12

Evaporation

Evaporation is a process of vaporising large quantities of volatile liquid to get a concentrated product.

Equipment used for the evaporation are known as *evaporators*. Heat is supplied to the evaporator, which transmits it to the evaporating liquid so as to provide latent heat of vaporisation. Steam is normally used as a source of heat. Evaporation is a surface phenomenon, i.e., mass transfer takes place from the surface. Thus no boiling occurs. In practice, surface evaporation is slow. Therefore, *the practical definition of evaporation* is the removal of solvent from the solution by boiling the liquor in a suitable vessel and withdrawing the vapour, leaving a concentrated liquid residue in the vessel.

Either solutions or suspensions can be subjected to evaporation. The only condition is that the liquid must be volatile, while the solute must be nonvolatile. Since heat is supplied, the constituents should be thermostable. In most of the operations, the liquid is water with a low solid content. The liquid to be evaporated may be less viscous than water or it may be so viscous that it will hardly flow. At the end of the process, the concentrate will be so viscous that further evaporation will be drastically reduced.

Evaporation some times overlap with other heat processes, though some distinctions can be drawn. These are given in Table 12-1.

Although the purpose of evaporation is to obtain a concentrated product, the solvent vapour is sometimes valuable, so recovery is essential. This prevents the environmental pollution, fire hazards and at the same time makes the process economical.

TABLE 12-1
Distinguishing Features of Evaporation with other Heat Processes

S.No.	*Evaporation*	*Other heat process*
1	The residue is a concentrated liquid.	*Drying*: the residue is solid.
2	Evaporating liquid is only one component in most of the cases.	*Distillation*: Evaporating liquid is a combination of two or more components.
3	No attempt is made to separate the mixture of vapour, even if any.	*Distillation*: It is compulsory to separate each component.
4	The purpose of evaporation is to get a concentrated liquid only, but not to get crystals as it happens in some situations.	*Crystallization*: The purpose of concentrating the solution is to get crystals.

Applications

Manufacture of bulk drugs : Evaporation process is used in pharmacy practice, pharmaceutical industries, chemical industries etc.

Manufacture of biological products : Evaporation is used in the manufacture of biological products such as insulin, biochemical products (example is penicillin) and plant products. Preparation of blood products such as blood plasma and serum involves evaporation. Enzymes, hormones and antibiotics are prepared.

Miscellaneous : Water containing minerals is subjected to evaporation to get demineralised water after condensation. The water so obtained is used for human consumption and for special processes. This is some sort of evaporation though the process is generally called distillation.

FACTORS INFLUENCING EVAPORATION

The rate of evaporation depends on several factors. The relationship may be expressed mathematically as:

$$M = \frac{KS}{p}(b - b') \qquad (1)$$

where M = mass of vapour formed per unit time (Rate), m^3/s
S = surface area of the liquid exposed, m^2
p = atmospheric pressure, kPa
b = maximum vapour pressure at the temperature of air, kPa

b' = pressure due to the vapour of the liquid, actually present in the air, kPa
K = constant, m/s

In general mass transfer also depends on the temperature.

Temperature

The higher the temperature, the greater the value of b and hence greater will be the evaporation.

At a given temperature, some molecules possess higher kinetic energy than average, while others have lower than average kinetic energy. Fast moving molecules escape from the surface of the liquid into vapour, while slow moving ones remain behind. When temperature of the liquid is raised, more molecules acquire sufficient kinetic energy and escape from the surface to vapour state. This is the situation below the boiling point of the liquid.

Below boiling point, vapour is formed from the surface only. At boiling point, vapour is formed throughout the body of the liquid as well as from surface. The vapour pressure of a liquid is lowered when a substance is dissolved in it and consequently the boiling point of the liquid increases.

Normally, glycosides and alkaloids decompose at high temperature. Hormones, enzymes and antibiotics are even more heat-sensitive. These products require special techniques to prevent decomposition during evaporation. For example, malt extract is prepared by evaporation under reduced pressure to avoid loss of enzymes. Antibiotics are concentrated by freeze-drying.

Vapour Pressure

Rate of evaporation is directly proportional to the vapour pressure of the liquid. The lower the p value in equation (1), the greater the evaporation. Lower the external pressure, the lower the boiling point of the liquid and hence greater will be the rate of evaporation. This condition is achieved by applying vacuum.

The nature of liquid is also important for rate of evaporation. Liquids with low boiling points evaporate quickly because of high vapour pressures at lower temperatures.

If the outer atmosphere is dry, the value of b' will be low and hence greater the evaporation. If the vapour of the liquid is removed as soon as it is formed (under reduced pressure or vacuum), the space above the liquid does not become saturated with the vapour. Hence, evaporation proceeds faster.

Surface Area

From equation (1), it is clear that the greater the surface area of the liquid, the greater will be the evaporation. For this reason, evaporation is conducted in evaporators with larger heating surface area.

Moisture Content of the Feed

Some drug constituents undergo hydrolysis readily in presence of moisture at high temperatures. To prevent decomposition, the material is exposed to lower temperature initially, then exposed to higher temperature for final concentration. For example, dry extract of belladonna is prepared in this manner.

Type of Product Required

Type of product required some times decides the apparatus for evaporation. Open pan produces liquid or dry concentrate. Film evaporator yields liquid concentrate. Spray dryer produces dry products with good solubility. Vacuum evaporator gives porous product suitable for conversion to granules, for example, preparation of granular extract of cascara for tablet making.

Time of Evaporation

If the time of exposure is longer, greater will be the evaporation, provided the constituents are thermostable. Exposure of a drug to a relatively high temperature for a short period of time may be less destructive of active principles than a lower temperature with long exposure period. For this reason, film evaporators are used.

Film and Deposits

When vegetable extracts are concentrated in steam pan, a film may be formed on the surface and/or precipitated matter may deposit on the heating surface. Film reduces the evaporating surface and precipitated matter hinders the transfer of heat. To avoid these problems, efficient stirring is necessary.

Economic Factors

Economies of labour, fuel, floor space and materials are of primary considerations. The recovery of solvents and the utilization of *waste heat* are also important as they involve considerable reduction of costs.

For evaporation, heat is necessary to provide the latent heat of vaporisation. Hence, rate of evaporation is controlled by rate of heat transfer. Therefore, evaporator is designed to give maximum heat transfer to the liquid.

CLASSIFICATION OF EVAPORATORS

I. Evaporators with heating medium in jacket

Example: Steam jacketed kettle (evaporating pan)

II. Vapour heated evaporators with tubular heating surfaces

(A) Evaporators with tubes placed horizontally

Examples: Horizontal tube evaporator

(B) Evaporators with tubes placed vertically

i. Evaporators with short tubes

(a) Single effect evaporators

Examples: Short tube vertical evaporator (Standard vertical tube evaporator)

Short tube vertical evaporator with propeller

Basket type evaporator

(b) Multiple effect evaporator

Example: Triple effect evaporator

ii. Evaporators with long tubes

(a) Evaporators with natural circulation

Examples: Climbing film evaporator (Rising-film evaporator)

Falling film evaporator

(b) Evaporators with forced circulation

Example: Forced circulation evaporator

EQUIPMENT

STEAM JACKETED KETTLE OR EVAPORATING PAN

Principle : Steam is supplied to a jacketed kettle (evaporating pan) in which aqueous extract is placed. Steam gives out heat to the kettle. The heat is transferred to the aqueous extract by conduction and convection. The temperature raises and the escaping tendency of the solvent molecules into vapour increases. Stirring further enhances the vaporisation of solvent molecules.

Construction : The construction of a steam jacketed kettle is shown in Figure 12-1. It is a hemispherical structure consisting of an inner pan called *kettle.* It is enveloped with an outer pan called *jacket.* The two pans are joined to enclose a space through which steam is passed.

For smaller quantities, kettle is made up of a single sheet of metal. For larger capacities, several sheets are welded. Though several metals are used as a material of construction, for practical purposes the following are used. Copper is an excellent material for the kettle, because of its good conductivity. If acidic materials are evaporated, some quantity of copper would dissolve. For such preparations, tinned copper is used. Iron is used for the construction of the jacket, because it has minimum conductivity. To prevent rusting of the jacket, the iron is either tinned or enamelled on inner surface.

An inlet for the steam and an outlet (vent) for noncondensed gases are provided near the top of the jacket. Condensate leaves the jacket through the outlet provided at the bottom. The kettle is provided with one outlet for product discharge at its bottom.

