

EVAPORATION

INTRODUCTION

Evaporation is an important unit operation commonly employed to remove water from dilute liquid foods to obtain concentrated liquid products. Removal of water from foods provides microbiological stability and assists in reducing transportation and storage costs. A typical example of the evaporation process is in the manufacture of tomato paste, usually around 35% to 37% total solids, obtained by evaporating water from tomato juice, which has an initial concentration of 5% to 6% total solids. Evaporation differs from dehydration, since the final product of the evaporation process remains in liquid state. It also differs from distillation, since the vapors produced in the evaporator are not further divided into fractions.

In Figure 1 a simplified schematic of an evaporator is shown. Essentially, an evaporator consists of a heat exchanger enclosed in a large chamber; a noncontact heat exchanger provides the means to transfer heat from low-pressure steam to the product. The product inside the evaporation chamber is kept under vacuum. The presence of vacuum causes the temperature difference between steam and the product to increase, and the product boils at relatively low temperatures, thus minimizing heat damage. The vapors produced are conveyed through a condenser to a vacuum system. The steam condenses inside the heat exchanger and the condensate is discarded.

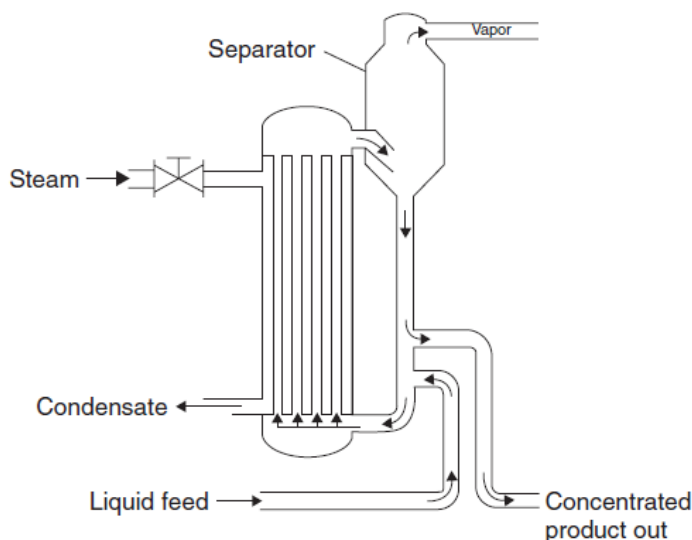


Figure 1. Schematic diagram of an evaporator.

The characteristics of the liquid food have a profound effect on the performance of the evaporation process. As water is removed, the liquid becomes increasingly concentrated, resulting in reduced heat transfer. The boiling point rises as the liquid concentrates, resulting in a smaller differential of temperature between the heating medium and the product. This causes reduced rate of heat transfer.

Food products are noted for their heat sensitivity. Evaporation processes must involve reducing the temperature for boiling as well as the time of heating, to avoid excessive product degradation.

In addition, fouling of the heat-exchange surface can seriously reduce the rate of heat transfer. Frequent cleaning of heat-exchange surfaces requires shutdown of the equipment, thus decreasing the processing capacity. Liquid foods that foam during vaporization cause product losses as a result of escape through vapor outlets. In designing evaporation systems, it is important to keep in perspective the preceding characteristics of liquid food.

Heat transfer in evaporation

An evaporator body is essentially a heat exchanger, equipped with appropriate devices for the separation of the vapors from the boiling liquid. The evaporation capacity of the system is determined, first and foremost, by the rate of energy transfer from the heating medium to the boiling liquid. In the following discussion, we shall analyze ways to maximize the rate of heat transfer in evaporators.

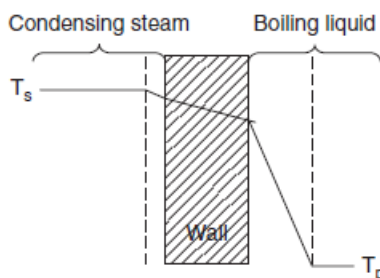


Figure 2. Path of heat transfer in an evaporator

In an evaporator, heat is typically transferred from a film of condensing steam to a film of boiling liquid through a heat-conducting solid wall (Figure 2).

The rate of heat transfer per unit area (heat flux) is given by:

$$\frac{q}{A} = U(T_s - T_c) \quad \text{---- Eq. 1}$$

where U is the overall coefficient of heat transfer ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$).

Heat flux can be increased by increasing the coefficient U or the temperature difference $T_s - T_c$ or both.

1. The overall coefficient of heat transfer U

The overall resistance to heat transfer is the sum of three resistances in series, namely, that of the condensing steam film, that of the solid wall and that of the boiling liquid.

$$\frac{1}{U} = \frac{1}{\alpha_c} + \frac{\varepsilon}{k} + \frac{1}{\alpha_b} \quad \text{---- Eq. 2}$$

α_c and α_b = heat transfer coefficients of condensing steam and boiling liquid films respectively.

