

(5) High pressure steam means high temperature.

Characteristics of the steam : (1) Steam should be as dry as possible, thereby heat losses can be minimized.

(2) Since the latent heat is the useful heat, steam should be used at the lowest pressure that will give a suitable temperature gradient.

(3) Steam should be pumped at its saturated temperature. Superheated steam should not be used.

(4) Steam should be replaced continuously so that the process proceeds indefinitely.

Hot liquid–condensing of vapour : Steam gives its heat of vaporisation during condensation. This heat is transferred to the cold liquid through a metal wall.

In a heater, steam is passed through the tubes or outside the tubes. In each case, the metal surface of the tube gets heated up. While transmitting heat to a metal surface, the saturated vapour condenses into two distinct forms based on the nature of wetting of the metal surface. These are as follows.

Film type condensation : In this type, the condensed liquid wets the surface on which it is condensing and forms a continuous film of condensate.

If condensation is occurring on the outside surface of a horizontal metal tube (a very common case), this film of condensate drops off beneath the tube. If the tube is vertical, then it runs down the whole length and drops off from the edge. Generally, smooth and clean surfaces tend to form film type. For film type condensation the film coefficients are low. Equations have been proposed for heat transfer calculations.

Drop-wise condensation : In this type, the condensed liquid collects as drops that may range from microscopic size up to drops that are seen with the naked eye.

If the condensed liquid does not wet the surface, the drops grow and then fall off the surface, leaving an apparent bare area on which new drops form. Normally, oily or greasy surfaces tend to induce drop-wise condensation. The coefficients for drop-wise condensation may be double or more than double that of film type under identical conditions. It is difficult to estimate the coefficients of heat transfer for drop-wise condensation.

In general, the film coefficient between condensing vapour and metal wall increases with increasing temperature of vapour. Film coefficients decrease with increasing temperature drop. When steam is employed as a source of heat, it is necessary to remove non-condensable gases. Otherwise, they reduce the film coefficients, because of their accumulation.

Cold liquid–boiling of liquids : When heat is supplied to a liquid, it boils and the vapour pressure increases. This process continues until the vapour pressure is equal to the atmospheric pressure. At this stage, the temperature of the liquid remains constant, which is known as boiling point. Generally, heat is supplied to a liquid through a heater by passing steam.

Consider a horizontal tube, which is immersed in a pool of pure liquid. Steam is passed through the tube. The heat transfer depends on the differences in temperatures on each side of the tube wall. The relationship between temperature differences and heat transfer coefficients in liquids (boiling outside the horizontal tube) is shown in Figure 5-6. Δt may be defined as:

Δt = tube wall temperature–saturated temperature of liquid (= vapour pressure in spaces)

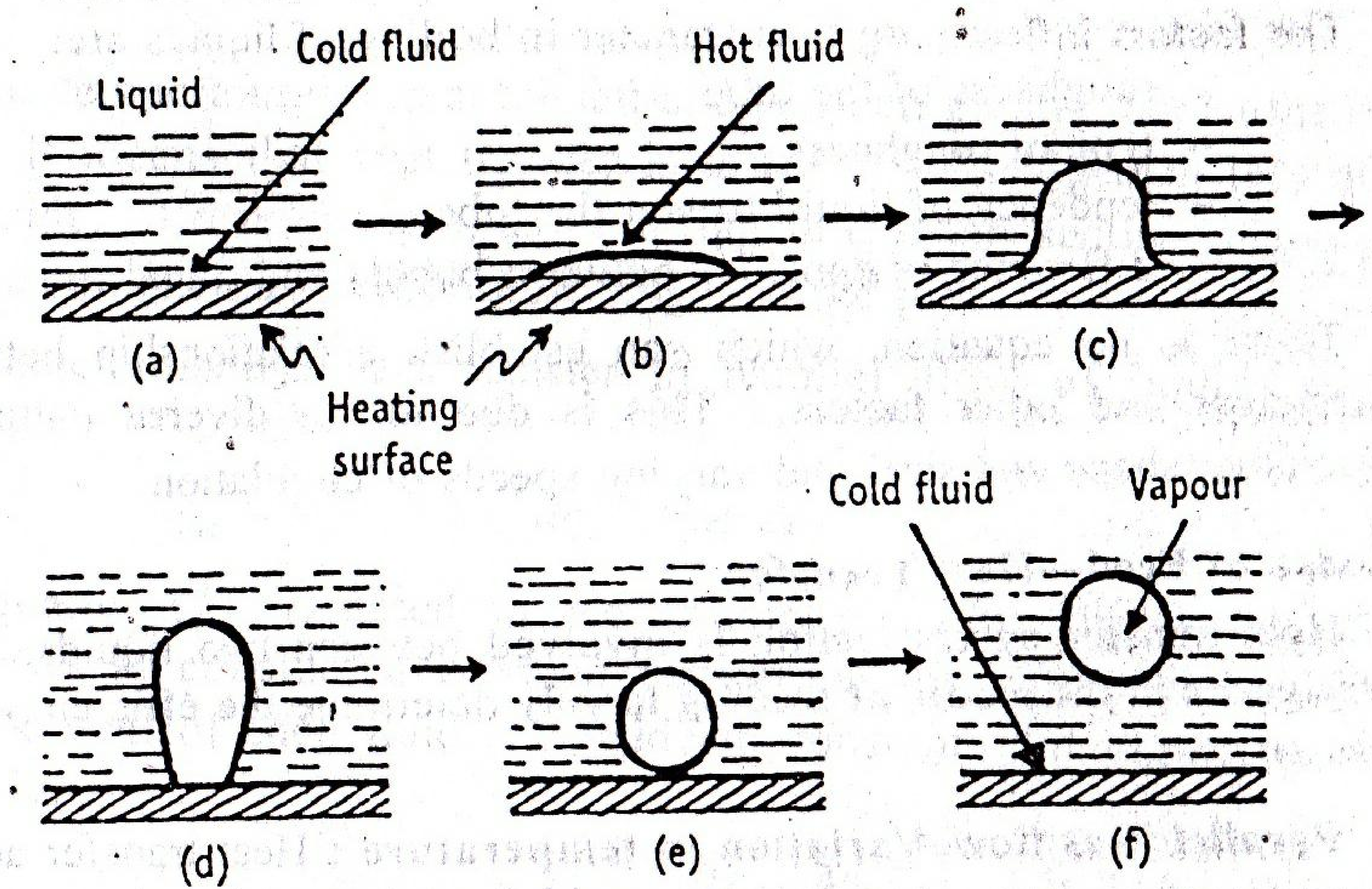


Figure 5-6. Effect of temperature difference on the behaviour of a liquid boiling outside the horizontal tube.

The following conclusions may be drawn from Figure 5-6.

(1) If Δt is very small, the rate of heat transfer (q/A) is not much. Hence, liquid doesn't boil.

(2) If Δt is increased, the rate of heat transfer (q/A) will be increased, because heat transfer coefficient increases rapidly. The mechanism is as follows. The heated liquid at the wall forms bubbles of vapour and gets detached from the surface. These vapour bubbles rise through the liquid. This type of boiling is called *nucleate boiling*. The cold fluid now wets the tube wall. Thus bubbles produce a series of currents, which have a stirring effect.

(3) If Δt is increased further, the surface temperature increases continuously up to a point, where the heat transfer coefficient reaches a maximum. This temperature is known as *critical* Δt. At this stage, the bubbles begin to coalesce into a continuous film of vapour, which insulates the tube.

(4) Beyond critical Δt, further increase in Δt leads to lowering of heat transfer coefficients rapidly. The continuous film of vapour insulates the tube, thereby the effective Δt fails to increase. Thus rate of heat transfer is decreased.

For some organic liquids, the heat transfer coefficient may decrease rather slowly after critical Δt. Therefore, maximum heat flux may occur at higher Δt than the maximum coefficient.

The factors influencing heat transfer in boiling of liquids are:

- roughness of the tube
- type of roughness
- tendency of liquid to wet the tube
- difference in densities between bubble and liquid

There is no equation, which can establish a relationship between coefficient and other factors. This is due to the diverse nature of apparatus (shape and size) and varying speeds of circulation.

Modes of Feed—Heat Transfer

Heat transfer by convection is involved between two liquids. The differences in the modes of feeding largely determine the efficiency of a heat process.

Parallel heat flow–Variation in temperature : Heat transfer across a metal surface from a hot fluid to a cold fluid depends on the temperature gradient (Δt). Generally, it is assumed to be constant for all parts of heating surface.

When the hot fluid and the cold fluid enter the apparatus from the same end, the flow is parallel to each other. This arrangement is known as *parallel flow*.

Consider a heat interchanger. The temperature of the hot fluid inside a pipe decreases from T_1 to T_2 by transferring heat to a cold fluid outside the pipe. As a result, the cold fluid temperature is increased from t_1 to t_2. This condition is represented in Figure 5-7.