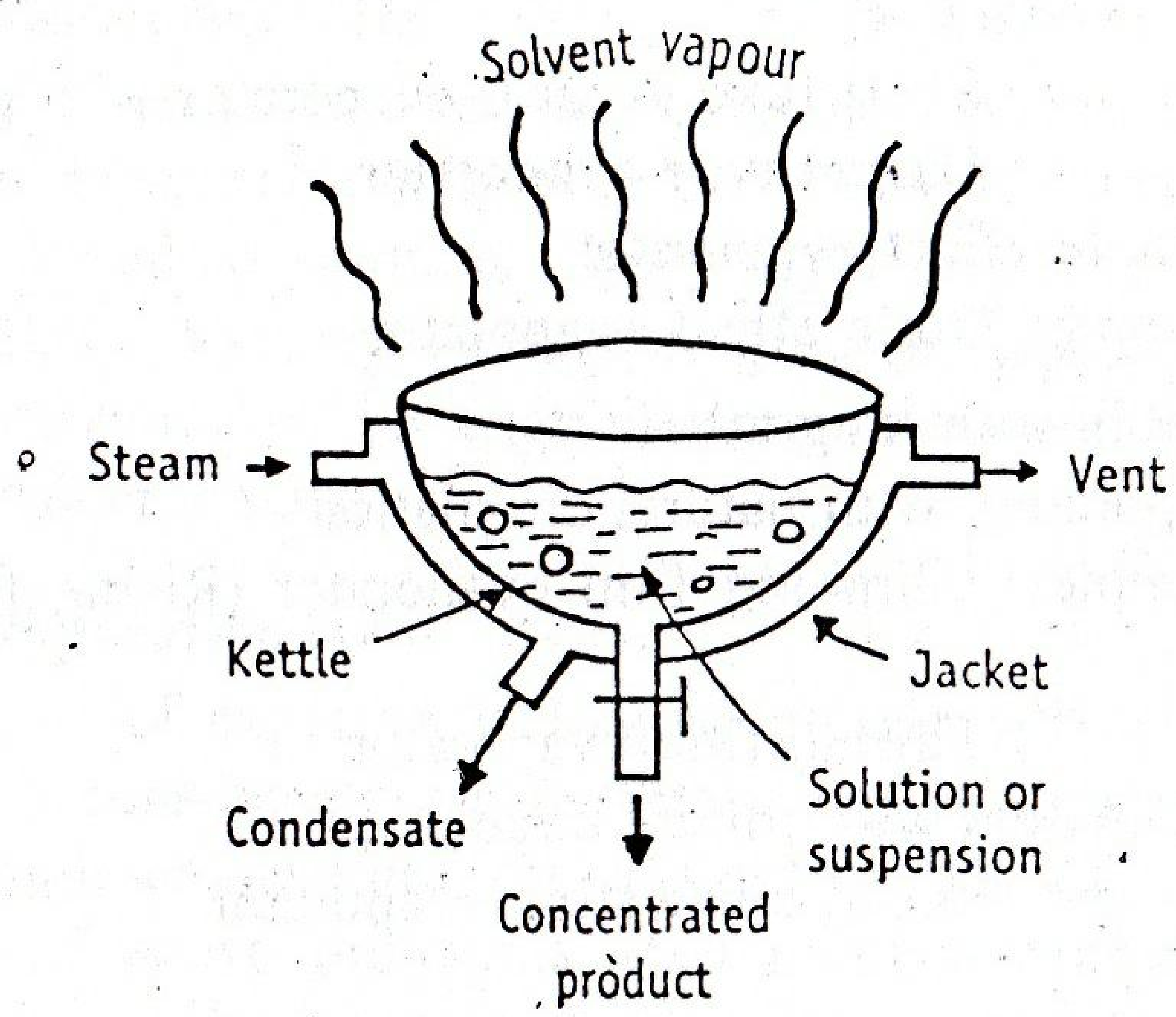

Figure 12-1. Steam jacketed kettle.

Working : Aqueous extract to be evaporated is placed in the kettle. Steam is supplied through the inlet. Steam gives out its heat to the contents and the condensate leaves through the outlet. The contents must be stirred manually for smaller volumes and mechanically for larger volumes. Mechanical stirrer is not shown in Figure 12-1. The rate of evaporation is fast in the initial stages and decreases gradually as the liquid gets concentrated.

Any room where evaporation is carried by this apparatus must have good ventilation to remove the vapour. Otherwise, the room is quickly filled with a dense fog of condensed vapour and water falls from the roof and runs down the walls. Fans fitted over the pan not only remove the vapour and prevent condensation in the room, but also accelerate the rate of evaporation by quickly removing saturated air from the surface of the liquid.

The kettle may be fixed or made to tilt. A kettle of capacity upto about 90 litres may be made to tilt. But above this capacity, the weight of the pan along with its contents becomes too great to tilt. Hence, the bottom outlet is used to collect the concentrated product.

Uses : Evaporating pan is suitable for concentrating aqueous and thermostable liquors, for example, liquorice extract.

Advantages : (1) Evaporating pan is constructed both for small scale and large scale operations.

(2) It is simple in construction and easy to operate, clean and maintain.

(3) Its cost of installation and maintenance is low.

(4) Wide variety of materials can be used for construction such as copper, stainless steel and aluminium.

(5) Stirring of the contents and removal of the product is easy.

Disadvantages : (1) In evaporating pans, heat economy is less. Hence, cost per unit material production is more.

(2) It is not suitable for heat sensitive materials due to long time of exposure.

(3) The heating area decreases as the product gets more concentrated.

(4) As it is open type, vapour passes into the atmosphere, which can lead to saturation of the atmosphere, slowing evaporation as well as causing discomfort.

(5) Boiling point of water cannot be reduced, since reduced pressure can not be created in open type evaporator.

HORIZONTAL TUBE EVAPORATOR

Principle : In horizontal tube evaporator, steam is passed through the horizontal tubes, which are immersed in a pool of liquid to be evaporated. Heat transfer takes place through the tubes and the liquid outside the tubes gets heated. The solvent evaporates and escapes from the top of the evaporator. The concentrated liquid is collected from the bottom.

Construction : The construction of a horizontal tube evaporator is shown in Figure 12-2. It consists of a large cylindrical body with conical or dome-shaped top and bottom. It is made up of cast iron or plate steel. An average size of the body ranges from 1.8 to 2.4 metres diameter and from 2.4 to 3.6 metres height.

The lower part of the body consists of a steam compartment with an inlet for steam at one end and a vent for noncondensed gases on the other end. A condensate outlet is provided at the bottom of the steam compartment. In the steam compartment, 6-8 stainless steel horizontal tubes are placed. The tubes are cut long enough so that they project about 25.0 millimetres beyond the tube sheet on both ends. The width of steam compartment is usually half the diameter of the body.

At one convenient point, an inlet for feed is provided (Figure 12-2). One outlet for vapour is placed at the top of the dome. Another outlet for thick liquid is placed at the centre of the conical bottom of the body.