ε = thickness of the solid wall, m

k = thermal conductivity of the solid, ($\text{w.m}^{-1}.\text{K}^{-1}$).

The three resistances are not of equal importance. Typical values of the individual coefficients are given in Table 1.

Table 1. Typical values of the three components of Eq. (2)

Coefficient	Characterization	$\text{w.m}^{-2}\text{K}^{-1}$
α_c	Steam, condensing as film	10 000
	Steam, condensing as drops	50 000
k/ε	Stainless steel, 1 mm thick	15 000
α_b	Water, forced convection, no boiling	2000
	Water, forced convection, boiling	5000
	Tomato paste, boiling	300

1.1. Heat transfer at the steam side

Semi-empirical methods for the prediction of heat transfer from condensing vapor films are available. The resistance of condensing films is usually low and its contribution to the total resistance is negligible. Care should be taken, however, to avoid superheat (apply de-superheating if necessary), to purge non-condensable gases (air) and to remove the condensates from the heat transfer surface as soon as they are formed.

1.2. Heat transfer through the wall and the problem of fouling

The thermal resistance of the solid wall is also relatively low. The wall (wall of tubes, heating jackets etc.) is usually thin. The wall material is usually a metal with fairly high thermal conductivity, even in the case of stainless steel, which now replaces copper for obvious food safety reasons (typical k values are 17 w/mK for stainless steel, 360 w/mK for copper). The thermal resistance of the 'wall', however, may increase considerably and even become a serious rate limiting factor as a result of *fouling*. Fouling is the deposition of certain solids on the heat transfer area, particularly at the product side. These solids may be coagulated proteins (milk), caramelized sugars (fruit juices, coffee solubles), scorched pulp (tomato paste) or solutes that reach their limit of solubility as the material is concentrated (calcium salts in milk, hesperidin in orange juice). Excessive fouling is detrimental not only to the rate of heat transfer but also to product quality and to equipment lifetime. As fouling builds up on the heat transfer surface, the temperature of the wall increases and the sediments may 'burn', imparting to the product a 'burnt' taste and unsightly black specs.

The rate of fouling often determines the frequency and duration of 'down' periods of the evaporator (for cleaning). The rate of fouling can often be reduced by increasing the turbulence

on the product side (flow, agitation, swept surface) or by pre-treatment of the feed. An example of the pre-treatment solution is found in a particular process for producing high-concentration tomato paste. In this process, tomato juice is centrifuged to separate the pulp from the liquid (serum). The serum, which produces much less fouling, is concentrated by evaporation and then remixed with the pulp.

1.3. Heat transfer at the product side

This is the most critical part of the overall heat transfer. This is also the most difficult to calculate or predict with confidence. Its analytical treatment is made complicated by the presence and action of a vapor phase mixed with the liquid, the discontinuity of the heat transfer surface and the tremendous change in liquid properties as water is removed.

The theoretical study of two-phase heat transfer, an extremely active area of research in the last decades, has not generated reliable and convenient methods for the analytical calculation of the heat transfer coefficient for the boiling liquid side, for the geometries, physical conditions and complex material properties prevailing in most cases of evaporation in the food industry.

Qualitatively, the heat transfer coefficient at the product side increases with the intensity of movement of the liquid in relation to the wall and decreases with liquid viscosity. Regarding viscosity it should be noted that:

- Viscosity increases strongly with concentration
- It is strongly affected by temperature
- Many food liquids are non-Newtonian, shear-thinning fluids. Their 'viscosity' is affected by flow and agitation. The beneficial effect of agitation on the rate of heat transfer is therefore more strongly accentuated in the case of shear-thinning foods such as fruit purees or ketchup.

The production of vapor has contradictory effects on heat transfer. On one hand, the bubbles formed as a result of boiling agitate the liquid and thus improve heat transfer. On the other hand, vapors have poor heat conductivity and therefore tend to impair heat transfer when part of the heat transfer area becomes covered with vapor. The relative importance of these two contradictory effects depend on the rate of vapor production and hence, on the temperature difference ΔT between the surface and the boiling liquid. In classical experiments with pool boiling of water, it has been observed that at low ΔT , vapor is formed as individual bubbles on the heating surface. When the bubbles become sufficiently large, buoyancy overcomes surface tension and the bubbles detach from the surface, to be replaced by new ones. The coefficient of heat transfer increases, due to agitation by the rising bubbles. This is *nucleate boiling*. Now, if ΔT is increased, vapor is generated at a higher rate. A point is reached where vapor is formed faster than it is removed and the surface becomes covered with an insulating blanket of vapor. The coefficient of heat transfer decreases. This is *film boiling*. A value of ΔT exists for which the coefficient is at a maximum (Figure 3).