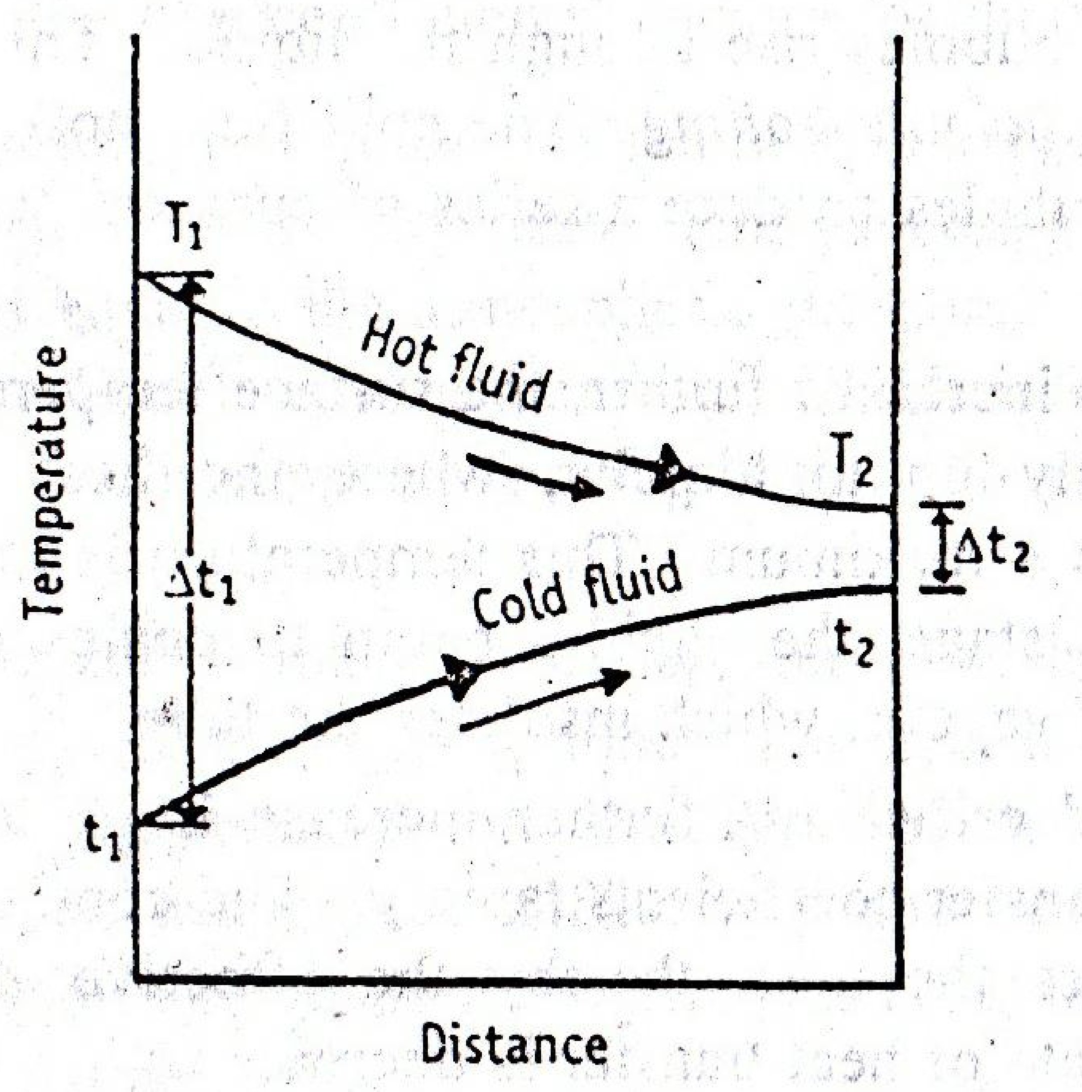


Figure 5-7. Temperature difference in parallel-current heat flow.

The temperature-drop at the left-end is much greater than at the right-end. It means that heat transfer is faster at left-side than that of the right-side. These changes, as occurring in a small section of the pipe can be considered for the whole length of the pipe.

Mathematically, heat transfer in parallel flow of liquids can be written as:

$$dq = U.A.\Delta t \qquad (31)$$

Equation (31) is based on two assumptions. (a) The overall coefficient (U) is considered constant throughout the equipment. (b) The specific heat of each fluid is considered constant. Integrating equation (31) gives:

$$q = UaL\frac{\Delta t_1 - \Delta t_2}{\ln\dfrac{\Delta t_1}{\Delta t_2}} \qquad (32)$$

where L = length of pipe, m
a = area of the pipe, m^2

Comparing equation (32) with the general equation of heat transfer (equation 25) gives:

$$\Delta t_m = \frac{\Delta t_1 - \Delta t_2}{\ln\dfrac{\Delta t_1}{\Delta t_2}} \qquad (33)$$

Thus logarithmic mean temperature difference (Δt_m) is used. The total heating surface (A) is equal to aL. Heat transfer equation in parallel flow heat exchanger is:

$$q = UA\Delta t_m \qquad (34)$$

The logarithmic mean temperature difference is used to account varying temperature drop in parallel flow. If the temperature drop is nearly equal ($\Delta t_1 \cong \Delta t_2$), then arithmetic average temperature (Δt_m) can be used, which is a general expression for heat transfer.

In parallel heat flow, the heating obtained per unit surface area is much less effective at the fluid exit point compared to it at the point of entrance of the apparatus.

Counter-current heat flow–temperature gradient : When the hot fluid is passed through one end of the apparatus while cold fluid is passed through the other end, fluids pass and by pass each other in the opposite directions. This arrangement is known as *counter-current* or *counter-flow*.

The temperature gradients for the counter-current flow are shown in Figure 5-8.

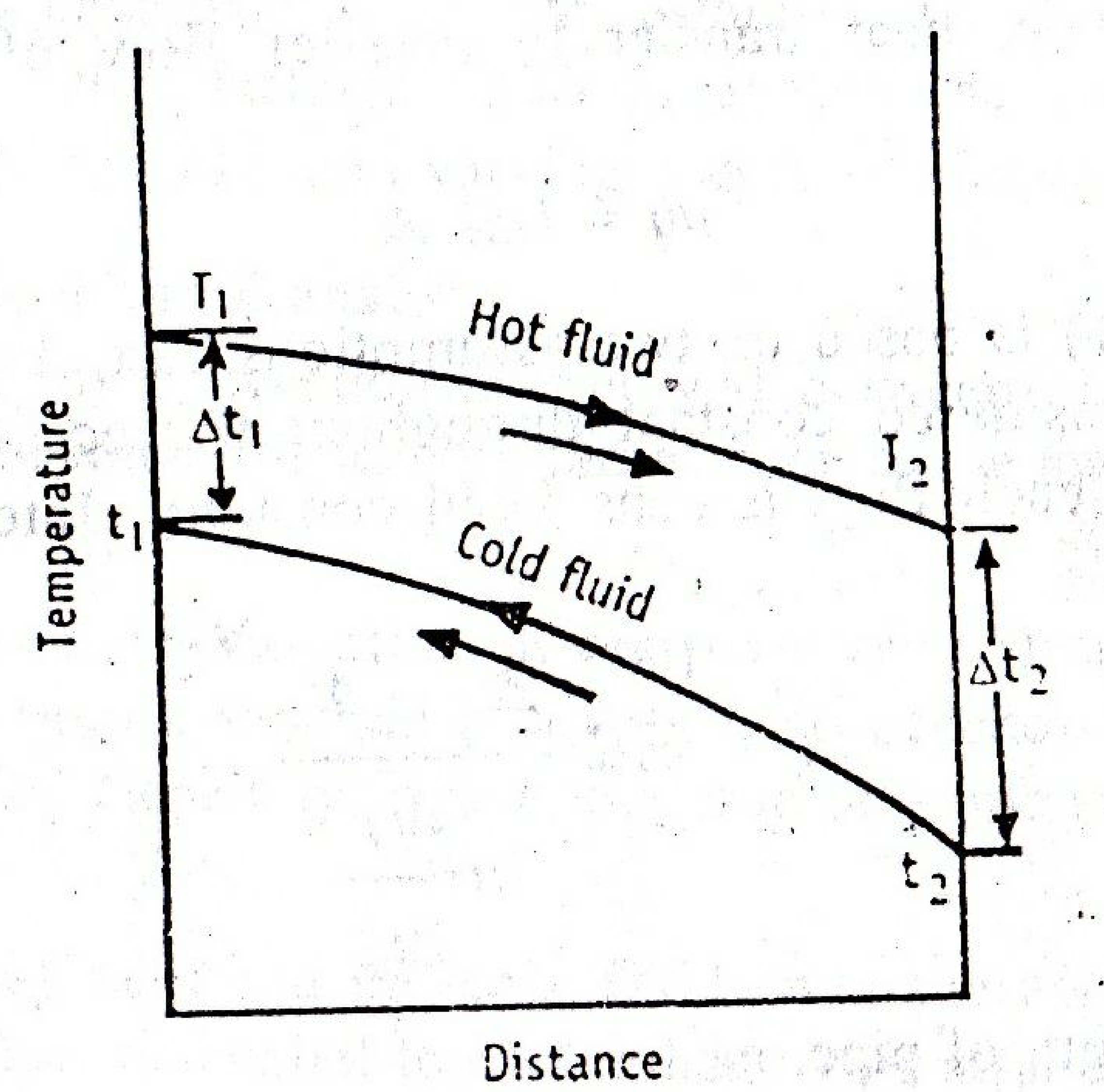


Figure 5-8. Temperature difference in counter-current heat flow.

From the Figure 5-8, it can be concluded that the temperature drop along the length of the apparatus is nearly constant. In other words, amount of heat transfer per unit area is substantially same at both ends. The heating surface is nearly constant throughout the apparatus.

