

CHAPTER 8

Evaporation

8.1 INTRODUCTION

8.1A Purpose

In Section 4.8 we discussed the case of heat transfer to a boiling liquid. An important instance of this type of heat transfer occurs quite often in the process industries and is given the general name *evaporation*. In evaporation the vapor from a boiling liquid solution is removed and a more concentrated solution remains. In the majority of cases the separation process called evaporation refers to the removal of water from an aqueous solution.

Typical examples of evaporation are concentration of aqueous solutions of sugar, sodium chloride, sodium hydroxide, glycerol, glue, milk, and orange juice. In these cases the concentrated solution is the desired product and the evaporated water is normally discarded. In a few cases, water, which contains a small amount of minerals, is evaporated to give a solids-free water to be used as boiler feed, for special chemical processes, or for other purposes. Evaporation processes to evaporate seawater to provide drinking water have been developed and used. In some cases, the primary purpose of evaporation is to concentrate a solution so that upon cooling, salt crystals will form and be separated. This special evaporation process, termed *crystallization*, is discussed in Chapter 12.

8.1B Processing Factors

The physical and chemical properties of the solution being concentrated and of the vapor being removed bear greatly on the type of evaporator used and the pressure and temperature of the process. Some of the properties which affect the processing methods are discussed next.

1. *Concentration in the liquid.* Usually, the liquid feed to an evaporator is relatively dilute, so its viscosity is low, similar to that of water, and relatively high heat-transfer coefficients are obtained. As evaporation proceeds, the solution may become very concentrated and quite viscous, causing the heat-transfer coefficient to drop markedly. Adequate circulation and/or turbulence must be present to keep the coefficient from becoming too low.

2. *Solubility.* As solutions are heated and the concentration of the solute or salt increases, the solubility limit of the material in solution may be exceeded and crystals may form. This may limit the maximum concentration in solution which can be obtained by evaporation. In Fig. 8.1-1 some solubilities of typical salts in water are shown as a function of temperature. In most cases the solubility of the salt increases with temperature. This means that when a hot, concentrated solution from an evaporator is cooled to room temperature, crystallization may occur.

3. *Temperature sensitivity of materials.* Many products, especially food and other biological materials, may be temperature-sensitive and degrade at higher temperatures or after prolonged heating. Such products include pharmaceutical products; food products such as milk, orange juice, and vegetable extracts; and fine organic chemicals. The amount of degradation is a function of the temperature and the length of time.

4. *Foaming or frothing.* In some cases materials composed of caustic solutions, food solutions such as skim milk, and some fatty-acid solutions form a foam or froth during boiling. This foam accompanies the vapor coming out of the evaporator and entrainment losses occur.

5. *Pressure and temperature.* The boiling point of the solution is related to the pressure of the system. The higher the operating pressure of the evaporator, the higher the temperature at boiling. Also, as the concentration of the dissolved material in solution increases by evaporation, the temperature of boiling may rise. This phenomenon is called *boiling-point rise* or *elevation* and is discussed in Section 8.4. To keep the temperatures low in heat-sensitive materials, it is often necessary to operate under 1 atm pressure, that is, under vacuum.

6. *Scale deposition and materials of construction.* Some solutions deposit solid materials called *scale* on the heating surfaces. These could be formed by decomposition products or by decreases in solubility. The result is that the overall heat-transfer coefficient decreases, and

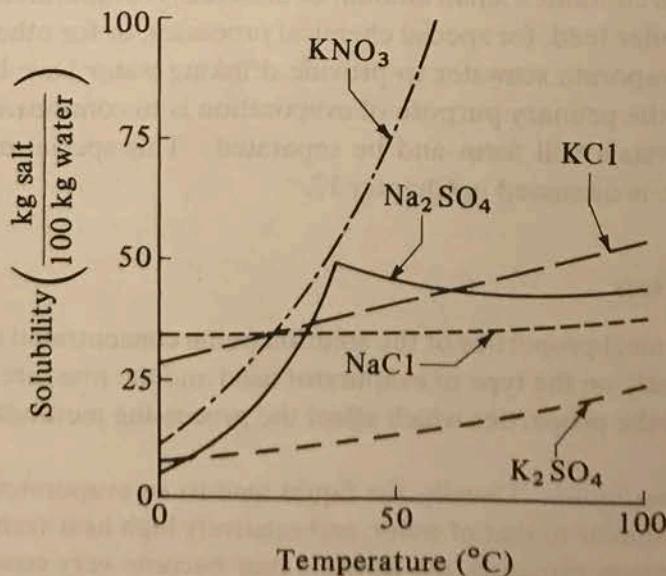


FIGURE 8.1-1. Solubility curves for some typical salts in water.

the evaporator must eventually be cleaned. The materials used in construction of the evaporator should be chosen to minimize corrosion.