Although these two stages with a clear transition between them are not observed in actual evaporation with food materials, dependence of coefficient of heat transfer on ΔT has been often

reported to follow the same trend. Considering the two phase nature of heat transfer in evaporation, one can expect to find that factors such as surface tension, vapor specific gravity and vapor mass ratio should have an effect on the heat transfer coefficient. In fact, a number of semi-empirical correlations for α_b feature dimensionless groups containing these parameters have been proposed. Many of these correlations have been developed for 'pool boiling', i.e. for stagnant boiling liquids with no flow or agitation. These correlations may well be useful in the analysis and design of steam boilers and evaporators in refrigeration systems but they are not easily applicable to the rational design of evaporators for food liquids.

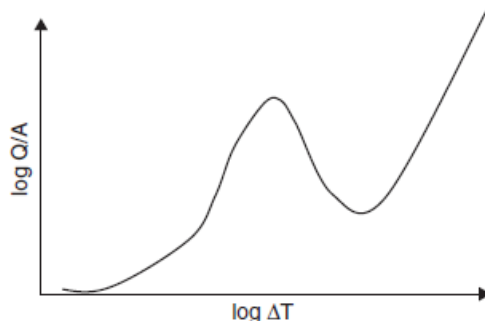


Figure 3. Effect of ΔT on heat flux

2. The temperature difference $T_s - T_C$ (ΔT)

This is, of course, the 'driving force' of heat transfer. It can be increased either by elevating the temperature of the steam or by lowering the temperature of evaporation. Each one of these two actions is applied in practice but each has its practical limitations:

- i. **Increasing the steam temperature:** higher steam temperature means higher wall temperature and increased risk of thermal damage to the product in direct contact with the wall, particularly if heat transfer at the product side is not sufficiently rapid (lack of turbulence, highly viscous products). Furthermore, this action implies higher steam pressure, therefore a mechanically stronger, more expensive structure.
- ii. **Lowering the boiling temperature:** the boiling temperature of a solution is a function of concentration and pressure. The boiling temperature of an aqueous solution is higher than that of pure water at the same pressure. The difference is known as the 'boiling point elevation' BPE. The boiling point elevation of a solution is a consequence of the water vapor pressure depression caused by the presence of solutes. BPE increases with the molar concentration of the solutes. In ideal solutions, the water vapor depression and hence the boiling point elevation can be easily calculated. Due to the relatively high molecular weight of the solutes, the boiling point elevation of food liquids is not large. In practice, the boiling temperature in an evaporator is lowered by reducing the pressure at the product side. Thus, evaporation under vacuum has the dual purpose of increasing the rate of heat transfer and avoiding excessive heat damage to the product. In an evaporator, pressure reduction is achieved by condensing the vapors in the condenser and eliminating the non-condensable

gases by means of a vacuum pump or ejector. In modern evaporators, moderate vacuum is preferred, resulting in somewhat higher evaporation temperature but allowing shorter residence time.

TYPES OF EVAPORATORS

Several types of evaporators are used in the food industry. In this section, a brief discussion of the more common types is given.

1. Batch-Type Pan Evaporator

One of the simplest and perhaps oldest types of evaporators used in the food industry is the batch-type pan evaporator, shown in Figure 4. The product is heated in a steam jacketed spherical vessel. The heating vessel may be open to the atmosphere or connected to a condenser and vacuum. Vacuum permits boiling the product at temperatures lower than the boiling point at atmospheric pressure, thus reducing the thermal damage to heat-sensitive products.

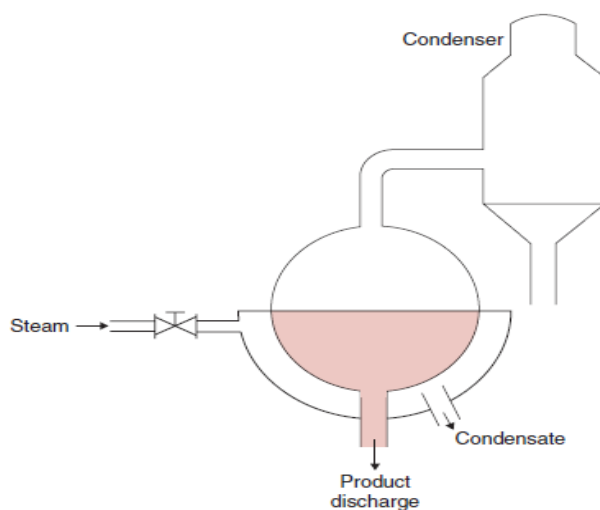


Figure 4. A batch-type pan evaporator.