In counter-current heat flow, the exit temperature of the hot fluid is considerably less than the exit temperature of the cold fluid. Hence a large proportion of the heat content of the hot fluid can be extracted for a given entrance temperature of the cold fluid. If $\Delta t_1 \cong \Delta t_2$, temperature ($\Delta t$) can be taken as arithmetic average.

$$\Delta t_{av} = \frac{\Delta t_1 + \Delta t_2}{2} \tag{35}$$

The heat transfer equation for counter-current heat flow can be written as:

$$q = UA.\Delta t_{av} \tag{36}$$

Consider a case, where steam is transferring its heat to a colder body. Let the pressure difference in steam be constant. The temperature difference when steam is in a heat exchanger is shown in Figure 5-9.

Initially steam cools down to the condensing temperature as indicated by AB in Figure 5-9. Then condensation occurs at constant temperature (section BC), and may further be allowed to cool (section CD). Here large errors would be introduced, if AF and DE are taken for Δt_1 and Δt_2, respectively. Separate heat transfer calculations must be done for the three sections in Figure 5-9 and then are added.

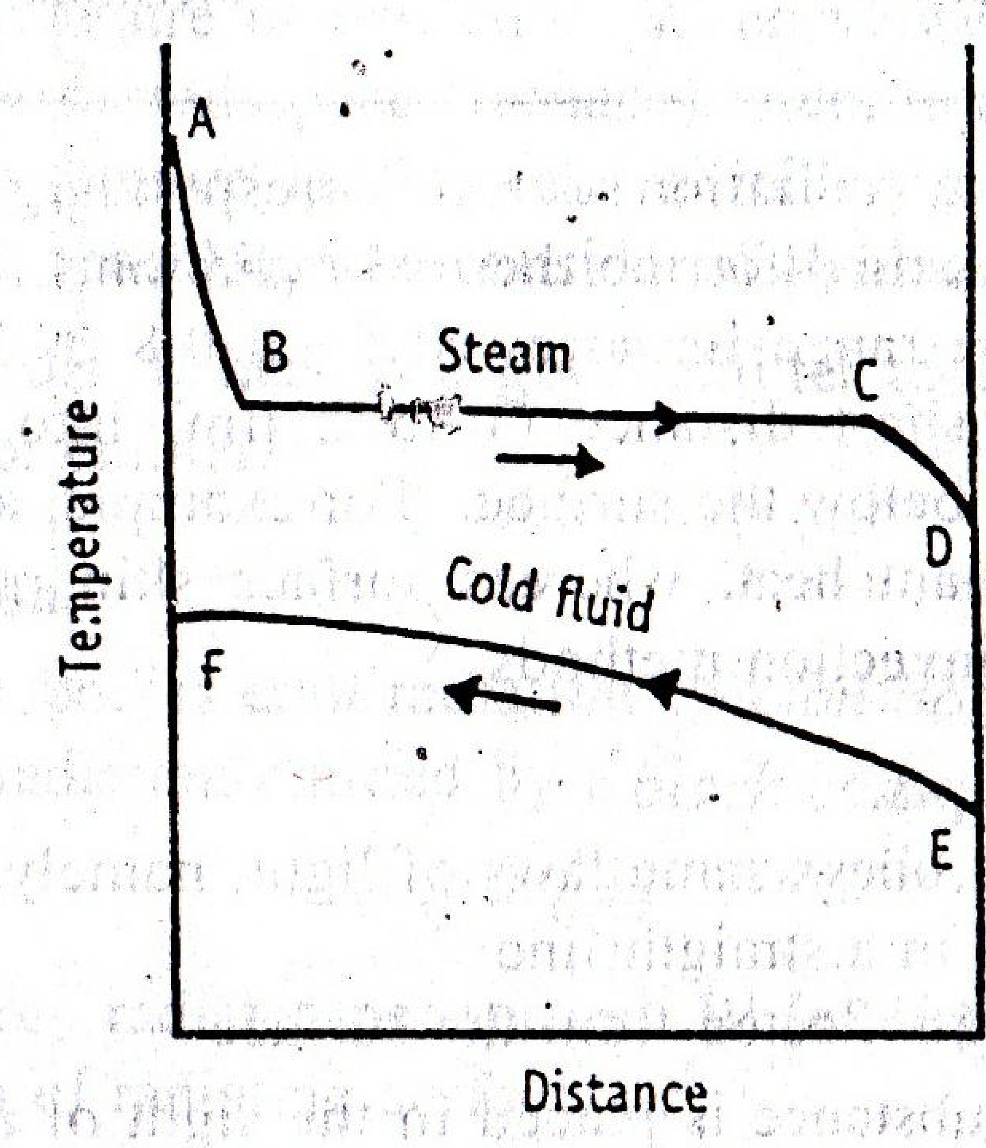


Figure 5-9. Temperature difference in counter-current heat flow in which steam is used as the heating medium.

RADIATION

Radiation is a process in which heat flows. Heat is transferred through space by means of electromagnetic waves.

Thermal Radiation

Heat transfer by radiation is known as *thermal radiation*.

Radiation is effective across perfect vacuum and also through layers of air.

All solid bodies radiate energy when their temperatures are above the absolute zero. A solid surface emits radiant energy continuously and distributes over all wavelengths (i.e.. from zero to infinity), although a major portion is concentrated within a relatively narrow range of wave-lengths.

Heat transfer (thermal energy) is predominant as the temperature of the body increases. The amount and kind of thermal energy radiated increases rapidly with temperature. Thermal radiation usually occurs simultaneously with heat transfer by convection and conduction.

Various Forms of Emitters

Various forms of emitters used for the supply of radiant energy are given below:

Radiation source	*Wavelength*	*Applications*
IR lamp (1000°C)	1 μm	high intensity radiation.
Ceramic rods and panels heated by gas or electricity (500° to 300°C).	2 to 4 μm	Pharmaceutical purposes, thermolabile substances.

Advantages : The radiation source corresponding to wavelengths from 0.8 to 400 μm is used for the thermal radiation. For most cases of industrial interest, the range is narrowed from 0.8 to 25 μm. Radiant energy penetrates a short distance (1 to 2 μm) into materials. The heating effect occurs below the surface. For example, a film of solution can be dried by radiant heat, whereas surface skin retards the drying process in case of convection methods.

Fundamental Concepts

Thermal radiation obeys same laws of light, namely—

(a) it travels in a straight line

(b) it may be reflected from the surface

Suppose a cold substance is placed in the sight of a hot body inside an enclosed space. The cold body intercept the radiation emitted by the hot body. The fraction of radiations falling on the body may be reflected, which is known as *reflectivity*, ρ. The fraction that is absorbed is known as *absorptivity*, α. The fraction that is transmitted is known as *transmissivity*, τ. The sum of these fractions must be unity or:

$$\alpha + \rho + \tau = 1$$

In practice, reflected and transmitted radiations usually fall on other absorptive bodies. The absorbed radiation is transformed into heat. This fraction is not available for the emission of radiation.

Black Body

All solid bodies radiate energy at a temperature above the absolute zero, however, not at the same rate. For the purpose of heat transfer, a theoretic substance is proposed and designated as black body.

Black body is defined as a body that radiates maximum possible amount of energy at a given temperature.

No physical substance is a perfect black body. The black matte surface approaches a black body, when visible light (rays) alone is considered. Light coloured substances deviate widely from it. Black surfaces are better emitters of heat radiation than polished surfaces.

Further the term 'black' is nothing to do with the colour of the body. Similarly it has nothing to do with the amount of energy it radiates.

In theory, a black body is considered to be an enclosed space with a small (negligible) opening. The temperature in the enclosed space should be constant and uniform, because the amount of energy escaping through a small opening is negligible. In practice, a convenient black body is made from a tube of carbon. Both the ends are plugged, with a small hole at the centre of one end. When viewed through this small hole, the inside enclosed space (furnace) is considered as a black body, provided the temperature is uniform. Similarly all objects within the furnace (enclosed space) can be considered as black bodies.

A good absorber of heat is a good emitter too. Conversely a poor absorber is a poor emitter.

Rate of Radiation

Normally, hot bodies emit radiation. *Stefan-Boltzmann law* gives the total amount of radiation emitted by a *black body*.

$$q = bAT^4 \qquad (37)$$

where q = energy radiated per second, W (or J/s)

A = area of radiating surface, m^2

T = absolute temperature of the radiating surface, K

b = constant, $W/m^2 \cdot K^4$

According to equation (37), the rate of heating depends upon the temperature and surface area of the emitter. At the same time, it also depends upon the absorption capacity of the material to be heated.

For a black body, the value of b is 5.67×10^{-8} $W/m^2 \cdot K^4$. Actual bodies do not radiate as much as the black body. Therefore, equation (37) is modified for the *actual bodies*

$$q = \varepsilon bAT^4 \qquad (38)$$

where ε is equal to the emissivity of the actual body. Emissivity may be expressed at the same temperature as:

$$\text{Emissivity, } \varepsilon = \frac{\text{energy emitted by actual body}}{\text{energy emitted by black body}} \qquad (39)$$

As per equation (39), emissivity is one for a black body. For actual bodies, ε is less than one, because a fraction of the radiation is absorbed, which appears as heat. The fraction of energy absorbed is denoted by absorptivity, α (other fractions are either reflected or transmitted).