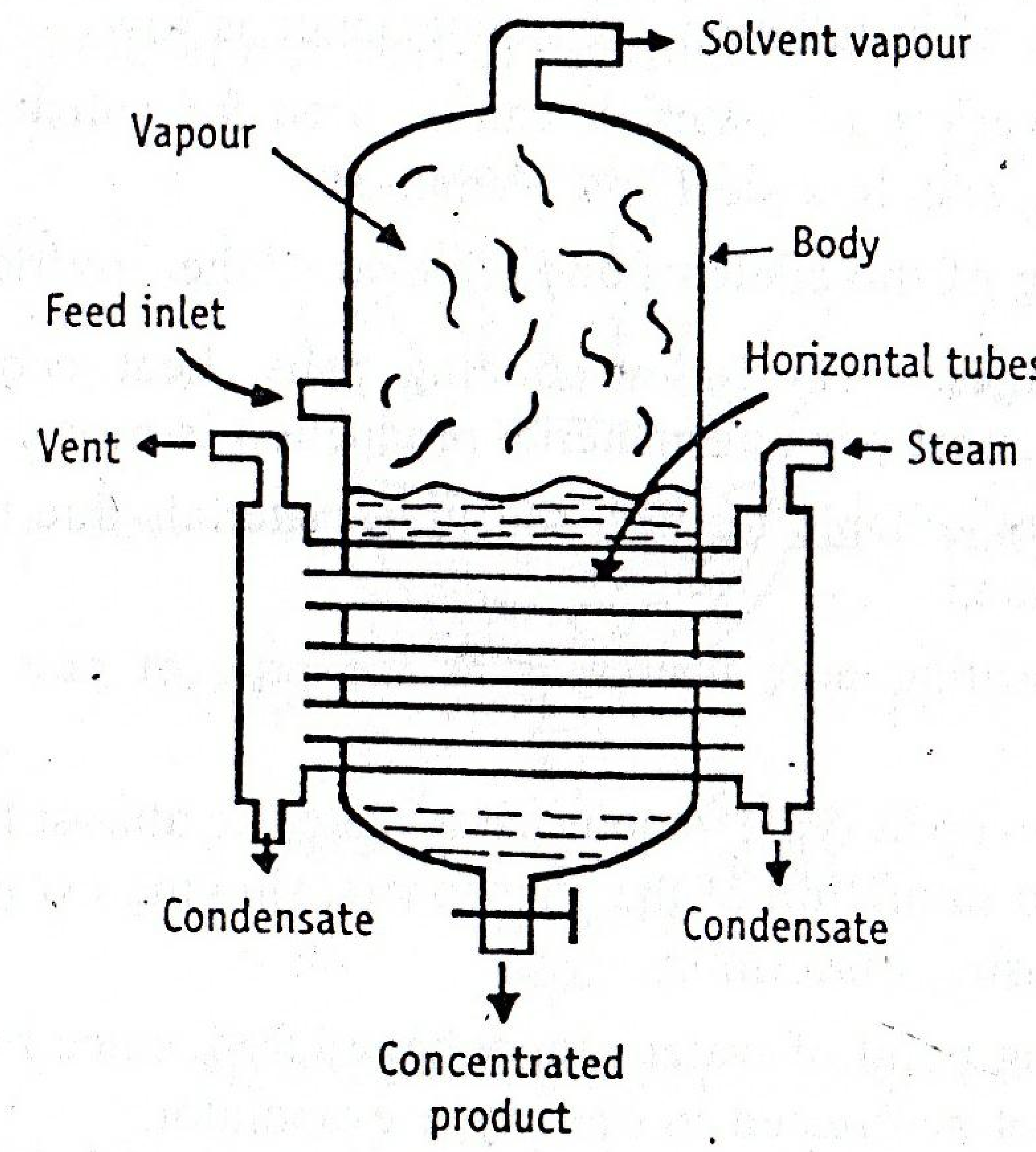

Figure 12-2. Construction of a horizontal tube evaporator.

Working : The feed is introduced into the evaporator until the steam compartment is satisfactorily immersed. Steam is introduced into the steam compartment. The horizontal tubes receive heat from the steam and conduct it to the liquid due to temperature gradient. Steam condensate passes through the corresponding outlet. The feed absorbs heat and solvent gets evaporated. The vapour then escapes through the outlet placed at the top. This process is continued until a thick liquid is formed, which can be collected from the bottom outlet.

Uses : Horizontal tube evaporator is the best suited for non-viscous solutions that do not deposit scales or crystals on evaporation, for example cascara extract.

Advantage : The cost per square metre of heating surface is usually less in horizontal tube evaporator.

VERTICAL TUBE EVAPORATOR
(Short Tube Evaporator)

Principle : In standard vertical tube evaporator, liquid is passed through the vertical tubes and the steam is supplied from outside the tubes. Heat transfer takes place through the tubes and the liquid inside the tubes gets heated. The solvent evaporates and the vapour escapes from the top. The concentrated liquid is collected from the bottom.

Construction : The construction of a standard vertical tube evaporator is shown in Figure 12-3. It consists of a large cylindrical body made up of cast iron with dome shaped top and bottom (Figure 12-3). In side the body, calandria is fitted at the bottom. Calandria consists of a number of vertical tubes, whose diameter ranges from 0.05 to 0.075 metres and length of 1-2 metres. About 100 such tubes are fitted in a body measuring 2.5 metres or more diameter. Inlets are provided for steam and feed. Outlets are provided for vapour, concentrated product, non-condensed gases and condensate.

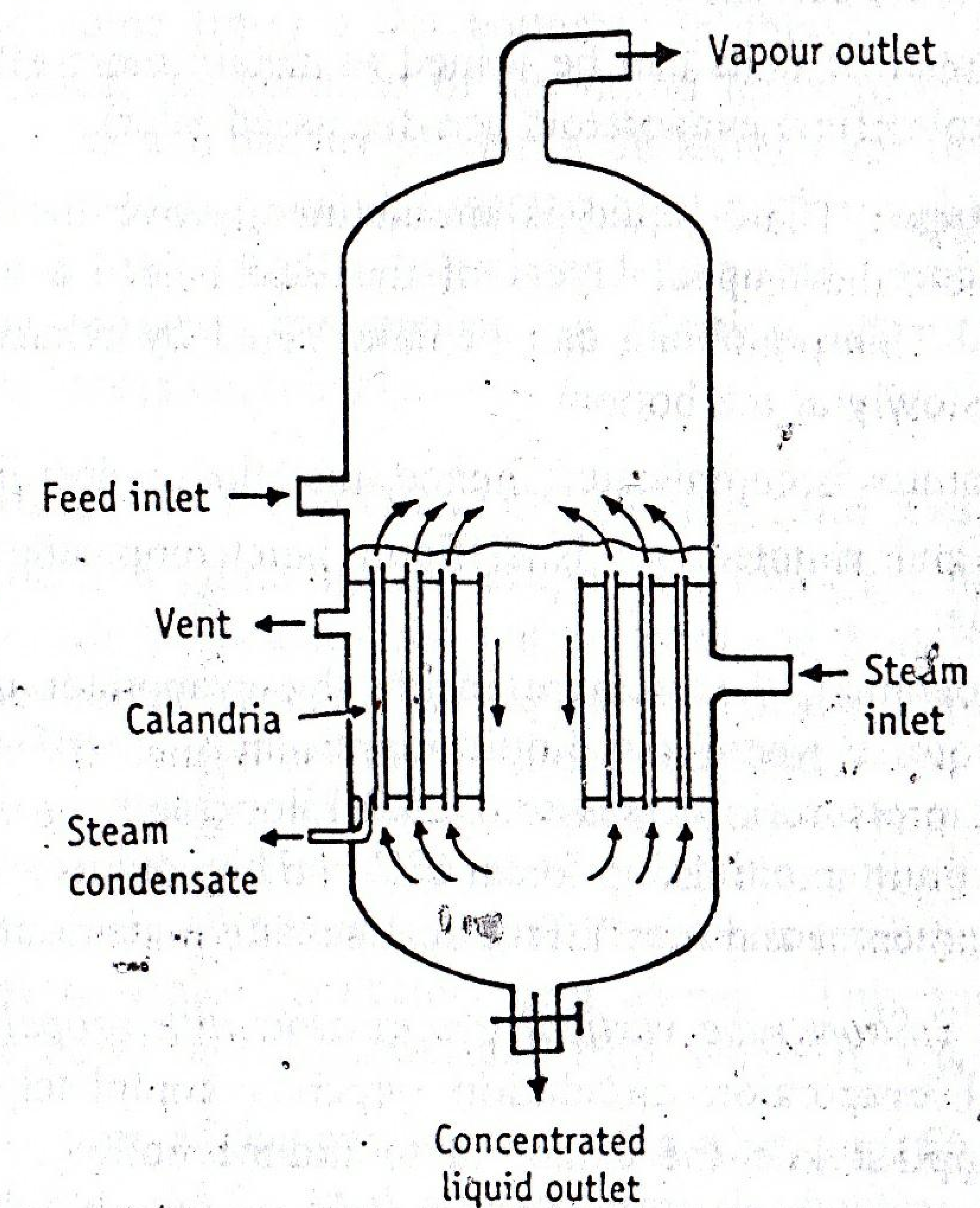

Figure 12-3. Construction of a short tube evaporator.

Working : Steam is introduced outside the tubes. The condensate is passed through the corresponding outlet and non-condensed gases escape through the vent. The feed is introduced in such a way as to maintain the liquid level slightly above the top of the tubes. The liquid inside the tubes is heated by the steam and begins to boil. As the liquid boils, it spouts up through the tubes and returns through the central down-take. It sets up a circulation of hot liquid, which enhances the rate of heat transfer. The vapour escapes through the top outlet. Steam is supplied until required concentration of the product is obtained. Finally, the product can be withdrawn from the bottom outlet.