The heat-transfer area per unit volume in a pan evaporator is small. Thus, the residence time of the product is usually very long, up to several hours. Heating of the product occurs mainly due to natural convection, resulting in smaller convective heat-transfer coefficients. The poor heat-transfer characteristics substantially reduce the processing capacities of the batch-type pan evaporators.

2. Natural Circulation Evaporators

In natural circulation evaporators, short vertical tubes, typically 1–2 m long and 50–100 mm in diameter, are arranged inside the steam chest. The whole calandria (tubes and steam chest) is located in the bottom of the vessel. The product, when heated, rises through these tubes by natural circulation while steam condenses outside the tubes. Evaporation takes place inside the tubes, and the product is concentrated. The concentrated liquid falls back to the base of the vessel through a central annular section. A natural-circulation evaporator is shown in Figure 5. A

shell-and-tube heat exchanger can be provided outside the main evaporation vessel to preheat the liquid feed.

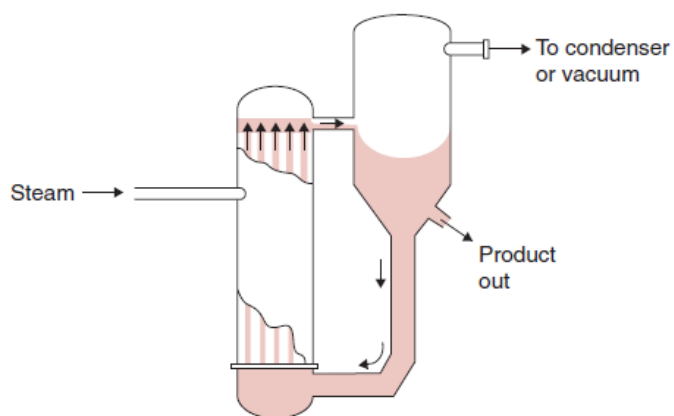


Figure 5. A natural-circulation evaporator.

3. Rising-Film Evaporator

In a rising-film evaporator (Fig. 6), a low-viscosity liquid food is allowed to boil inside 10–15 m-long vertical tubes. The tubes are heated from the outside with steam. The liquid rises inside these tubes by vapors formed near the bottom of the heating tubes. The upward movement of vapors causes a thin liquid film to move rapidly upward. A temperature differential of at least 14°C between the product and the heating medium is necessary to obtain a well-developed film. High convective heat-transfer coefficients are achieved in these evaporators. Although the operation is mostly once-through, liquid can be recirculated if necessary to obtain the required solid concentration.

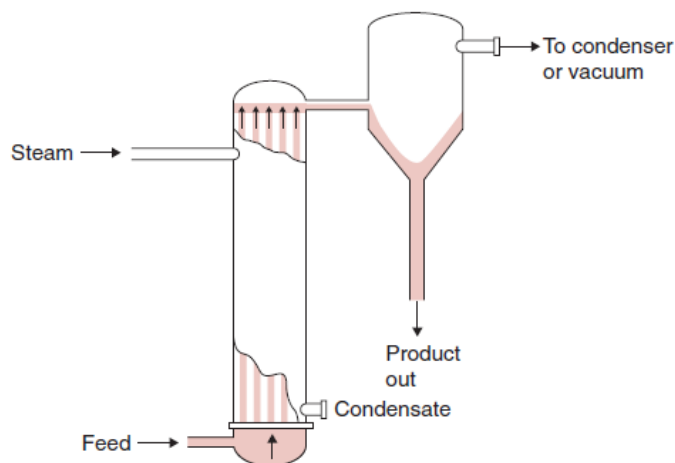


Figure 6. A rising-film evaporator.

4. Falling-Film Evaporator

In contrast to the rising-film evaporator, the falling-film evaporator has a thin liquid film moving downward under gravity on the inside of the vertical tubes (Fig. 7). The design of such evaporators is complicated by the fact that distribution of liquid in a uniform film flowing downward in a tube is more difficult to obtain than an upward-flow system such as in a rising-film evaporator. This is accomplished by the use of specially designed distributors or spray nozzles.

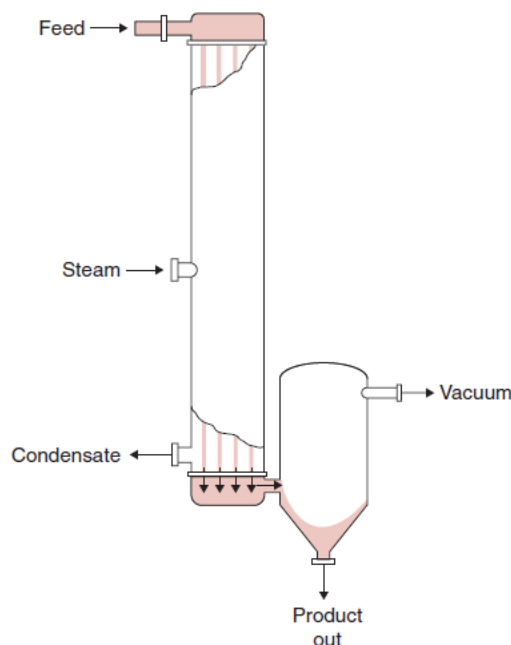


Figure 7. A falling-film evaporator.