A good absorber of heat is also a good emitter at a given temperature. If emissivity is equal to absorptivity ($\varepsilon = \alpha$), then a substance is considered as a black body. Since emissivity of a black body is 1, the absorptivity must be one. Therefore, the black body absorbs all the radiation falling on it.

Grey Body

Absorption of energy by a substance depends on its properties. Fairly high amount of energy will be absorbed by dark coloured, opaque and rough surface bodies. Least energy is absorbed by light coloured, transparent and smooth surfaced substances.

At a given temperature, the value of α varies somewhat with the wavelength of the radiation falling on it. This complicates the solving of problems in practice. Therefore, the concept of grey body has been introduced.

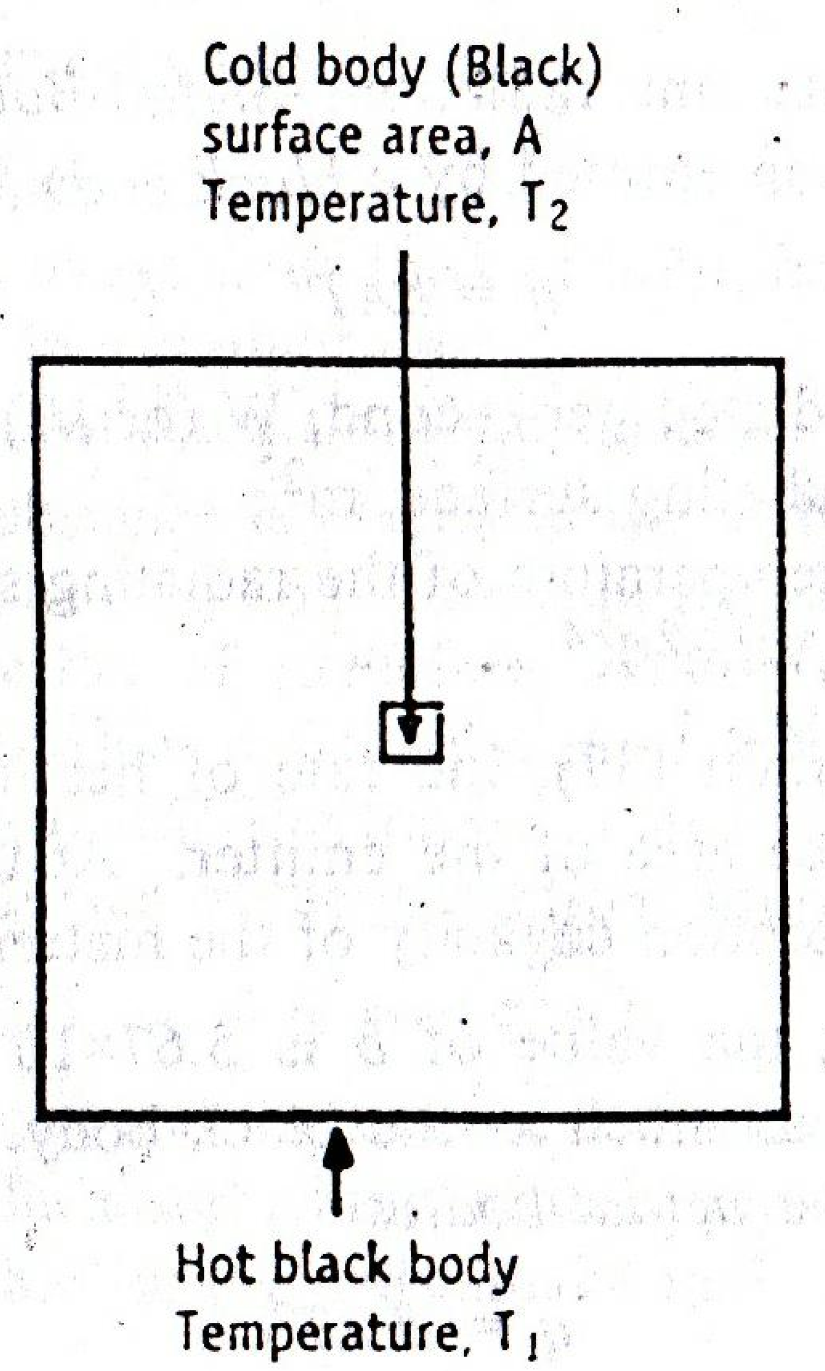


Figure 5-10. Heat transfer through radiation.

A *grey body* is defined as that body whose absorptivity is constant at all wavelengths of radiation, at a given temperature.

Consider a small cold body with a surface area of A and temperature of T_2 is completely surrounded by a hot black body at temperature T_1 (Figure 5-10). The amount of heat transferred in such a process is expressed by the Stefan law, which may be written as:

$$q = bA(T_1^4 - T_2^4) \qquad (40)$$

Equation (40) assumes that all the heat radiated by a cooler body also falls on the hotter body.

EQUIPMENT

HEAT EXCHANGERS AND HEAT INTERCHANGERS

Most of the chemical and pharmaceutical industries employ a variety of heat transfer equipment. The materials to be heated may be liquids or gases and occasionally solids (which is a separate case by itself). The heating media may be a hot fluid or condensed steam. Some of the processes, which involve the heat transfer encountered in pharmacy are:

- Preparation of starch paste (steam jacketed kettles) for granulation
- Crystallization
- Evaporation
- Distillation

In industrial processes, heat energy is transferred by various methods. The principles, construction and working of equipment used for the transfer of heat energy are as follows:

Heat exchangers : *Heat exchangers* are the devices used for transferring heat from one fluid (hot gas or steam) to another fluid (liquid) through a metal wall.

Heat interchangers : *Heat interchangers* are the devices used for transferring heat from one liquid to another or from one gas to another gas through a metal wall.

The classification given above is vague and many times used interchangeably. Therefore, it is appropriate to call them as heat transfer equipment.

Some of them are discussed in the following sections.

Heaters or Heat Exchangers

Heat exchangers are the devices used for transferring heat from one fluid (hot gas or steam) to another fluid (liquid) through a metal wall.

Some heat transfer (or heaters) equipment are:

(1) tubular heater (shell-and-tube heater)
(2) multipass heater
(3) two pass floating head heater

In heat exchangers, the film coefficients on the steam side are usually much larger than the film coefficients on the cold liquid side. Therefore, the overall heat transfer coefficients will be nearer to the cold liquid side (because it is smaller of the two coefficients). Hence, heat transfer becomes less. The efficiency can be improved by passing the liquid at a high velocity. As a result, the thickness and resistance of the liquid film decrease. Normally, the space outside the tubes is large, but steam velocity is low. Still heat exchangers are useful, because of the high values of the steam film coefficients.

Tubular heater (Shell-and-tube heater) : Shell-and-tube heater is the simplest form of a tubular heater. It is a single-pass tubular heater.

Construction : The construction of a simple tubular heater is shown in Figure 5-11. Tubular heater consists of a bundle of parallel tubes, which are relatively thin walled. The ends of these tubes are expanded into two tube sheets, B_1 and B_2. The bundle of tubes is enclosed in a cylindrical shell or casing, C, to which the tube-sheets are fitted. Many heaters have a cast iron shell.