8.2 TYPES OF EVAPORATION EQUIPMENT AND OPERATION METHODS

8.2A General Types of Evaporators

In evaporation, heat is added to a solution to vaporize the solvent, which is usually water. The heat is generally provided by the condensation of a vapor such as steam on one side of a metal surface, with the evaporating liquid on the other side. The type of equipment used depends primarily on the configuration of the heat-transfer surface and on the means employed to provide agitation or circulation of the liquid. The general types of equipment are discussed below.

1. *Open kettle or pan.* The simplest evaporator consists of an open pan or kettle in which the liquid is boiled. The heat is supplied by condensation of steam in a jacket or in coils immersed in the liquid. In some cases the kettle is direct-fired. These evaporators are inexpensive and simple to operate, but the heat economy is poor. In some cases, paddles or scrapers are used for agitation.

2. *Horizontal-tube natural circulation evaporator.* The horizontal-tube natural circulation evaporator is shown in Fig. 8.2-1a. The horizontal bundle of heating tubes is similar to the bundle of tubes in a heat exchanger. The steam enters the tubes, where it condenses. The steam condensate leaves at the other end of the tubes. The boiling liquid solution covers the tubes. The vapor leaves the liquid surface, often goes through some de-entraining device such as a baffle to prevent carryover of liquid droplets, and leaves out the top. This type of evaporator is relatively cheap and is used for nonviscous liquids with high heat-transfer coefficients and liquids that do not deposit scale. Since liquid circulation is poor, they are unsuitable for viscous liquids. In almost all cases, this evaporator and the types discussed below are operated continuously, that is, the feed enters at a constant rate and the concentrate leaves at a constant rate.

3. *Vertical-type natural circulation evaporator.* In this type of evaporator, vertical rather than horizontal tubes are used; the liquid is inside the tubes and the steam condenses outside the tubes. Because of boiling and decreases in density, the liquid rises in the tubes by natural circulation, as shown in Fig. 8.2-1b, and flows downward through a large, central open space or downcomer. This natural circulation increases the heat-transfer coefficient. This type of evaporator is not used with viscous liquids. It is often called the *short-tube evaporator*. A variation is the basket type, where vertical tubes are used but the heating element is held suspended in the body so there is an annular open space as the downcomer. In this way, it differs from the vertical natural circulation evaporator, which has a central instead of annular open space as the downcomer. The basket type is widely used in the sugar, salt, and caustic-soda industries.

4. *Long-tube vertical-type evaporator.* Since the heat-transfer coefficient on the steam side is very high compared to that on the evaporating-liquid side, high liquid velocities are desirable. In a long-tube vertical-type evaporator, shown in Fig. 8.2-1c, the liquid is inside the tubes. The tubes are 3 to 10 m long and the formation of vapor bubbles inside the tubes