Uses : Vertical tube evaporator is used in the manufacture of cascara extract, sugar, salt, caustic soda.

Advantages : (1) In vertical tube evaporator, tubes increase the heating surface nearly 10 to 15 times when compared with steam jacketed kettle.

(2) Vigorous circulation enhances the rate of heat transfer.

(3) It can be connected to a condenser and receiver, which further increases rate of evaporation. Such attachment is also suitable for volatile solvents.

(4) A number of units can be joined to obtain more efficient effect (multiple effect evaporators are discussed later).

Disadvantages : The liquid is maintained above the level of the calandria. Hence, the upper layers of the liquid need a long time for getting heated. This problem can be minimised by removing concentrated liquid slowly at the bottom.

The evaporator is complicated, hence, installation cost increases.

Cleaning and maintenance is difficult when compared with steam jacketed kettle.

During operation, the pressure inside the evaporator increases. In large evaporators, where the liquid depth may be of the order of 2.0 metres, the pressure increases to 25.0 kilopascals, leading to elevation of the boiling point by 5 or 6°C. This reduces the effective temperature gradient and may affect heat sensitive materials.

Variants : *Short tube vertical evaporator with propeller* : In short tube vertical evaporator, circulation depends completely on boiling. Steam is supplied into the calandria to induce boiling. When steam supply is stopped, automatically boiling stops. As a result the particles (if any) settle down. These particles act as nuclei which grow as crystals.

Therefore, this evaporator is sometimes used as a *crystallizing evaporator*. If such crystallization is undesirable, the problem can be avoided by installing a propeller in the central portion close to the bottom. By increasing the revolutions per minute of the propeller, the capacity of the evaporator can be doubled.

Uses : Since mild steel or cast iron is used, the evaporator suits well for clear liquids and crystallizing solutions. Non corrosive liquids and mild scaling solutions can also be handled.

Advantages : Heat transfer coefficients are high due to high temperature gradient values. It requires low head-room. Cleaning and maintenance is easy. It is relatively inexpensive.

Disadvantages : Heat transfer coefficients are low due to low temperature gradient. It requires high floor space and is more in weight. Relatively more liquid is retained. Rate of heat transfer further decreases due to high viscosity liquids. Since body is large, mild steel or cast iron are used for its construction to make it less expensive.

Basket type evaporator : The basket type of evaporator has a conical bottom and some times a flat bottom. In this type, boiling is quite violent. Hence, the spouting of the liquid leads to entrainment. This problem can be avoided by placing a deflector over the tubes. In this case, the down-take is annular instead of being central. The advantage of this type is that entire heating element is a single unit. The complete unit can be removed for repairs. In addition, the deflector prevents entrainment losses completely.

CLIMBING FILM EVAPORATOR (Rising Film Evaporator)

Principle : In climbing film evaporator, tubes are heated externally by steam. The preheated feed enters from the bottom and flows up through the heated tubes. The liquid gets heated rapidly due to enhanced overall coefficient of the preheated feed. The liquid near the wall becomes vapour and forms small bubbles. These tend to fuse to larger bubbles, which travel up in the tubes along with entrapped slug. The liquid films are blown up from the top of the tubes and strikes entrainment separator (deflector) kept above. This throws the liquid concentrate down into the lower part from where it is withdrawn.

Construction : The construction of a climbing film evaporator is shown in Figure 12-4. In this evaporator, the heating unit consists of steam jacketed tubes. Here, the tubes (long and narrow) are held between two plates. An entrainment separator is placed at the top to the vapour head. The evaporator carries steam inlet, vent outlet and condensate outlet. The feed inlet is from the bottom of the steam compartment.

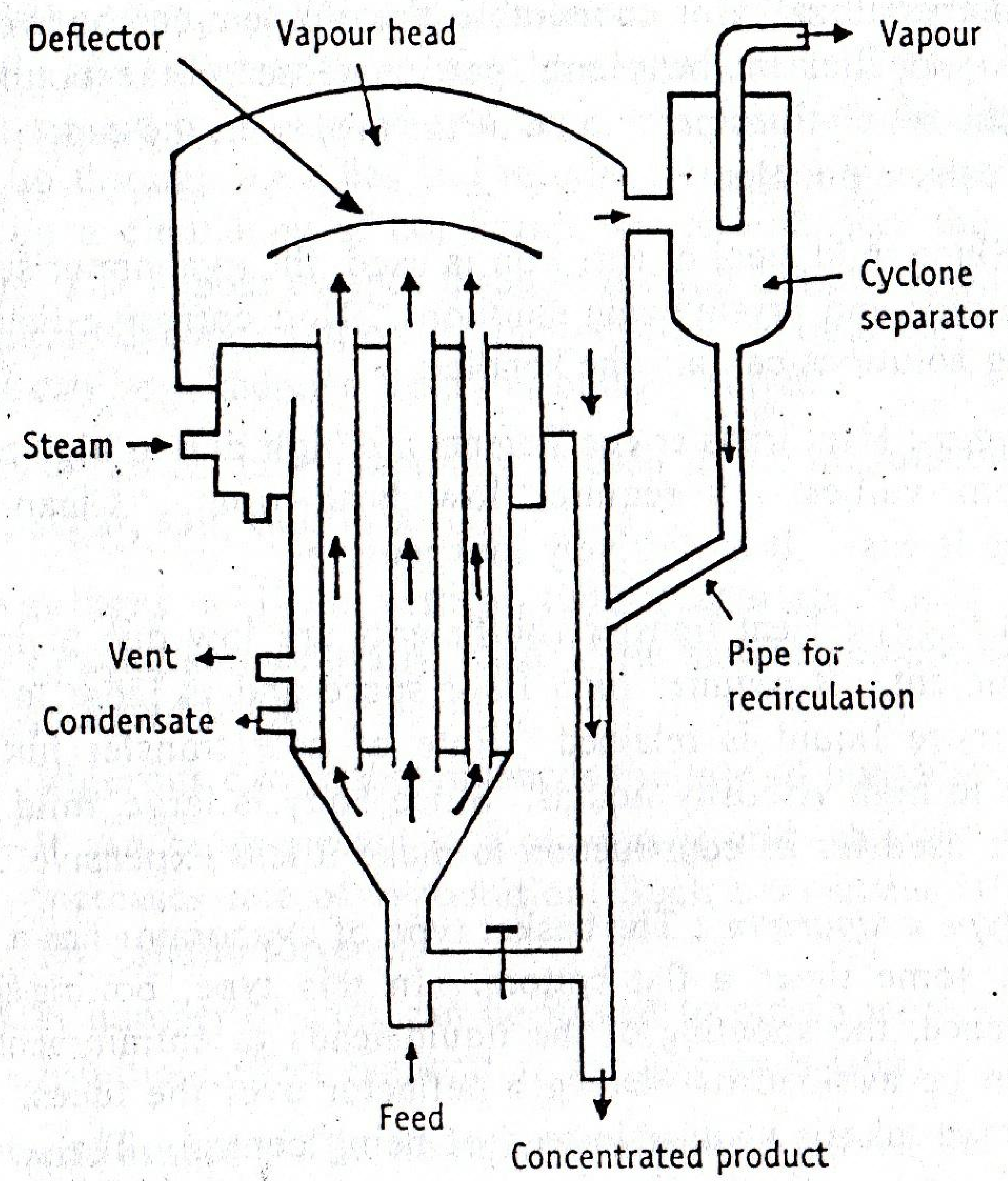

Figure 12-4. Construction of a climbing film evaporator.

Working : The preheated liquid feed (to be evaporated) is introduced from the bottom of the unit. The height of the liquid column is maintained low, i.e., 0.6 or 1.2 metres above the bottom tube sheet. Steam enters into the spaces outside the tubes through the inlet. Heat is transferred to the liquor through the walls of the tubes. The liquid becomes vapour and forms smaller bubbles, which tend to fuse to larger bubbles. These are of the width of the tubes, thereby the bubbles trap a part of the liquid (slug) on its way up in the tubes. As more vapour is formed, the slug of liquid is blown up in the tubes facilitating the liquid to spread as a film over the walls. This film of liquid continues to vaporise rapidly. Finally, the mixture of liquid concentrate and vapour eject at a high velocity from the top of the tubes.

The entrainment separator not only prevents entrainment, but also acts as a foam breaker. The vapour leaves from the top, while concentrate is collected from the bottom.