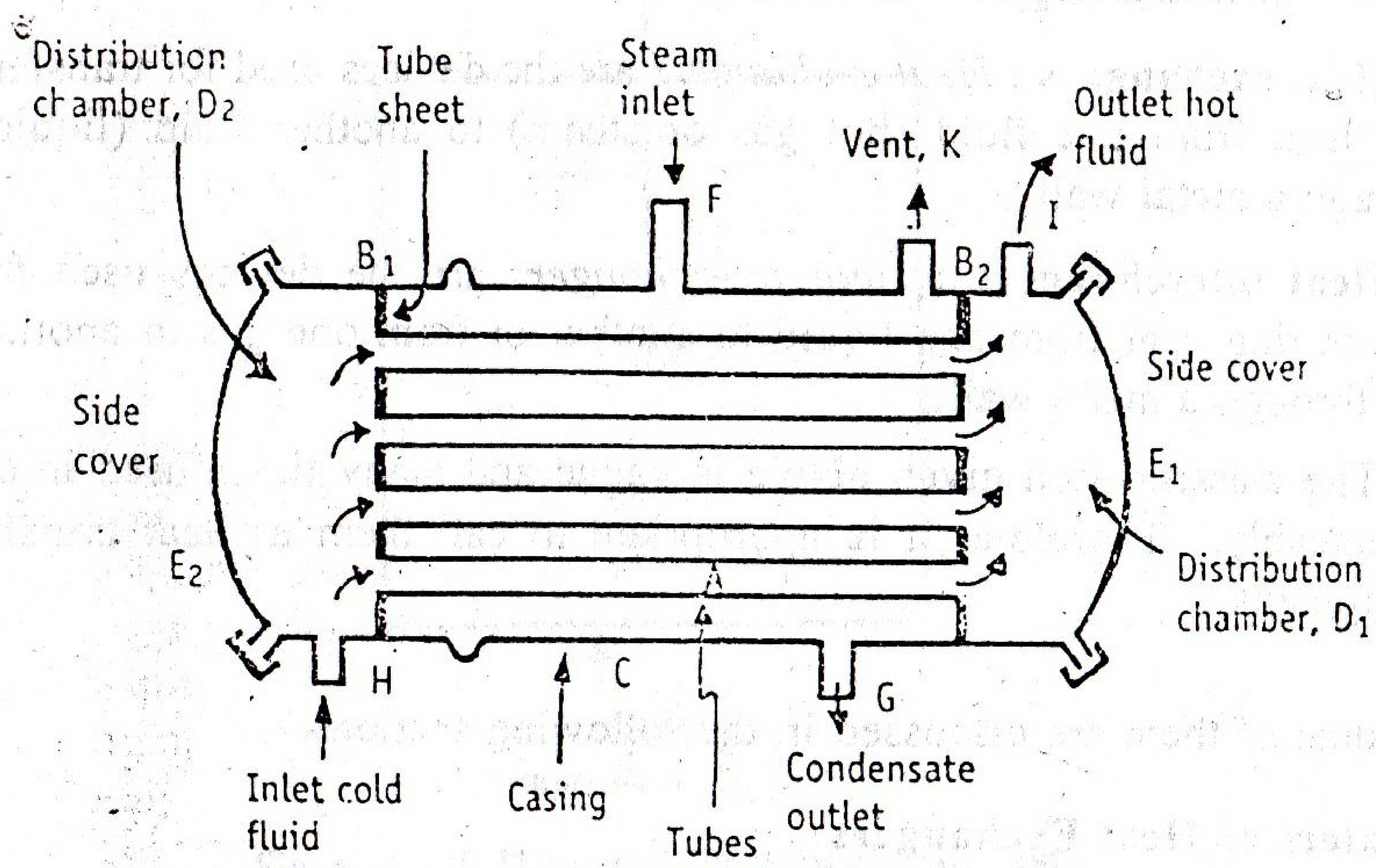


Figure 5-11. Construction of single-pass tubular heater.

Two distribution chambers, D_1 and D_2 are provided at each end of the casing C. Fluid inlet is provided to the distribution chamber D_2. The heated fluid outlet is provided to the distribution chamber D_1. Two covers, E_1 and E_2 are provided to close the distribution chambers from the sides. Steam or other vapour is introduced by a connection, F. Provisions are made for the escape of non-condensable vapour K and condensed vapour to drain at G.

Working : Steam or other vapour is introduced through a connection F into the space surrounding the tubes. The steam flows down the tubes. In this process, the tubes get heated. The condensed vapour is drained at G. Non-condensable gases, if any, escape through the vent K provided at the top of the casing.

The fluid to be heated is pumped through the connection H into distributing chamber D_2. The fluid flows through the tubes. The steam and fluid are physically separated, but are in thermal contact through the thin tube walls. The fluid in the tubes get heated due to heat transfer by conduction through the metal wall, followed by stagnant layer and finally by convection. The total heat transfer is effected by single pass of fluid. Thus, the heated fluid reaches the distributing chamber D_1 and leaves through the exit point, I

In the sheet-and-tube heater, the cross sectional area of the tubes is larger. Hence, the velocity of the fluid inside the tubes is low.

Advantage : In single-pass tubular heater, large heating surface can be packed into a small volume.

Disadvantages : (1) The velocity of fluid flowing in these tubes is low, because of large cross-sectional area or larger surface.

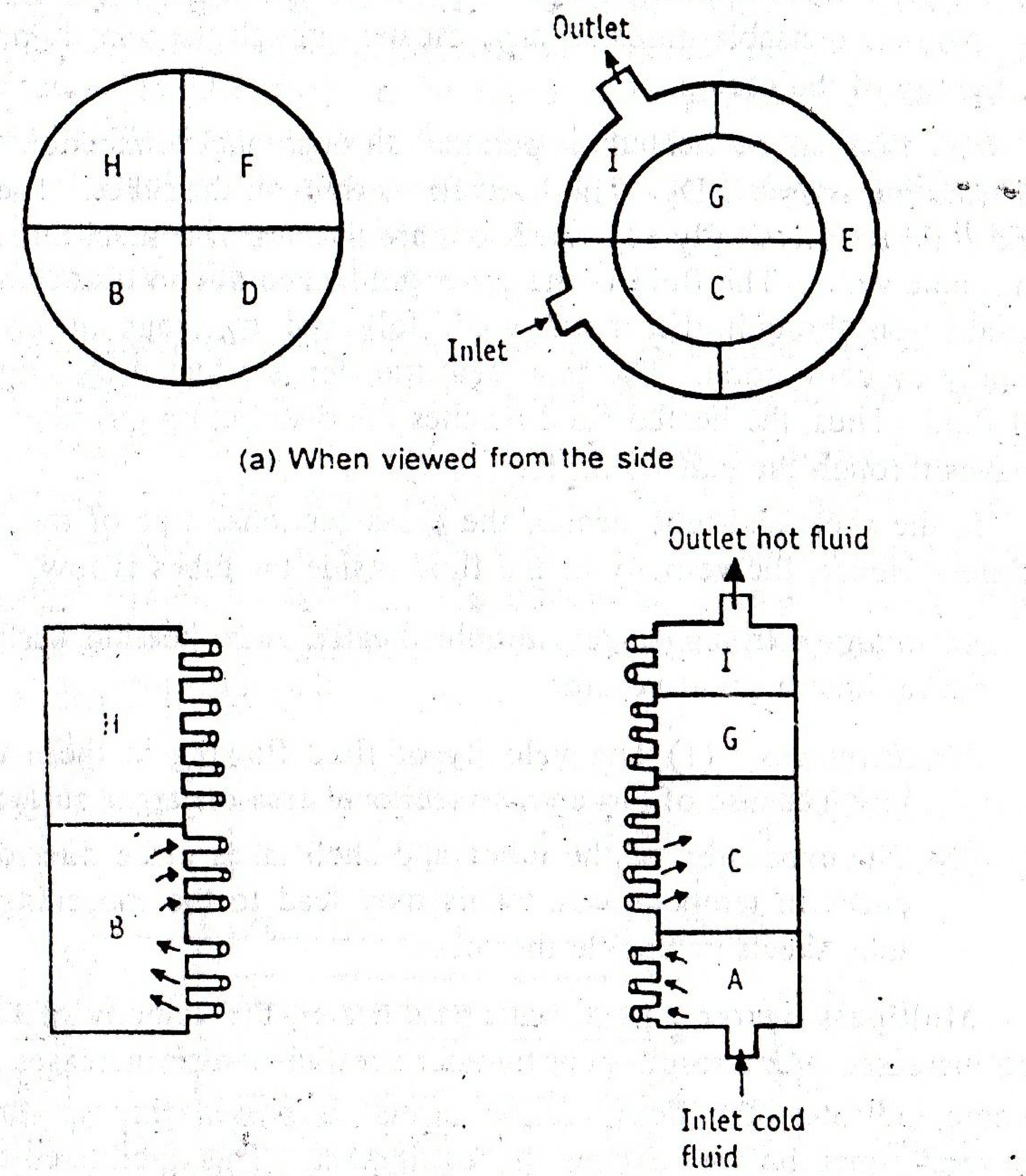
(2) The expansion of the tubes and shell takes place due to differences in temperatures. This may lead to the loosening of the tube sheets or buckle the tubes.

Multipass heater : In a multi-pass heater, the velocity of fluid can be increased. As a result, heat transfer coefficient also increases. As the name indicates, the liquid to be heated is passed through the tubes several times before leaving the equipment. This facilitates the heat transfer. Therefore, multipass tubular heaters are superior to the single-pass shell-and-tube heaters.

Construction : The construction of a multipass heater is same as tubular heater mentioned above, however, with some modifications (Figure 5-12).

Tubular multipass heater consists of a bundle of parallel tubes. The ends of these tubes are expanded into two tube sheets. The tubes bundle is wrapped in a cylindrical casing. Two distribution chambers are provided at each end of the casing. Since the heater is multipass, the same liquid has to flow through several tubes back and forth. In order to facilitate this process, distribution chambers are partitioned by means of baffles and their arrangements are different in the two chambers (Figure

5-12). The entrance and exit points of the fluid are arranged in the same distribution chamber (right side).



(a) When viewed from the side

Left-side distribution chamber (partitions F and D are below the page)

Right-side distribution chamber (Partition E is below the page)

(b) When viewed from the front

Figure 5-12. Construction of a multipass heater. In this figure, the modifications of distribution chambers and partitions are shown.

Working : Steam is introduced through the connection into the space surrounding the tubes. As the steam flows down, the tubes get heated. The condensed vapour is drained. Non-condensable gases, if any, escape through the vent provided at the top of the casing.

The fluid to be heated is pumped at high velocities into the right distribution chamber through the compartment, A. High velocity facilitates the effective heat transfer. In this construction, fluid is directed to

enter only a fraction of the tubes by means of baffles placed in the distribution chamber.

The liquid enters compartment A and flows to the left into compartment B, back to the right to compartment, and so on in the same sequence of alphabetical order. During this process, fluid in the tubes get heated, due to heat transfer by conduction through the metal wall, followed by a stagnant layer and finally by convection. The net result is enhanced rate of heat transfer. Thus, the fluid passes back and forth through the several tubes and then leaves the equipment at I.

If the fluid is to be introduced at high velocities, pumping should be effective, which increases the cost of the power, though the cost of heater is low. Too low a velocity saves power for pumping, but needs a very large heater. Therefore, a balanced approach should be worked out based on economy.