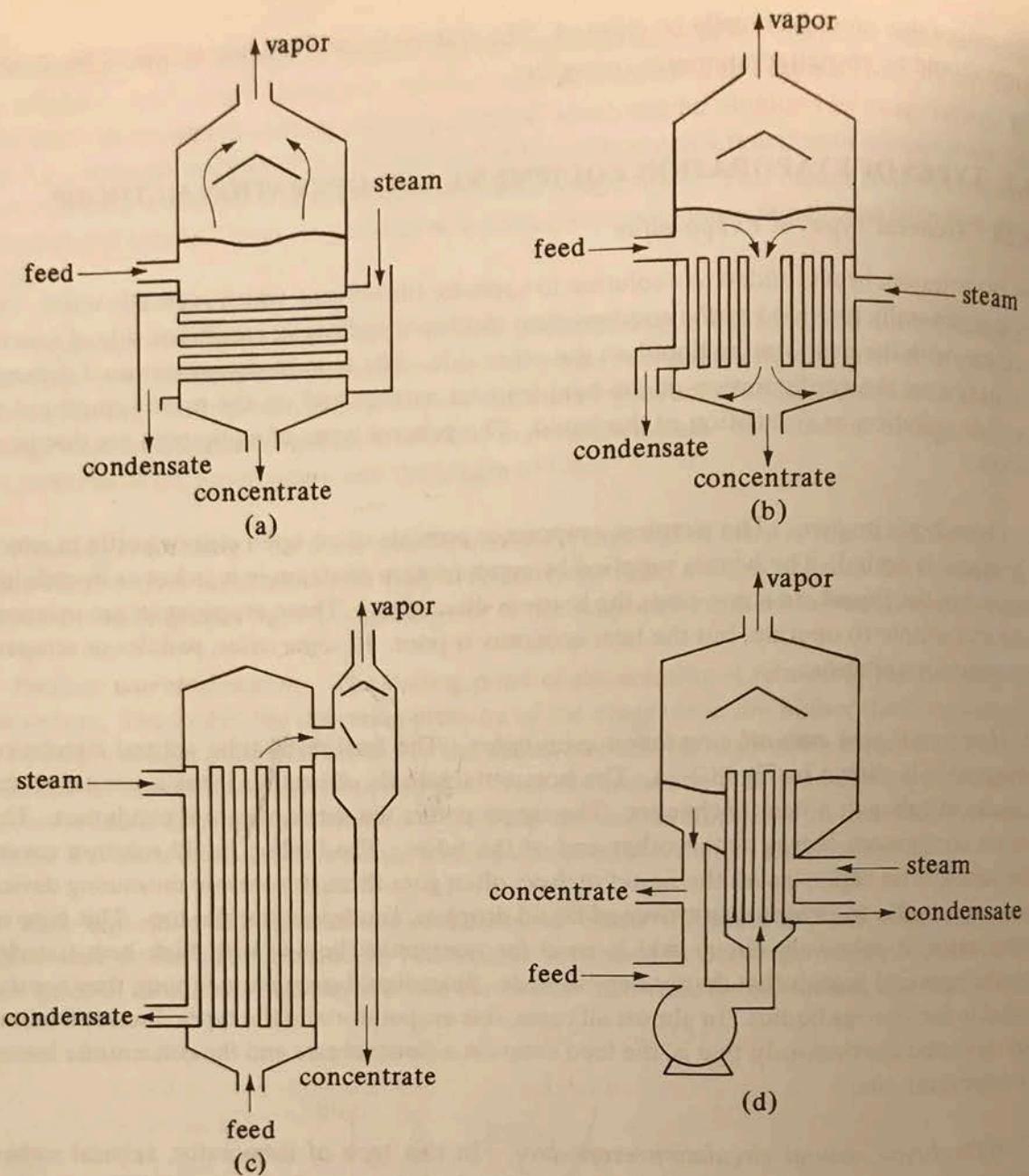


FIGURE 8.2-1. *Different types of evaporators: (a) horizontal-tube type, (b) vertical-tube type, (c) long-tube vertical type, (d) forced-circulation type.*

causes a pumping action, which gives quite high liquid velocities. Generally, the liquid passes through the tubes only once and is not recirculated. Contact times can be quite low in this type. In some cases, as when the ratio of feed to evaporation rate is low, natural recirculation of the product through the evaporator is effected by adding a large pipe connection between the outlet concentrate line and the feed line. This is widely used for producing condensed milk.

5. Falling-film-type evaporator. A variation on the long-tube-type evaporator is the falling-film evaporator, wherein the liquid is fed to the top of the tubes and flows down the walls as a thin film. Vapor-liquid separation usually takes place at the bottom. This type is widely

used for concentrating heat-sensitive materials such as orange juice and other fruit juices, because the holdup time is very small (5 to 10 s or more) and the heat-transfer coefficients are high.

6. *Forced-circulation-type evaporator.* The liquid-film heat-transfer coefficient can be increased by pumping to cause forced circulation of the liquid inside the tubes. This could be done in the long-tube vertical type shown in Fig. 8.2-1c by adding a pipe connection shown with a pump between the outlet concentrate line and the feed line. In the forced-circulation type, however, the vertical tubes are usually shorter than in the long-tube type, as shown in Fig. 8.2-1d. Additionally, in some cases a separate and external horizontal heat exchanger is used. This type of evaporator is very useful for viscous liquids.