Uses : Using climbing film evaporator, thermolabile substances such as insulin, liver extracts and vitamins can be concentrated. Clear liquids, foaming liquids and corrosive solutions in large quantities can be operated. Deposit of scales can be removed quickly by increasing the feed rate or reducing the steam rate so that the product is unsaturated for a short time.

Advantages : (1) In a climbing film evaporator, large area for heat transfer is provided employing long and narrow tubes.

(2) Since liquid flows at a high velocity, the resistance for heat transfer at the boundary layers is reduced. As a result, the heat transfer is enhanced.

(3) The time of contact between the liquor and the heating surface is very short. The liquid is in the heater for one second, while its residence time, is 20 seconds in the evaporator. Hence it is suitable for heat sensitive materials.

(4) Unlike short tube evaporator, the tubes are not submerged. So there is no elevation of boiling point due to hydrostatic head.

(5) It is suitable for foam-forming liquids, because foam can be broken by an entrainment separator.

(6) It requires low hold up and small floor space.

Disadvantages : (1) Climbing film evaporator is expensive, construction is quite complicated.

(2) It is difficult to clean and maintain.

(3) Large head space is required.

(4) It is not advisable for very viscous liquids, salting liquids and scaling liquids.

(5) If feed rate is high, the liquor may be concentrated insufficiently. If feed rate is low, film cannot be maintained. Dry patches may form on the tube walls.

FALLING FILM EVAPORATOR

Principle : In a falling film evaporator, feed enters from the top and flows down the walls of the tubes. The liquid gets heated rapidly due to heat transfer from steam. The liquid boils and becomes vapour, which forms small bubbles. They tend to fuse to form layers of bubbles, which travel down the tubes. Concentration takes place during this downward journey. Vapour and liquid are separated at the bottom.

Construction : The construction of a falling film evaporator is shown in Figure 12-5. It resembles climbing film evaporator, but is inverted. In this evaporator, the heating unit consists of steam jacketed tubes. The feed inlet is from the top of the steam compartment. The other provisions are steam inlet, vent and condensate outlet remain same. The outlet for the product is provided at the bottom and is connected to a cyclone separator.

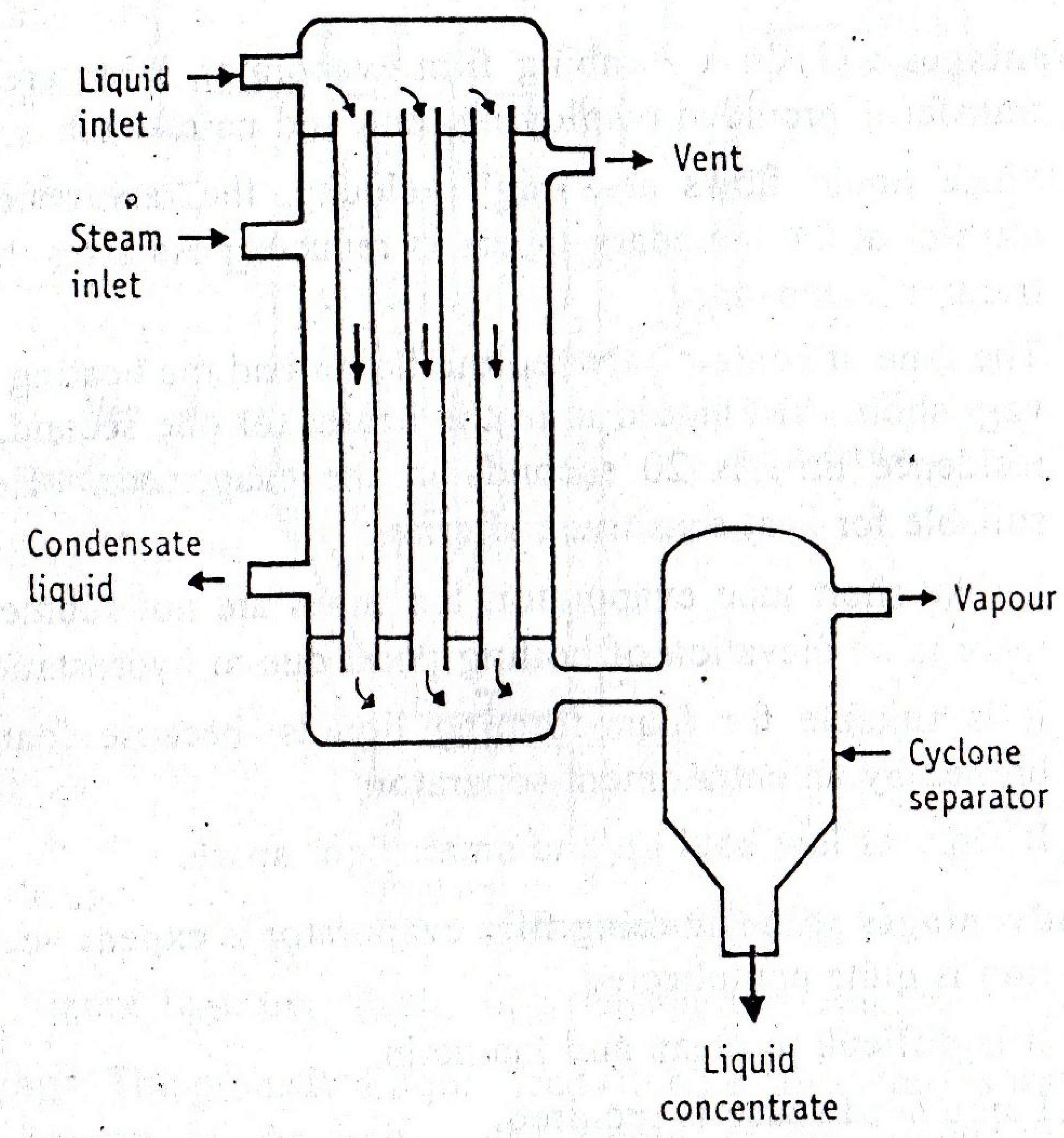

Figure 12-5. Falling film evaporator.

Working : Steam is supplied into the steam compartment. Feed enters from the top of the tubes. The temperature of the boiling liquid is same as that of the vapour head. The feed flows down the walls of the tubes. The liquid gets heated rapidly. The liquid boils and becomes vapour, which forms smaller bubbles. These tend to fuse to form layers of bubbles, which travel down the tubes. Concentration takes place during this downward journey. Vapour and liquid are separated in the cyclone separator.

Uses : Falling film evaporator is used to separate volatile and non-volatile materials, when the feed is of low viscosity. It is used for the concentration of yeast extract, manufacture of gelatin, extracts of tea and

coffee. It is also useful for concentrating the heat sensitive materials such as fruit juices.

Advantages : (1) Falling film evaporator is suitable for high viscous liquids, because the flow of vapour film is assisted by gravity.

(2) The liquid hold-up is less and hold-up time is very small.

(3) The liquid is not overheated during passage and heat transfer coefficients are high even at low boiling temperature.

(4) Highly acidic and corrosive feeds can be concentrated using impervious graphite tubes and rubber lined vapour heads.

Disadvantages : Easy distribution of feed to the individual tubes may be accomplished using a perforated plate above the tubes or using spray nozzles. Hence, it is not suitable for suspensions, as the solids clog the perforated plate. It is not suitable for salting or scaling liquids. The feed distribution in the tubes is poor. For continuous supply, the liquid may be recirculated or the ratio of feed to evaporation is kept high.

FORCED CIRCULATION EVAPORATOR

Principle : In forced circulation evaporator, liquid is circulated through the tubes at high pressures by means of a pump. Hence, boiling does not takes place because boiling point is elevated. Forced circulation of the liquid also creates some form of agitation. When the liquid leaves the tubes and enters the vapour head, pressure falls suddenly. This leads to the flashing of super heated liquor. Thus evaporation is effected.

Construction : The construction of a forced circulation evaporator is shown in Figure 12-6. The steam jacketed tubes are held between two tube sheets. The tube measures 0.1 metres inside diameter and 2.5 metres long. The part of the tubes projects into the vapour head (flash chamber), which consists of a deflector. The vapour head is connected to a return pipe, which runs downwards and enters into the inlet of a pump.