Advantages : Multipass construction decreases the cross section of the fluid path, thereby increases the fluid velocity. Thus, multipass tubular heaters are superior to the single-pass shell-and-tube heaters.

Disadvantages : (1) The fabrication of a multipass heater is more complicated. (2) The pressure-drop through the apparatus is increased, because of enhanced velocity of fluid flow. (3) More number of exit and entrance points increase the friction losses. This increases the cost of pumping of fluid.

Floating-head two-pass heater : In floating-head two-pass heater, the ends of the tubes are structurally independent of the shell.

Construction : The construction of a two-pass floating head heater is shown in Figure 5-13. Its construction is the same as tubular heater with some modifications.

Two-pass floating head heater consists of a bundle of parallel tubes. These are enclosed in a shell (casing). The right-side of the distribution chamber is partitioned and fluid inlet and outlet are connected to the same chamber. The partition is such that both have equal number of tubes. On left-side, the distribution chamber is not connected to the casing. It is structurally independent, which is known as *floating head*. The other end of the tubes is embedded into the floating head. Steam or other vapour is introduced through inlet provided to the shell. Provisions are made for the escape of non-condensed vapour and an exit for the condensate.

Working : Steam is introduced through the inlet (Figure 5-13). As the steam flows down the tubes, they get heated. The condensed vapour escape through the bottom of the shell. Non-condensable gases, if any, escape through the vent at the top of the shell.

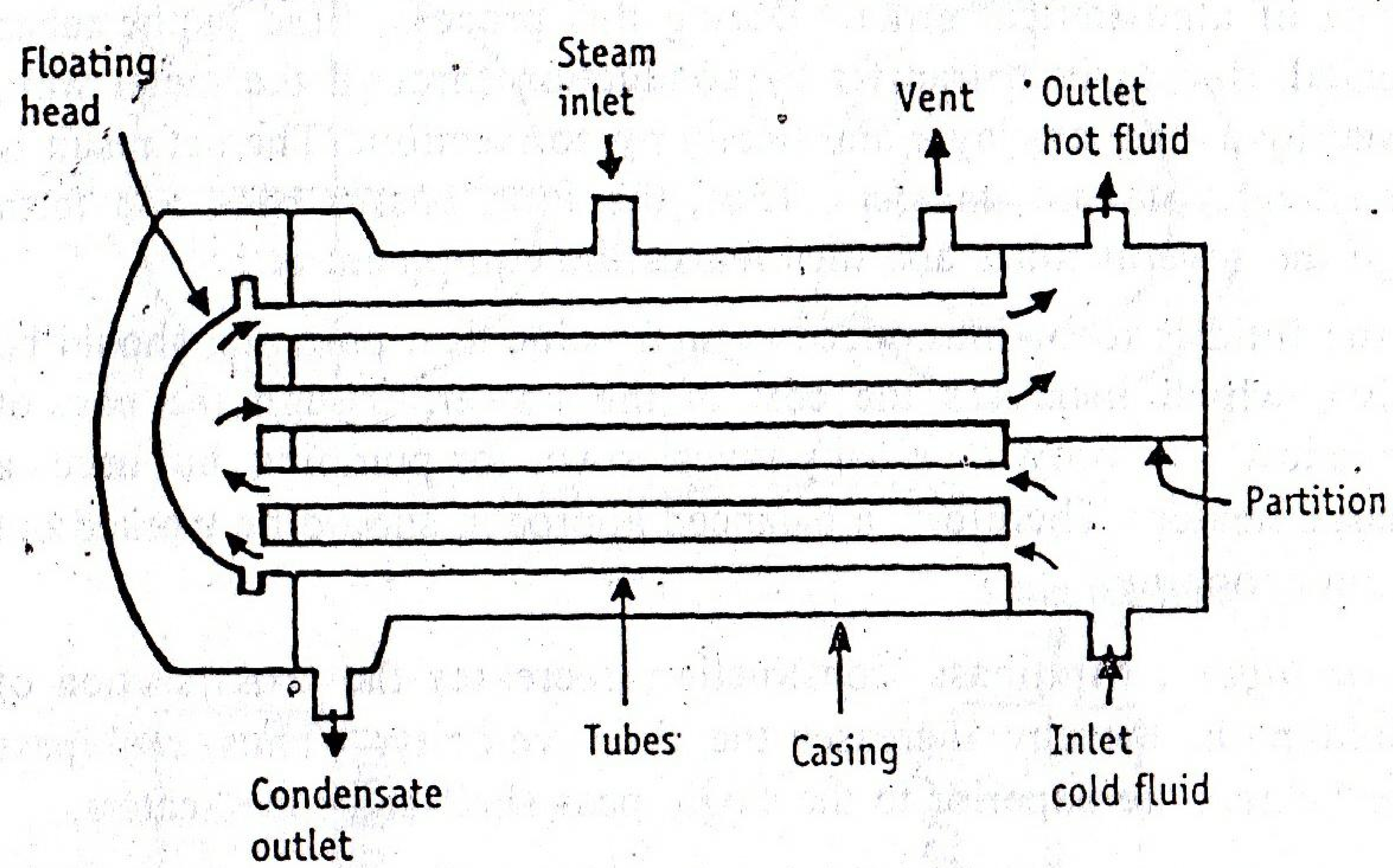


Figure 5-13. Construction of a two-pass floating head heater.

The fluid to be heated is introduced into the distribution chamber on right-side of the heater. The fluid flows through few tubes present in that part of the partition. The fluid reaches the floating head and changes direction. Now it passes back to the next part of the partition chamber on right-side. Therefore, the fluid flows twice through the tubes, i.e., two pass. During this process, fluid in the tubes get heated, due to heat transfer by conduction through the metal wall, followed by a stagnant layer and finally by convection. Then the fluid leaves the outlet provided in the shell.

Advantages : In a shell-and-tube heat exchanger, tubes and shell may get expanded due to differences in temperature. Similarly contractions are also possible when heater is switched off. It leads to loosening of tube sheets or buckles the tubes. Therefore, constructing the tubes independent of the shell can prevent these effects. Such an arrangement is *floating head.*

Heat Interchangers

Heat interchangers are the devices used for transferring heat from one liquid to another or from one gas to another gas through a metal wall.

In heat interchangers, the heating medium is a hot liquid. The liquid to be heated is the cold liquid. In this case, the film coefficients both outside and inside the tubes are nearly of same magnitude. The value of the overall heat transfer coefficient, U, will be near that of the smaller of the two film coefficients. Hence, heat transfer is not efficient.

The film coefficients can be enhanced by increasing the velocity of flow. From the point of construction, it is difficult to increase the velocity of the hot fluid outside the tubes. However, surface area of contact can be increased, by introducing baffles in the construction. The increased surface area of contact enhances the coefficient. Thus the rate of heat transfer is enhanced. These principles are illustrated using different heat interchangers.

Baffles : Baffles consist of circular discs of sheet metal with one side cut away. These are perforated to receive tubes. To minimize leakage, the clearance between the baffles, shell and tubes should be small. The baffles are supported by one or more guide rods, which are fastened between the tube sheets by set-screws.

Working : Baffles are placed outside the tubes. These increase the velocity of liquid outside the tubes. Baffles make the liquid flow more or less right angles to the tubes, which creates more turbulence. This helps in reducing the resistance to heat transfer outside the tubes. Therefore, baffles constitute an important part in the heat transfer.

The construction of a liquid-to-liquid heat interchanger illustrates the principle of introducing the baffles into the equipment.

Liquid–to–liquid interchanger : The basic construction and working of any heat transfer equipment more or less remains the same. Only a few modifications are included.

Construction : The construction of a liquid-to-liquid heat interchanger is shown in Figure 5-14. Normally, tube sheets, spacer rods and baffles are assembled first and then tubes are installed. The most important parts in the construction of the heat interchanger are the baffles.

Appropriate size of tube sheets is chosen for the fabrication. One or more guide rods are fixed to the tube sheets by means of set-screws. Baffles consist of circular discs of a metal sheet, with one side cut away. Baffles are placed at appropriate places using guide rods. The baffles are arranged with appropriate spacing using short sections of the same tubing as shown in Figure 5-14. Baffles have perforations through which tubes are inserted. The ends of tubes are expanded into the tube sheets. The above assembly is enclosed in a shell.

The shell has a provision for introducing the heating medium, hot fluid. The outlet for the fluid is at right-side top.

On each side of the tubes, two distribution chambers are provided. Left-side chamber contains an inlet for fluid to be heated. The outlet for the hot fluid (that is heated) is provided at the centre of the right-side distribution chamber.