The falling-film evaporator allows a greater number of effects than the rising-film evaporator. For example, if steam is available at 110°C and the boiling temperature in the last effect is 50°C, then the total available temperature differential is 60°C. Since rising-film evaporators require 14°C temperature differential across the heating surface, only four effects are feasible. However, as many as 10 or more effects may be possible using a falling-film evaporator. The falling-film evaporator can handle more viscous liquids than the rising-film type. This type of evaporator is best suited for highly heat-sensitive products such as orange juice. Typical residence time in a falling-film evaporator is 20 to 30 seconds, compared with a residence time of 3 to 4 minutes in a rising-film evaporator.

5 Rising/Falling-Film Evaporator

In the rising/falling-film evaporator, the product is concentrated by circulation through a rising-film section followed by a falling-film section of the evaporator. As shown in Figure 8, the product is first concentrated as it ascends through a rising tube section, followed by the pre-concentrated product descending through a falling-film section; there it attains its final concentration.

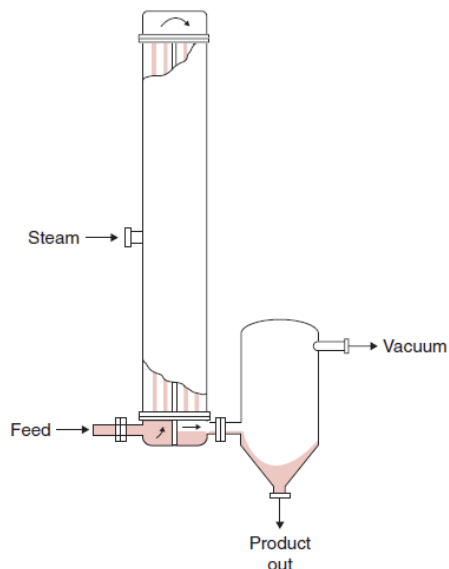


Figure 8. A rising/falling-film evaporator.

6. Forced-Circulation Evaporator

The forced-circulation evaporator involves a noncontact heat exchanger where liquid food is circulated at high rates (Fig. 9). A hydrostatic head, above the top of the tubes, eliminates any boiling of the liquid. Inside the separator, absolute pressure is kept slightly lower than that in the tube bundle. Thus, the liquid entering the separator flashes to form a vapor. The temperature difference across the heating surface in the heat exchanger is usually 3–5°C. Axial flow pumps are generally used to maintain high circulation rates with linear velocities of 2–6 m/s, compared with a linear velocity of 0.3–1 m/s in natural circulation evaporators. Both capital and operating costs of these evaporators are very low in comparison with other types of evaporators.

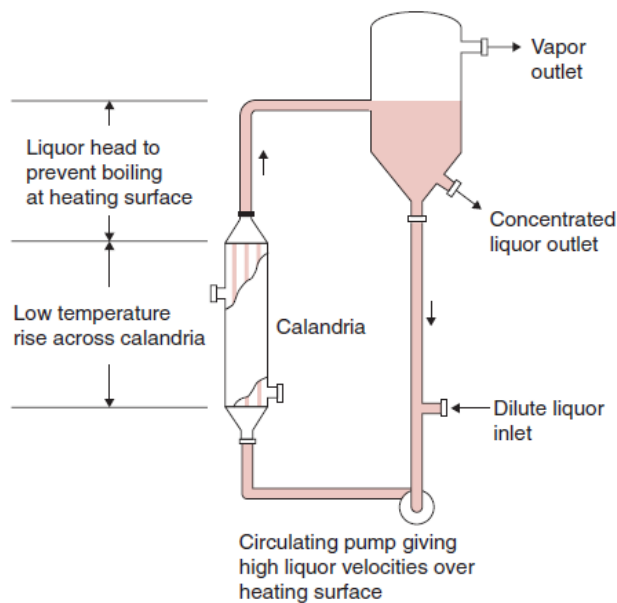


Figure 9. A forced-circulation evaporator

7. Agitated Thin-Film Evaporator

For very viscous fluid foods, feed is spread on the inside of the cylindrical heating surface by wiper blades, as shown in Figure 10. Due to high agitation, considerably higher rates of heat transfer are obtained. The cylindrical configuration results in low heat-transfer area per unit volume of the product. High-pressure steam is used as the heating medium to obtain high wall temperatures for reasonable evaporation rates. The major disadvantages are the high capital and maintenance costs and low processing capacity.