Working : Steam is introduced into calendria. Pump sends the liquid to the tubes with a positive velocity. As the liquid moves up through the tubes, it gets heated and begins to boil. As a result, the vapour and liquid mixture rushes out of the tubes at a high velocity. This mixture strikes the deflector, which throws the liquid downward. This results in an effective separation of liquid and vapour. The vapour enters the cyclone separator and leaves the equipment. The concentrated liquid returns to the pump for further evaporation. Finally the concentrated product is collected.

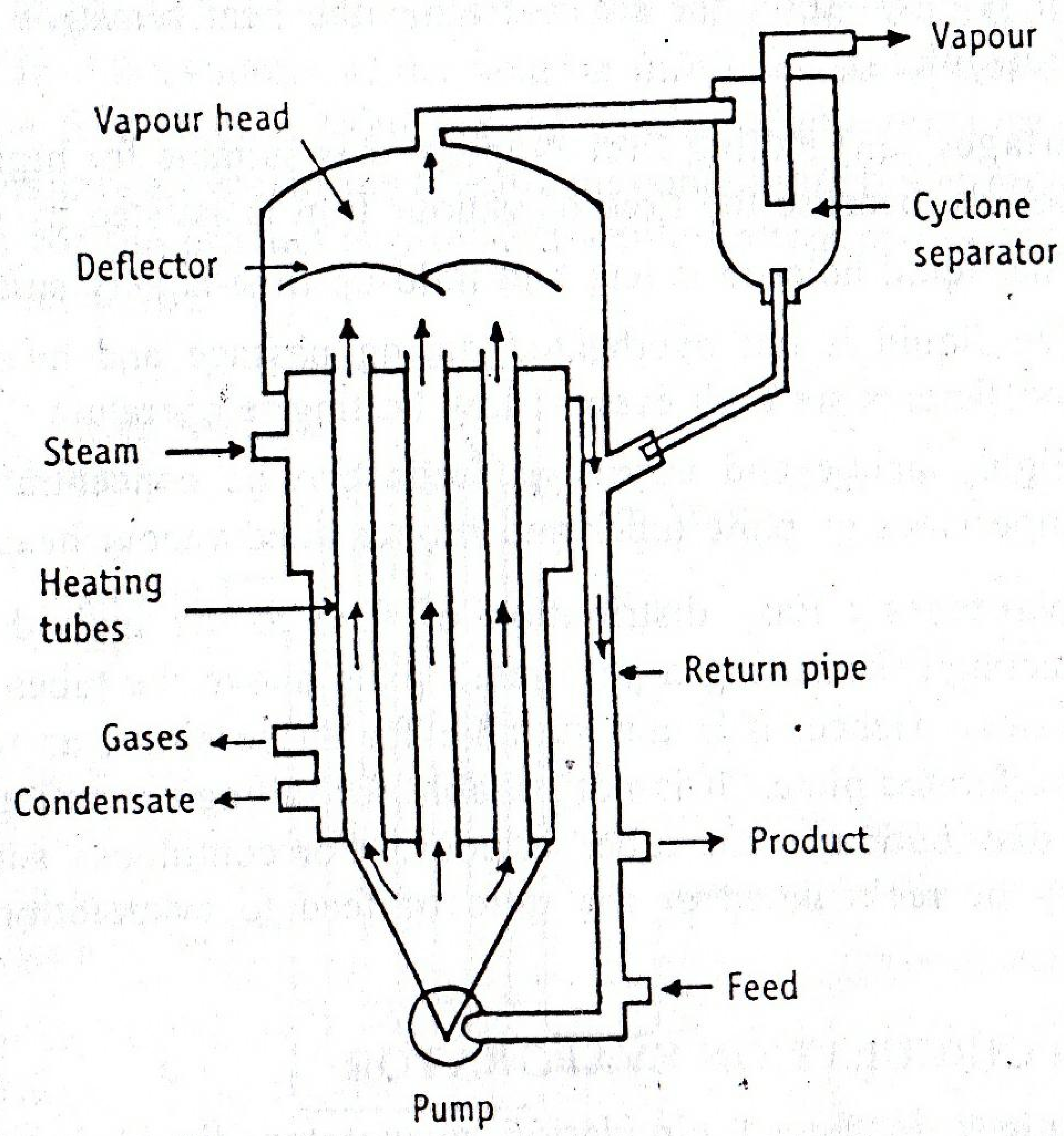

Figure 12-6. Forced circulation evaporator.

Uses : If evaporation is conducted under reduced pressure, forced circulation evaporator is suitable for thermolabile substances. This method is used for the concentration of insulin and liver extracts. It is well suited for crystallizing operations where crystals are to be suspended at all times.

Advantages : (1) In forced circulation evaporator, the heat transfer coefficient is high due to rapid liquid movement.

(2) Salting, scaling and fouling are not possible due to forced circulation.

(3) This evaporator is suitable for thermolabile substances because of rapid evaporation.

(4) It is suitable for high viscous preparations because pumping mechanism is used.

Disadvantages : In forced circulation evaporator, the hold-up of liquid is high. The equipment is expensive, because power (pump) is required for circulating the liquid.

THEORY

In an evaporator, heat is transferred to the evaporating liquid so as to provide latent heat of vaporisation. Generally, steam is used as a source of heat. Several heat exchangers have been discussed in Chapter 'Heat Flow'. Normally, tube and shell heat exchangers are used for heat transfer.

The amount of heat, which must be transferred through the walls of a calandria, varies with the nature of the liquid to be evaporated. The liquids used in pharmacy practice are water and hydroalcoholic solutions with low solid content. In case of bulk drugs, organic solvents are also used.

Evaporator Capacity

The total amount of heat required can be obtained by considering a simple diagram of an evaporator as shown in Figure 12-7.

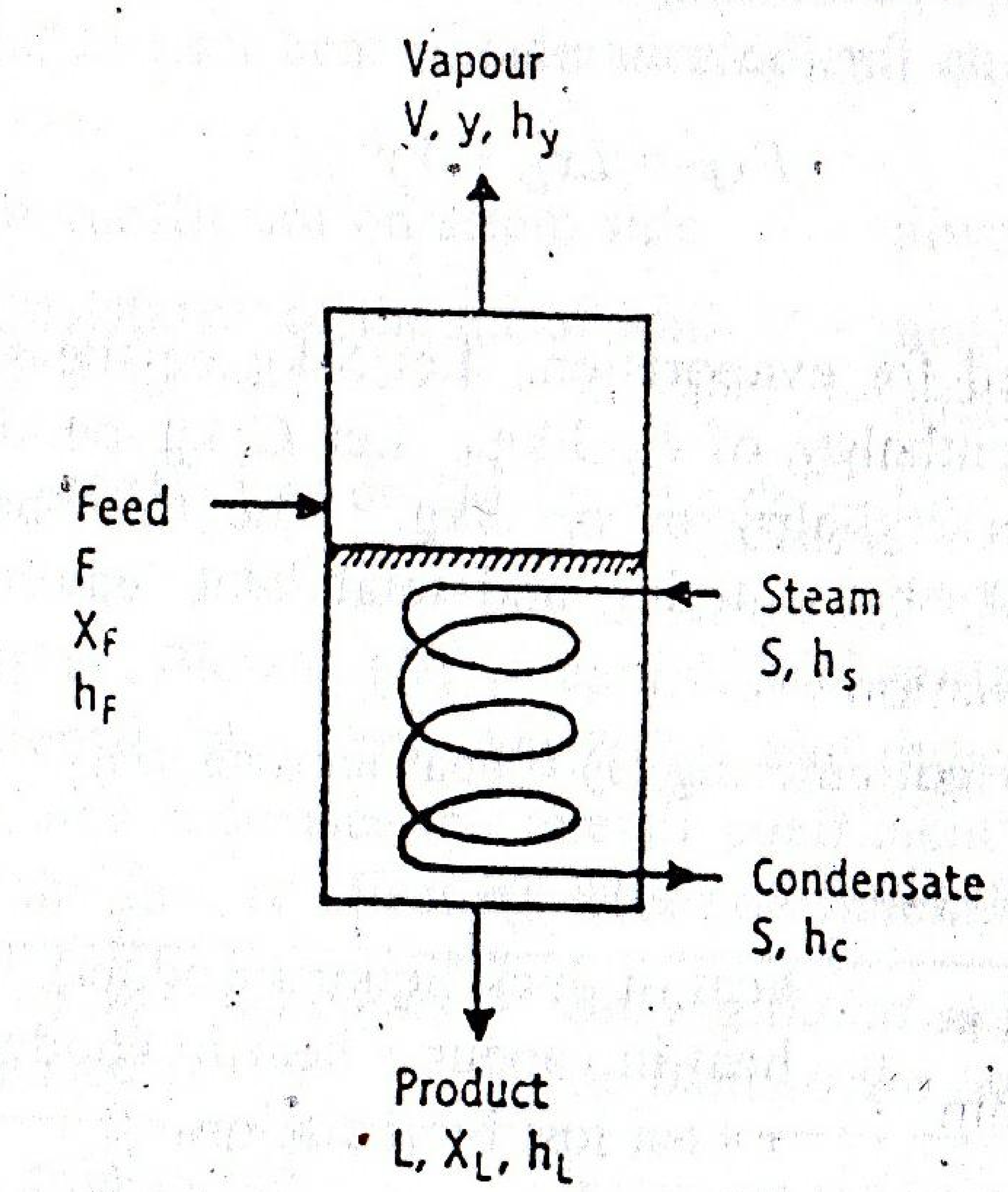

Figure 12-7. Evaporator system with its parameters.