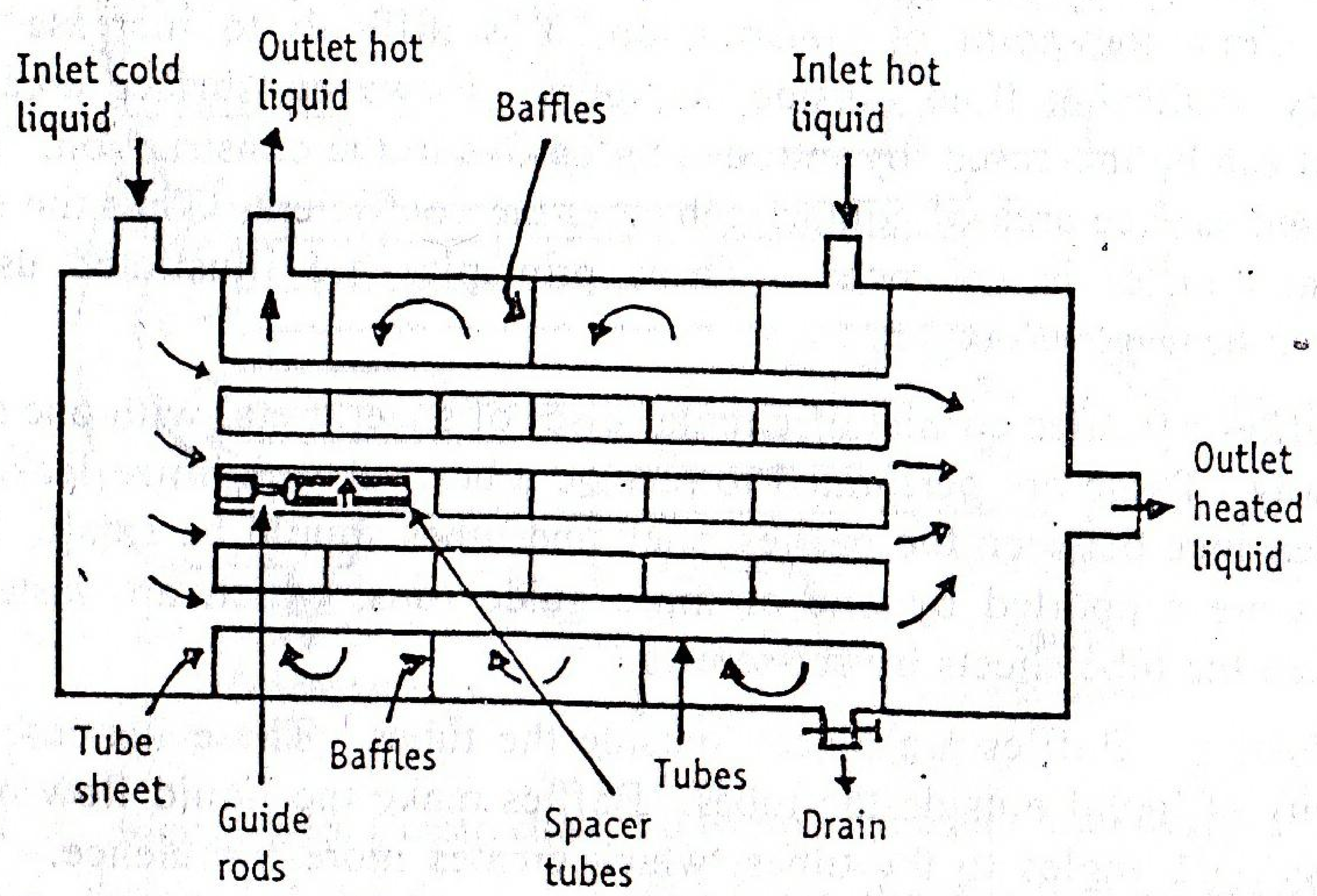


Figure 5-14. Construction of liquid-to-liquid heat interchanger.

Working : The hot fluid (heating medium) is pumped from the left-side top of the shell. The fluid flows outside the tubes and moves down directly to the bottom. Then, it changes the direction and rises again. This process is continued till it leaves the heater. Baffles increase the velocity of the liquid outside the tubes. Baffles also allow the fluid to flow more or less right angles to the tube, which creates more turbulence. These help in reducing the resistance to heat transfer outside the tubes. Baffles lengthen the path and decrease the cross-section of path of the cold fluid. The path of travel is as shown in Figure 5-14. The baffles get heated and provide greater surface area for heat transfer. Simultaneously, during the flow, the tubes also get heated. As a result, the film coefficient inside the tube also increases.

The liquid to be heated is pumped through the inlet provided on left-side distribution chamber. The liquid passes through the tubes and gets heated. The flow of liquid is single-pass. The heated liquid is collected from the right-hand side distribution chamber.

Advantages : In a liquid-to-liquid interchanger, heat transfer is rapid as the liquid

(1) passes at high velocity outside the tubes.

(2) flows more or less at right angles to the tubes.

Double-pipe heat interchanger : In a liquid-to-liquid heat interchanger, the fluid to be heated is passed only once through the tubes before it gets discharged, i.e. single pass. The heat transfer in this case is not efficient. When few tubes per pass is desirable, double pipe heat interchanger is employed.

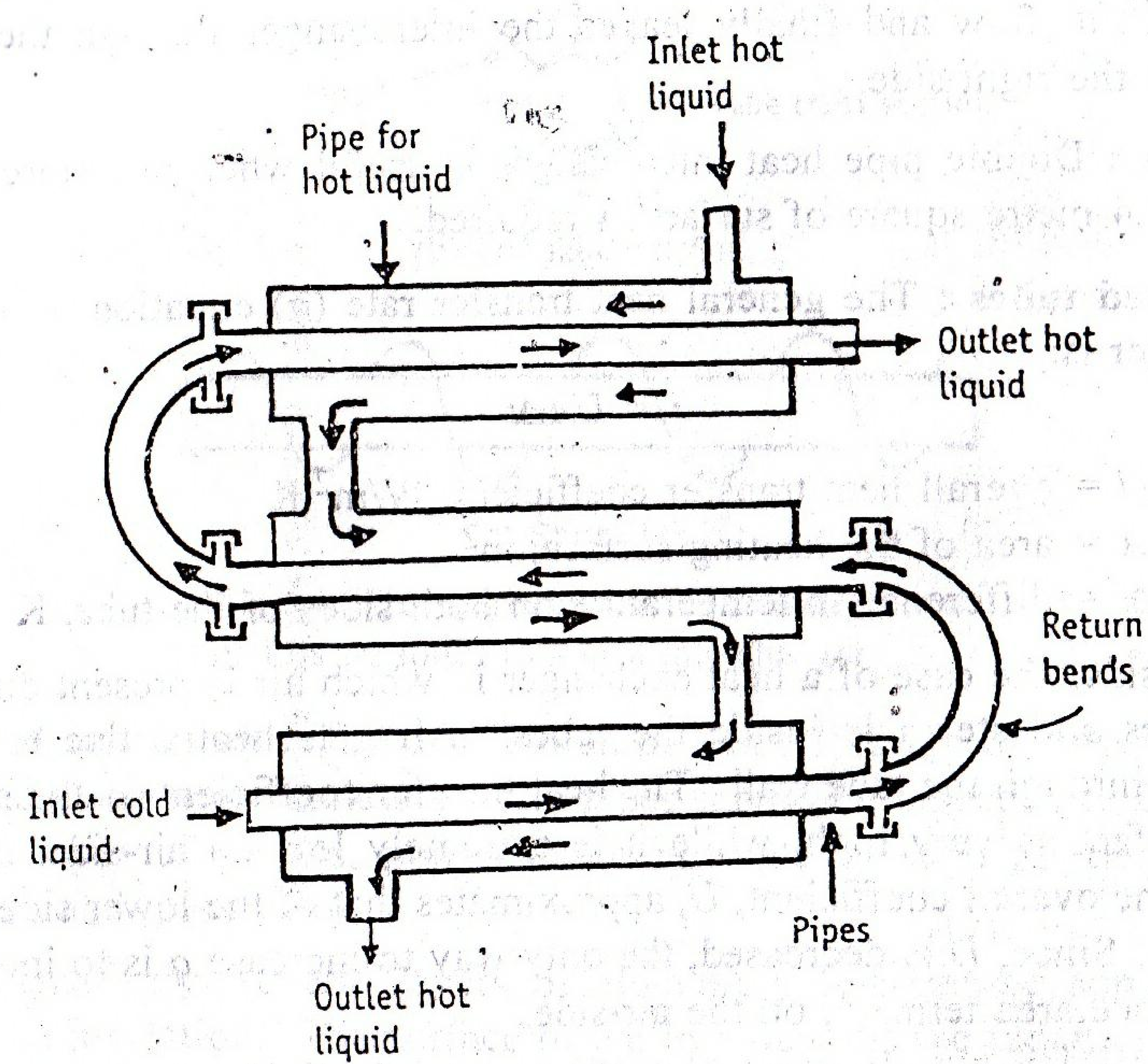


Figure 5-15. Construction of double-pipe heat interchanger.

Construction : The construction of a double-pipe heat interchanger is shown in Figure 5-15. In this, two pipes are used: one is inserted in the other. The inside pipe (or tube) is used for the pumping of cold liquid to be heated. The outer pipe acts as a jacket for the circulation of the hot liquid. All jacketed sections are inter-connected.

Normally, the number of pipe sections is few. The length of the pipe is also less. Glass tube, standard iron pipe and graphite constructions are available. Standard metal pipes are assembled with standard return bends. A proper number of such pipes are connected in parallel and stacked vertically. The pipes may have longitudinal fins on its outer surface.

Working : The hot liquid (heating medium) is pumped into the jacketed section. The hot fluid is circulated through the annular spaces between them and carried from one section to the next section. Finally it leaves the jacket. In this process the pipes get heated, while the hot fluid looses its temperature.

The liquid to be heated is pumped through the inlet provided at right side. The liquid gets heated up and flows through the bent tubes into the next section of the pipe. The liquid further gets heated. The same liquid continues to flow and finally leaves the interchanger through the exit point on the right side.