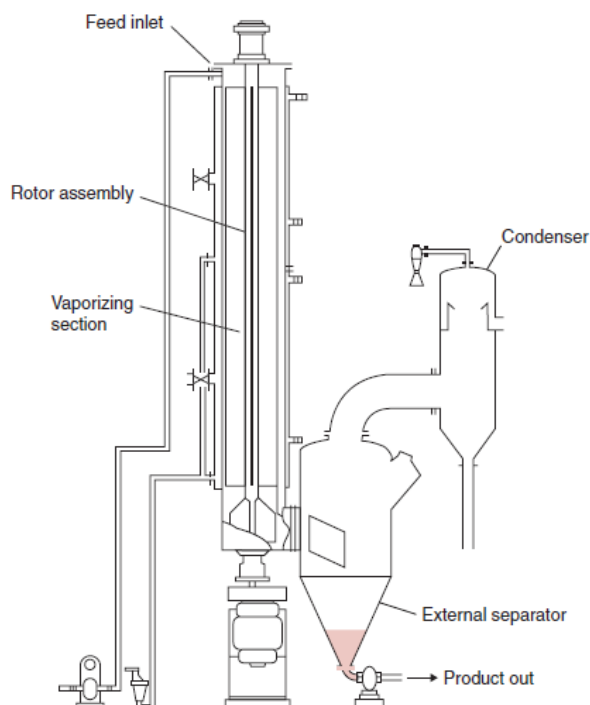


Figure 10. An agitated thin-film evaporator.

In addition to the tubular shape, plate evaporators are also used in the industry. Plate evaporators use the principles of rising/falling-film, falling-film, wiped-film, and forced-circulation evaporators. The plate configuration often provides features that make it more acceptable. A rising/falling-film plate evaporator is more compact, thus requiring less floor area than a tubular unit. The heat-transfer areas can easily be inspected. A falling-film plate evaporator with a capacitor of 25,000 to 30,000 kg water removed per hour is not uncommon.

DESIGN OF A SINGLE-EFFECT EVAPORATOR

In a single-effect evaporator, as shown in Figure 11, dilute liquid feed is pumped into the heating chamber, where it is heated indirectly with steam. Steam is introduced into the heat exchanger, where it condenses to give up its heat of vaporization to the feed, and exits the system as condensate.

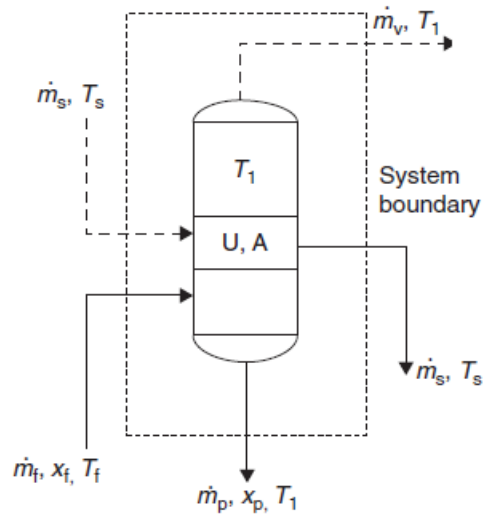


Figure 11. Schematic diagram of a single-effect evaporator.

The temperature of evaporation, T_1 , is controlled by maintaining vacuum inside the heating chamber. The vapors leaving the product are conveyed through a condenser to a vacuum system, usually a steam ejector or a vacuum pump. In a batch system, the feed is heated until the desired concentration is obtained. The concentrated product is then pumped out of the evaporator system.

Heat and mass balances conducted on the evaporator system allow determination of various design and operating variables. Such variables may include mass flow rates, final concentration of product, and heat-exchanger area.

The following expressions can be obtained by conducting a mass balance on flow streams and product solids, respectively.

$$\dot{m}_f = \dot{m}_v + \dot{m}_p \quad \text{-----Eq. 3}$$

where \dot{m}_f is the mass flow rate of dilute liquid feed (kg/s), \dot{m}_v is the mass flow rate of vapor (kg/s), and \dot{m}_p is the mass flow rate of concentrated product (kg/s),

$$x_f \dot{m}_f = x_p \dot{m}_p \quad \text{-----Eq. 4}$$

where x_f is the solid fraction in the feed stream (dimensionless) and x_p is the solid fraction in the product stream (dimensionless).