Feed and steam are admitted into the evaporator. By consuming heat, the feed undergoes evaporation to form vapour, which will be allowed to escape. The concentrated product will be collected at its bottom. Simultaneously steam looses its heat energy and undergoes condensation, the condensate of which will be removed.

- Let F kg be the feed per hour to the evaporator, whose solid content is x_F (weight fraction) and enthalpy is h_F J/kg.

- Let L kg be the product collected per hour from an evaporator, whose solute composition is x_L (weight fraction) and enthalpy is h_L J/kg.
- Let V kg be the vapour liberated per hour from an evaporator, whose solute composition is y (weight fraction) and enthalpy is h_V J/kg. In most evaporators, the vapour is pure water as there is no entrainment and therefore y is zero.

Material Balancing

The material balance can be obtained from total material entering and total material leaving. It can be represented by an equation for the evaporation process.

Feed (kg) = product collected (kg) + vapour liberated (kg)

$$F = L + V \qquad (1)$$

Equation (1) can also be written for material balancing in terms of mass x weight fraction for the solute as:

$$Fx_F = Lx_L + Vy \qquad (2)$$

Energy Balancing

Steam is supplied for evaporation. Let S kg be the steam supplied per hour with an enthalpy of h_S J/kg. Let C kg be the condensate removed having an enthalpy of h_C J/kg. The heat balance can be obtained from total heat entering and total heat leaving. It can be represented by equation (3).

Heat entering (J) = heat leaving (J) (3)

Equation (3) can also be written as:

Heat in feed + heat in steam = heat in thick liquor (product) + heat in vapour + heat in condensate + heat lost by radiation. (4)

Loss of heat by radiation is less and can be neglected. The equation (4) can also be written in terms of mass x enthalpy as:

$$Fh_F + Sh_S = Lh_L + Vh_V + Sh_C \qquad (5)$$

Temperature difference is the difference between the saturation temperature of the steam and the boiling point of the liquid. Generally, a temperature difference of 20 to 30°C is sufficient for rapid evaporation of solution. But in practice, the feed may have the temperature less than boiling point of the liquid. The steam may be superheated and the condensate may get cooled. All these factors influence evaporator calculation with respect to mass balance.

Improving Heat Transfer Coefficients

Evaporator is considered as a heat exchanger. Like any heat exchanger, heat is transferred from steam to the product. The general equation for heat transfer can be expressed by equation (6)

$$Q = UA\Delta t \qquad (6)$$

where Q = rate of heat transfer, W
U = overall heat transfer coefficient, W/m^{2}K
A = heating surface area, m^2
Δt = temperature difference, K

Equation (6) can be used to determine the Q.

Heating surface (A in equation 6) must be large. For this purpose more number of tubes are mounted in parallel to form a unit known as *calandria*. The overall heat transfer coefficient, U, can be regarded as follows.

- Fluid film coefficient on steam side – always relatively higher.
- Thermal resistance of the metal wall. – neglected because it is small.
- Fluid film coefficient on the liquid side – low, major determinant in heat transfer.

The overall coefficient (U) is approximately nearer to the lowest surface coefficient of the film. Any factor that improves the coefficient on the boiling side increases the overall coefficient almost proportionally. Some of the factors affecting these coefficients are:

Steam side – film coefficients can be increased	*Boiling liquid side–surface coefficient can be increased*
Temperature drop should be large	increasing the velocity by pumping the liquid
High temperature at which condensation takes place	decreasing the viscosity by feeding hot liquid
Amount of non-condensed gas in steam should be minimum.	cleaning of the heating surface

Pumping liquids at high velocities (forced circulation) through the tubes has beneficial effect. Such high velocities tend to decrease the thickness of the viscous film and the buffer layer.

Overall coefficients may be seriously lowered because of—

- corrosion of the surfaces.
- deposition of solid material from the evaporating liquid.
- The presence of noncondensable gases in the heating steam (air).

Efforts should be made to prevent the above effects. Forced circulation is an important measure, i.e., increase the velocity of liquid flow to increase the capacity of the evaporator.

MULTIPLE EFFECT EVAPORATOR

Vertical tube evaporator discussed earlier is a single effect evaporator (Figure 12-3). Such evaporators are connected in several ways so as to achieve large scale evaporation as well as greater economy. Although multiple effect evaporators are not used in the pharmaceutical industry, the principles are of interest and should be understood. This is illustrated using an example of triple effect evaporator with a parallel feed mechanism.

Advantages : (1) It is suitable for large scale and for continuous operation.

(2) It is highly economical when compared with single effect.

(3) About 5 evaporators can be attached.

Construction : The construction of a multiple effect evaporator is shown in Figure 12-8 using 3 evaporators, i.e., triple effect evaporator. The other aspects of construction of vertical tube evaporator remain same as mentioned earlier. A perusal to Figure 12-8 indicates that the vapour from first evaporator serves as a heating medium for the 2[nd] evaporator. Similarly, vapour from 2[nd] evaporator serves as a heating medium for the 3[rd] evaporator. Last evaporator is connected to a vacuum pump.

Working : Parallel feed arrangement is used in this example.

Parallel feed : In this method, a hot saturated solution of the feed is directly fed to each of the three effects (evaporation) in parallel without transferring the material from one effect to the other. The parallel feed arrangement is commonly used in the concentration of salt solutions, where the solute crystallizes on concentration without increasing the viscosity.

Operations : In the beginning, the equipment is at room temperature and atmospheric pressure. The liquid feed is introduced to all the three

evaporators up to the level of the upper tube sheets. The following operations are attempted to achieve the effects as specified below.

1. The vent valves V_1, V_2 and V_3 are kept open and all other valves are closed (not shown in Figure 12-8).
2. Now a high vacuum is created in the liquid chambers of evaporators.
3. The steam valve S_1 and condensate valve C_1 are opened. Steam is supplied. Steam first replaces cold air in the steam space of 1[st] evaporator. When all the cold air is removed, the valve, V_1 is closed.
4. The supply of steam is continued until the desired pressure P_0 is created in the steam space of 1[st] evaporator. At this pressure, the temperature of the steam is t_0.