Uses : Double pipe heat interchanger is useful when not more than 0.9 to 1.4 metre square of surface is required.

Finned tubes : The general heat transfer rate (q) equation in a heat exchanger is:

$$q = UA\Delta t$$

where U = overall heat transfer coefficient, $W/m^2.K$
A = area of the heating surface, m^2
Δt = difference in temperature on both sides of the tube, K

Consider the case of a heat exchanger in which air is present outside the tubes and steam is inside the tubes. Air gets heated due to heat transfer through the tube wall. The heat transfer coefficient on the steam side surface is very high, while it is extremely low on air-side. As a result, the overall coefficient, U, approximates that of the lower side, i.e., air-side. Since, U is decreased, the only way to increase q is to increase the surface area term, A, on the air-side.

As metals generally have high thermal conductivity, the temperature of the metal surface approximates to that of steam. Surface area of contact is enhanced by fixing fins on outside of the tubes, without putting more number of tubes in the heater.

Construction : A variety of fins are used as shown in Figure 5-16. Fins may be placed on the inner wall as well as on the outside of the tubes. Rectangular discs of a metal may be placed at right angles to the tubes (Figure 5-16a). Longitudinal fins are also employed (Figure 5-16b). Spiral fins may be attached to the tubes (Figure 5-16c).

Uses : Fins greatly reduce the size of the apparatus. They also increase the surface area of contact. This in turn enhances the rate of

heat transfer in a heat exchanger. In double-pipe heat interchanger, fins are employed.

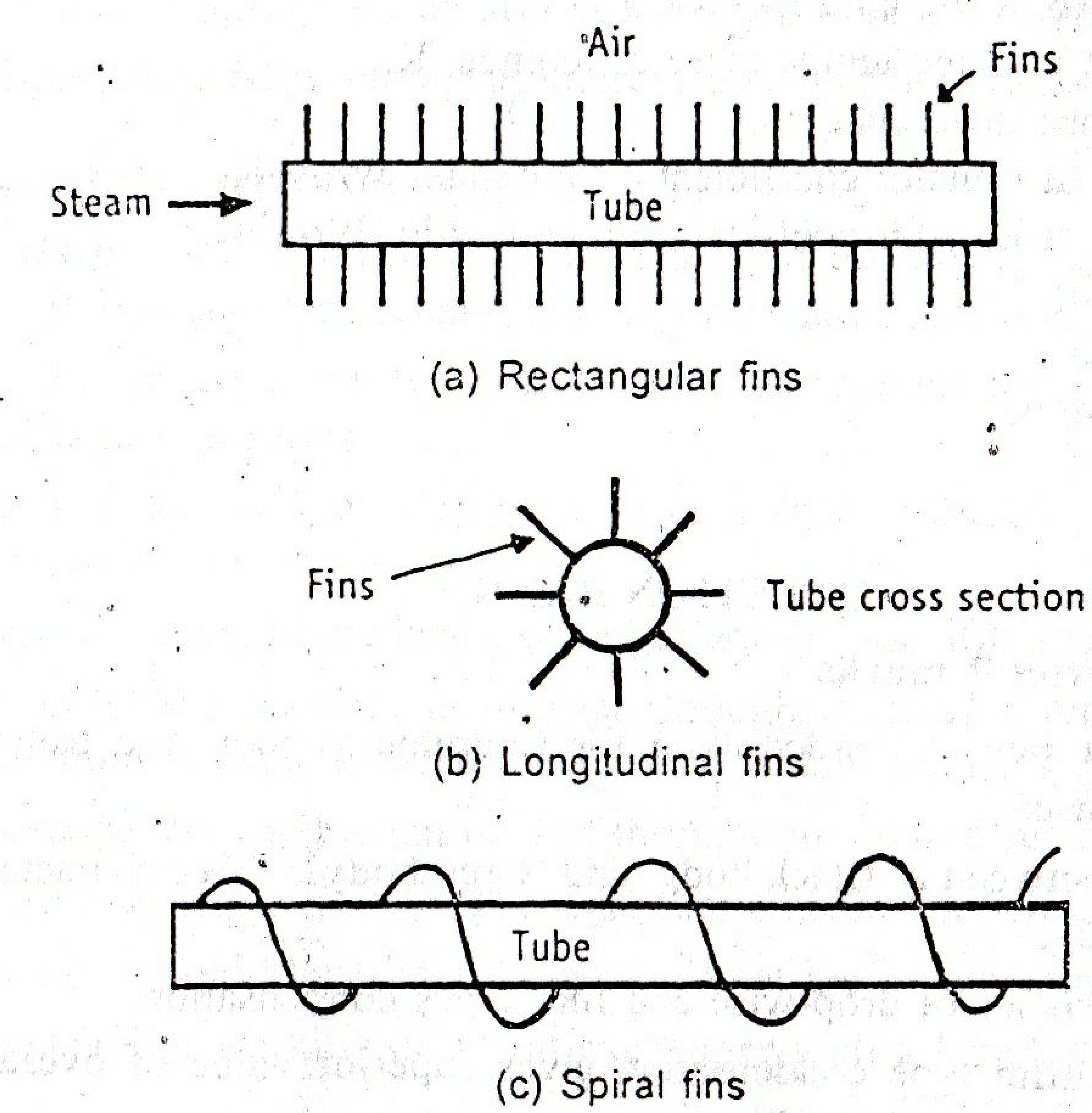


Figure 5-16. Variations in the arrangements of fins on tubes in a heat interchanger.

Heat insulation : The distribution of steam through the pipe can be reduced using heat insulators. The pipes should be lagged, i.e., covered with a layer of porous, poor conducting material such as kieselguhr, asbestos and glass wool.

Alternatively, several layers of aluminium foil can be applied for effective insulation. The surface of the foil prevents the radiation losses and air trapped between the layers minimizes convection losses.

Glossary of Symbols

A = Area of the heating surface, m^2.
A_m = Mean area of a cylinder, m^2.
b = Stefan Boltzmann's constant, $W/m^2 \cdot K^4$.
h_1 = Surface coefficient on the hot side, $W/m^2 \cdot K$.
h_2 = Surface coefficient on the cold side, $W/m^2 \cdot K$.
k_m = Mean proportionality constant, $W/m \cdot K$.
L = Thickness of the heating surface, m.
N = Length of the hollow cylinder, m.
q = Rate of heat transfer, W (J/s).

r = Radius of the thin cylinder for heat transfer, m.
r_m = Logarithmic mean radius, m.
T = Absolute temperature, K.
t_1 = Temperature at the hot surface, K.
t_2 = Temperature at the cold surface, K.
Δt_m = Arithmetic average temperature difference, K.
Δt = Temperature difference, K.
U_1 = Overall heat transfer coefficient on hot side, $W/m^2 \cdot K$.
U_2 = Overall heat transfer coefficient on cold side, $W/m^2 \cdot K$.
α = Absorptivity
ρ = Reflectivity
τ = Transmissivity
ε = Emissivity

QUESTION BANK

Each question carries 2 marks

1. Describe the types of condensation for saturated vapour free from non-condensible gases.
2. Differentiate between a 'Black body' and 'Grey body'. Give characteristics of a black body.
3. Give characteristics of drop-wise and film types condensation.
4. Drop-wise or film type condensation gives superior value of overall heat transfer coefficient and why?
5. List the characteristics of heat transfer by radiation.
6. What are 'Grey bodies'? How do they radiate heat?
7. Give the final equation for heat transfer by conduction through resistances in series and explain the terms.
8. What are 'overall heat transfer coefficient' and 'individual film coefficient'?
9. Explain the terms 'Black body' and 'Grey body'.
10. Differentiate between film coefficient and overall heat transfer coefficient.
11. State the relationship between individual film coefficients and overall heat transfer coefficient.
12. Define conductivity with a suitable example
13. State and explain Stefen Boltzmann's law of heat radiation.
14. State and explain Fourier's law of heat transmission with equation.
15. Explain 'nucleate boiling' and 'film boiling'.
16. Define radiation. Explain Stefan Boltzmann's law.
17. Write the final equation for heat transfer by conduction through resistances in parallel and explain the terms.

18. Differentiate log mean radius and arithmetic mean radius in conduction of heat. What are its applications?
19. What is meant by overall heat transfer coefficient? What is its significance?
20. Differentiate between a heat interchanger and heat exchanger.

Each question carries 5 marks

1. Compare and contrast heat transmission following counter-current and parallel-current feed techniques with relevant equations.
2. Derive an equation for heat transfer by conduction through compound resistances in series.
3. Draw a neat and labelled diagram of a shell-and-tube heat exchanger and explain its construction.
4. Describe finned tube heat exchanger and its specific advantages.
5. Describe the conduction of heat through a circular pipe. Give suitable equations for rate of heat transfer and explain terms.
6. Describe the conduction of heat through compound resistances in series.
7. Derive an expression for the logarithmic mean temperature difference.
8. Describe liquid heat interchangers. What are its advantages?
9. Explain the working of a heat exchanger with a labelled diagram.

Each question carries 10 marks

1. With the help of a neat diagram, explain the concept of film and overall heat transfer coefficients in forced convection. Deduce relevant mathematical equations.
2. Derive an equation for heat transmission through a circular pipe from Fourier's law.
3. Describe the construction, operation, advantages and disadvantages of a multipass heater.