An enthalpy balance conducted on the evaporator system gives the following expression:

$$\dot{m}_f H_f + \dot{m}_s H_{vs} = \dot{m}_v H_{v1} + \dot{m}_p H_{p1} + \dot{m}_s H_{cs} \quad \text{-----Eq. 5}$$

where \dot{m}_s is the mass flow rate of steam (kg/s); H_f is enthalpy of dilute liquid feed (kJ/kg); H_{p1} is enthalpy of concentrated product (kJ/kg); H_{vs} is enthalpy of saturated vapor at temperature T_s (kJ/kg); H_{v1} is enthalpy of saturated vapor at temperature T_1 (kJ/kg); H_{cs} is enthalpy of condensate (kJ/kg); T_s is temperature of steam ($^{\circ}\text{C}$); T_1 is the boiling temperature maintained inside the evaporator chamber ($^{\circ}\text{C}$); and T_f is the temperature of dilute liquid feed ($^{\circ}\text{C}$).

The first term in Equation (5), $\dot{m}_f H_f$, represents the total enthalpy associated with the incoming dilute liquid feed, where H_f is a function of T_f and x_f . The enthalpy content H_f can be computed from

$$H_f = c_{pf} (T_f - 0^{\circ}\text{C}) \quad \text{-----Eq. 6}$$

The specific heat may be obtained either from specific heat table or by using Equation (i) or Equation (ii).

$$c_p = 2.093 X_f + 1.256 X_s + 4.187 X_w \quad \text{----- Eq. (i)}$$

where X is the mass fraction; and subscripts f is fat, s is nonfat solids, and w is water.

$$c_p = 1.424X_h + 1.549X_p + 1.675X_f + 0.837X_a + 4.187X_w \quad \text{----- Eq. (ii)}$$

where X is the mass fraction; the subscripts on the right-hand side are h, carbohydrate; p, protein; f, fat; a, ash; and w, moisture.

The second term, $\dot{m}_s H_{vs}$, gives the total heat content of steam. It is assumed that saturated steam is being used. The enthalpy, H_{vs} , is obtained from the steam table as enthalpy of saturated vapors evaluated at the steam temperature T_s .

On the right-hand side of Equation (5), the first term, $\dot{m}_v H_{v1}$, represents total enthalpy content of the vapors leaving the system. The enthalpy H_{v1} is obtained from the steam table as the enthalpy of saturated vapors evaluated at temperature T_1 .

The second term, $\dot{m}_p H_{p1}$, is the total enthalpy associated with the concentrated product stream leaving the evaporator. The enthalpy content H_{p1} is obtained using the following equation:

$$H_{p1} = c_{pp} (T_1 - 0^{\circ}\text{C}) \quad \text{----- Eq. 7}$$

where c_{pp} is the specific heat content of concentrated product (kJ/[kg $^{\circ}\text{C}$]).

Again, c_{pp} is obtained from specific heat table or by using Equation (i) or Equation (ii). The last term, $\dot{m}_s H_{cs}$, represents the total enthalpy associated with the condensate leaving the evaporator. Since an indirect type of heat exchanger is used in evaporator systems, the rate of mass flow of incoming steam is the same as the rate of mass flow of condensate leaving the evaporator. The enthalpy H_{cs} is obtained from the steam table as enthalpy of saturated liquid

evaluated at temperature T_s . If the condensate leaves at a temperature lower than T_s , then the lower temperature should be used to determine the enthalpy of the saturated liquid.

In addition to the mass and enthalpy balances given previously, the following two equations are also used in computing design and operating variables of an evaporator system.

For the heat exchanger, the following expression gives the rate of heat transfer:

$$q = UA (T_s - T_1) = \dot{m}_s H_{vs} - \dot{m}_s H_{cs} \quad \text{----- Eq. 8}$$

where q is the rate of heat transfer (W), U is the overall heat transfer coefficient (W/[m² K]), and A is the area of the heat exchanger (m²).

The overall heat-transfer coefficient decreases as the product becomes concentrated, due to increased resistance of heat transfer on the product side of the heat exchanger. In addition, the boiling point of the product rises as the product becomes concentrated. In Equation (8), a constant value of the overall heat-transfer coefficient is used and would result in some “overdesign” of the equipment.

Steam economy is a term often used in expressing the operating performance of an evaporator system. This term is a ratio of rate of mass of water vapor produced from the liquid feed per unit rate of steam consumed.

$$\text{Steam economy} = \dot{m}_v / \dot{m}_s \quad \text{----- Eq. 9}$$

A typical value for steam economy of a single-effect evaporator system is close to 1.

DESIGN OF A MULTIPLE-EFFECT EVAPORATOR

In a triple-effect evaporator, dilute liquid feed is pumped into the evaporator chamber of the first effect. Steam enters the heat exchanger and condenses, thus discharging its heat to the product. The condensate is discarded. The vapors produced from the first effect are used as the heating medium in the second effect, where the feed is the partially concentrated product from the first effect. The vapors produced from the second effect are used in the third effect as heating medium, and the final product with the desired final concentration is pumped out of the evaporator chamber of the third effect. The vapors produced in the third effect are conveyed to a condenser and a vacuum system. In the forward feed system shown, partially concentrated product from the first effect is fed to the second effect. After additional concentration, product leaving the second effect is introduced into the third effect. Finally, product with the desired concentration leaves the third effect.