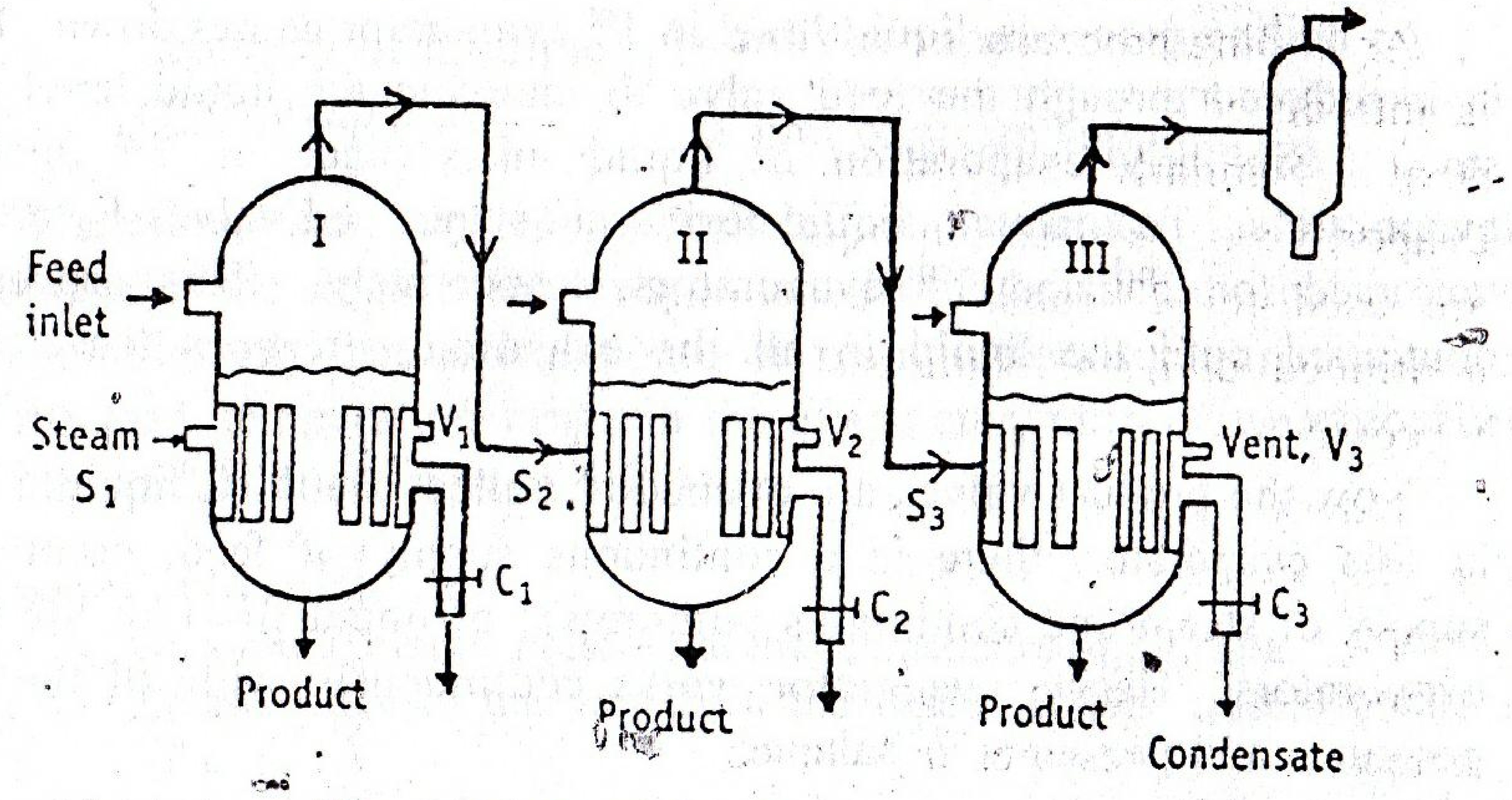

Figure 12-8. Triple effect evaporator with parallel feed arrangements.

5. Steam gives its temperature to the liquid feed in the 1[st] evaporator and gets condensed. Condensate is removed through the valve C_1.
6. Due to heat transfer, the liquid temperature increases and reaches the boiling point. During this process, vapour will be generated from the liquid feed.
7. So formed vapour displaces air in the upper part of 1[st] evaporator. Moreover, the vapour also displaces the air in the steam space of the 2[nd] evaporator.
8. After complete displacement of air by vapour in the steam compartment of 2[nd] evaporator, the valve V_2 is closed.

9. The vapour of 1st evaporator transmits its heat to the liquid of 2nd evaporator and gets condensed. Condensate is removed through the valve C_2. These steps continue in the 3rd evaporator also.

As the liquid in the 1st evaporator gains temperature, the difference in temperatures between the liquid and steam decreases, hence, the rate of condensation decreases. As a result, the pressure in the vapour space of 1st evaporator gradually increases to P_1 by increasing temperature to t_1, which is the boiling point of the liquid in 1st evaporator, and decreasing the temperature difference $(t_0 - t_1)$.

A similar change takes place in the 2nd evaporator and the liquid reaches the boiling point. Similarly, the process will be repeated in 3rd evaporator. Finally three evaporators (or effects as they are called) come to a steady state with the liquid boiling in all the three bodies.

As boiling proceeds, liquid level in 1st evaporator comes down. Feed is introduced through the feed valve to maintain the liquid level constant. Similarly evaporation of liquid takes place in 2nd and 3rd evaporators. To maintain liquid levels constant, feed valves F_2 and F_3 are used for 2nd and 3rd evaporators, respectively. This process is continued until the liquid in all the evaporators reaches the desired viscosity.

Now the product valves are opened to collect the thick liquid. Thus in this evaporator, there is a continuous supply of feed, continuous supply of steam and continuous withdrawal of liquid from all the three evaporators. Hence, evaporator works continuously with all the temperatures and pressures in balance.

The evaporator can also be fed by forward feed method, backward feed method and mixed feed method. In the forward feed method, the mother liquor is introduced into 1st then transferred to 2nd and then to 3rd. In the backward feed method, the mother liquor is introduced into the 3rd evaporator, then transferred to 2nd and then transferred to 1st. In mixed feed method, the mother liquor is introduced into 2nd evaporator then transferred to 3rd evaporator and then transferred to 1st evaporator.

Economy of Multiple Effect Evaporator

The economy of an evaporator is the quantity of vapour produced per unit steam admitted. It is calculated by considering the following assumptions.

Feed is admitted at its boiling point. Therefore, it does not require any more heat to raise its temperature. Hence, the supplied steam gets

condensed to give heat of condensation. This heat will then be transferred completely to the liquid. The heat transferred now serves as latent heat of vaporisation, i.e., liquid undergoes vaporisation by receiving heat. Loss of heat by any means is negligible.

The economy of an evaporator may be expressed as:

$$\text{Economy of an evaporator} = \frac{\text{total mass of vapour produced}}{\text{total mass of steam supplied}}$$

In single effect evaporator, steam produces vapour only once. Hence

$$\text{Economy of a single effect evaporator} = \frac{\text{N units of vapour produced}}{\text{N units of steam supplied}} = 1$$

In multiple effect evaporator, one unit of steam produces vapour many times, depending on the number of evaporators connected. Hence,

$$\text{Economy of multiple effect evaporator} = \frac{\text{N units of vapour produced}}{\text{1 unit of steam supplied}} = N$$

Therefore, economy of multiple effect evaporator is N times the economy of the single effect evaporator. However, such a great economy is approximately true as it depends on many factors such as temperature of the feed, temperature range in the evaporator, ratio of weight of feed to the product and pressure difference.

Glossary of Symbols

- b = Maximum vapour pressure at the temperature of air, kPa.
- b' = Pressure due to the vapour of the liquid actually present in the air, kPa.
- C = Amount of condensate removed, kg.
- F = Amount of feed, kg.
- h_C = Enthalpy of the condensate, J/kg.
- h_F = Enthalpy of the feed, J/kg.
- h_L = Enthalpy of the product concentrate, J/kg.
- h_S = Enthalpy of the steam, J/kg.
- h_V = Enthalpy of the vapour, J/kg.
- K = Constant. m/s.
- L = Mass of product collected from evaporator, kg.
- M = Mass of vapour formed per unit time, m^3/s.
- p = Atmospheric pressure, kPa.
- Q = Rate of heat transfer, W.
- S = Amount of steam introduced, kg.
- S = Surface area of the liquid exposed, m^2.
- Δt = Temperature difference. °K.

X_F = Solid content in the feed (weight fraction).
X_L = Solute composition in the product (weight fraction).
U = Overall heat transfer coefficient, W/m^2. K.
V = Amount of vapour liberated, kg.
y = Solute composition in vapour. (weight fraction)

QUESTION BANK

Each question carries 2 marks

1. Explain the term Evaporator capacity.
2. Define evaporation in terms of capacity and economy as applied to evaporation practice.
3. Explain the construction of calandria. Give its uses.

Each question carries 5 marks

1. Elaborate the concept of multiple effect evaporation. What specific advantages does it offer?
2. Describe the construction and working of film evaporator of any one type.
3. Explain the construction and working of a forced circulation evaporator.

Each question carries 10 marks

1. How do film evaporator function? Elaborate the answer with a neat sketch of one such evaporator. List the merits and demerits of film evaporator system.
2. Classify evaporators. Describe construction and working of a film evaporator.
3. Explain the terms 'multiple effect evaporation' and 'evaporator capacity'. How many effects generally go into a multiple effect evaporator?
4. What do you understand by 'multiple effect evaporator'? Describe one such evaporator. How do you feed such evaporator?