Design expressions for multiple-effect evaporators can be obtained in the same manner as for a single-effect evaporator.

Conducting mass balance analysis on the flow streams,

$$\dot{m}_f = \dot{m}_{v1} + \dot{m}_{v2} + \dot{m}_{v3} + \dot{m}_p \quad \text{----- Eq. 10}$$

where \dot{m}_f is the mass flow rate of dilute liquid feed to the first effect (kg/s); \dot{m}_{v1} , \dot{m}_{v2} and \dot{m}_{v3} are the mass flow rates of vapor from the first, second, and third effect, respectively (kg/s); and \dot{m}_p is the mass flow rate of concentrated product from the third effect (kg/s).

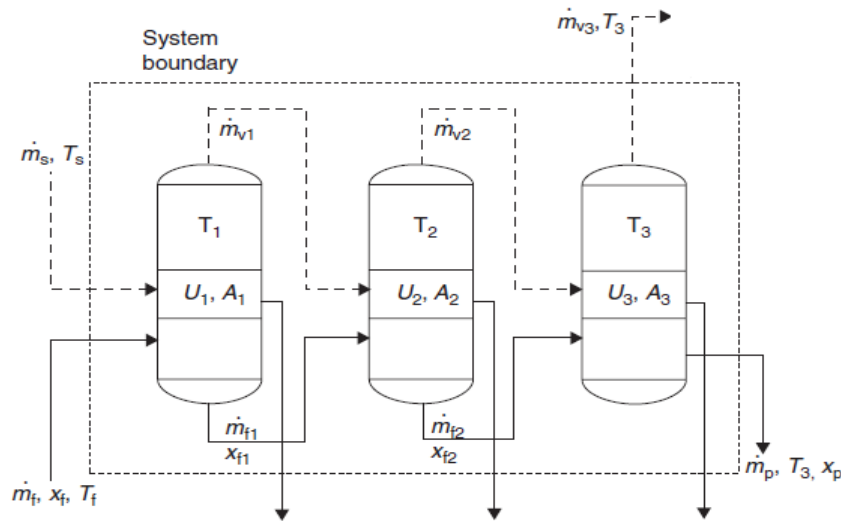


Figure 12. Schematic diagram of a triple-effect evaporator.

Using mass balance on the solids fraction in the flow streams,

$$x_f \dot{m} = x_p \dot{m}_p \quad \text{----- Eq. 11}$$

where x_f is the solid fraction in the feed stream to be consistent with the first effect (dimensionless) and x_p is the solid fraction in the product stream from the third effect (dimensionless).

We write enthalpy balances around each effect separately.

$$\dot{m}_f H_f + \dot{m}_s H_{vs} = \dot{m}_{v1} H_{v1} + \dot{m}_{f1} H_{f1} + \dot{m}_s H_{cs} \quad \text{----- Eq. 12}$$

$$\dot{m}_{f1} H_{f1} + \dot{m}_{v1} H_{v1} = \dot{m}_{v2} H_{v2} + \dot{m}_{f2} H_{f2} + \dot{m}_{v1} H_{c1} \quad \text{----- Eq. 13}$$

$$\dot{m}_{f2} H_{f2} + \dot{m}_{v2} H_{v2} = \dot{m}_{v3} H_{v3} + \dot{m}_p H_{p3} + \dot{m}_{v2} H_{c2} \quad \text{----- Eq. 14}$$

where the subscripts 1, 2, and 3 refer to the first, second, and third effect, respectively. The other symbols are the same as defined previously for a single-effect evaporator.

The heat transfer across heat exchangers of various effects can be expressed by the following three expressions:

$$q_1 = U_1 A_1 (T_s - T_1) = \dot{m}_s H_{vs} - \dot{m}_s H_{cs} \quad \text{----- Eq. 15}$$

$$q_2 = U_2 A_2 (T_1 - T_2) = \dot{m}_{v1} H_{v1} - \dot{m}_{v1} H_{c1} \quad \text{----- Eq. 16}$$

$$q_3 = U_3 A_3 (T_2 - T_3) = \dot{m}_{v2} H_{v2} - \dot{m}_{v2} H_{c2} \quad \text{----- Eq. 17}$$

The steam economy for a triple-effect evaporator as shown in Figure 12 is given by

$$\text{Steam economy} = \frac{\dot{m}_{v1} + \dot{m}_{v2} + \dot{m}_{v3}}{\dot{m}_s} \quad \text{----- Eq. 18}$$