7. *Agitated-film evaporator.* The main resistance to heat transfer in an evaporator is on the liquid side. One way to increase turbulence in this film, and hence the heat-transfer coefficient, is by actual mechanical agitation of this liquid film. This is done in a modified falling-film evaporator with only a single, large, jacketed tube containing an internal agitator. Liquid enters at the top of the tube and as it flows downward, it is spread out into a turbulent film by the vertical agitator blades. The concentrated solution leaves at the bottom and vapor leaves through a separator and out the top. This type of evaporator is very useful with highly viscous materials, since the heat-transfer coefficient is greater than in forced-circulation evaporators. It is used with heat-sensitive viscous materials such as rubber latex, gelatin, antibiotics, and fruit juices. However, it has a high cost and small capacity. For interested readers, Perry and Green (P1) give more-detailed discussions and descriptions of evaporation equipment.

8. *Open-pan solar evaporator.* A very old yet still-used process is solar evaporation in open pans. Saltwater is put in shallow open pans or troughs and allowed to evaporate slowly in the sun to crystallize the salt.

8.2B Methods of Operation of Evaporators

1. *Single-effect evaporators.* A simplified diagram of a single-stage or single-effect evaporator is given in Fig. 8.2-2. The feed enters at T_F K and saturated steam at T_S enters the heat-exchange section. Condensed steam leaves as condensate or drips. Since the solution in the evaporator is assumed to be completely mixed, the concentrated product and the solution in the evaporator have the same composition and temperature T_1 , which is the boiling point of

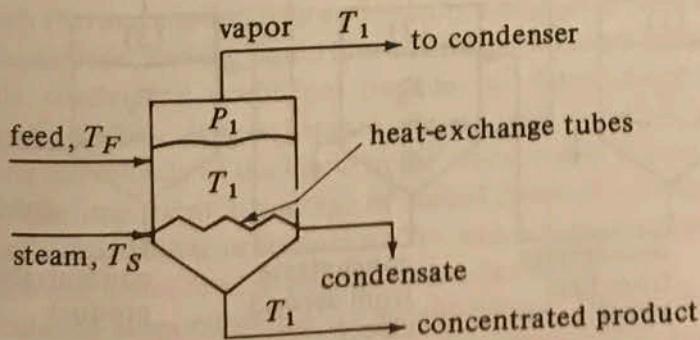


FIGURE 8.2-2. Simplified diagram of single-effect evaporator.

the solution. The temperature of the vapor is also T_1 , since it is in equilibrium with the boiling solution. The pressure is P_1 , which is the vapor pressure of the solution at T_1 .

If the solution to be evaporated is assumed to be dilute and like water, then 1 kg of steam condensing will evaporate approximately 1 kg of vapor. This will hold if the feed entering has a temperature T_F near the boiling point.

The concept of an overall heat-transfer coefficient is used in the calculation of the rate of heat transfer in an evaporator. The general equation can be written

$$q = UA \Delta T = UA(T_S - T_1) \quad (8.2-1)$$

where q is the rate of heat transfer in W (btu/h), U is the overall heat-transfer coefficient in $\text{W}/\text{m}^2 \cdot \text{K}$ ($\text{btu}/\text{h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$), A is the heat-transfer area in m^2 (ft^2), T_S is the temperature of the condensing steam in K (${}^\circ\text{F}$), and T_1 is the boiling point of the liquid in K (${}^\circ\text{F}$).

Single-effect evaporators are often used when the required capacity of operation is relatively small and/or the cost of steam is relatively cheap compared to the evaporator cost. However, for large-capacity operation, using more than one effect will markedly reduce steam costs.

2. Forward-feed multiple-effect evaporators. A single-effect evaporator as shown in Fig. 8.2-2 is wasteful of energy, since the latent heat of the vapor leaving is not used but is discarded. Much of this latent heat, however, can be recovered and reused by employing a multiple-effect evaporator. A simplified diagram of a forward-feed triple-effect evaporation system is shown in Fig. 8.2-3.

If the feed to the first effect is near the boiling point at the pressure in the first effect, 1 kg of steam will evaporate almost 1 kg of water. The first effect operates at a temperature that is high enough that the evaporated water serves as the heating medium to the second effect. Here, again, almost another kg of water is evaporated, which can then be used as the heating medium to the third effect. As a very rough approximation, almost 3 kg of water will be evaporated for 1 kg of steam in a three-effect evaporator. Hence, the *steam economy*, which is kg vapor evaporated/kg steam used, is increased. This also holds approximately for more than three effects. However, the increased steam economy of a multiple-effect evaporator is gained at the expense of the original first cost of these evaporators.

In forward-feed operation as shown in Fig. 8.2-3, the fresh feed is added to the first effect and flows to the next in the same direction as the vapor flow. This method of operation is

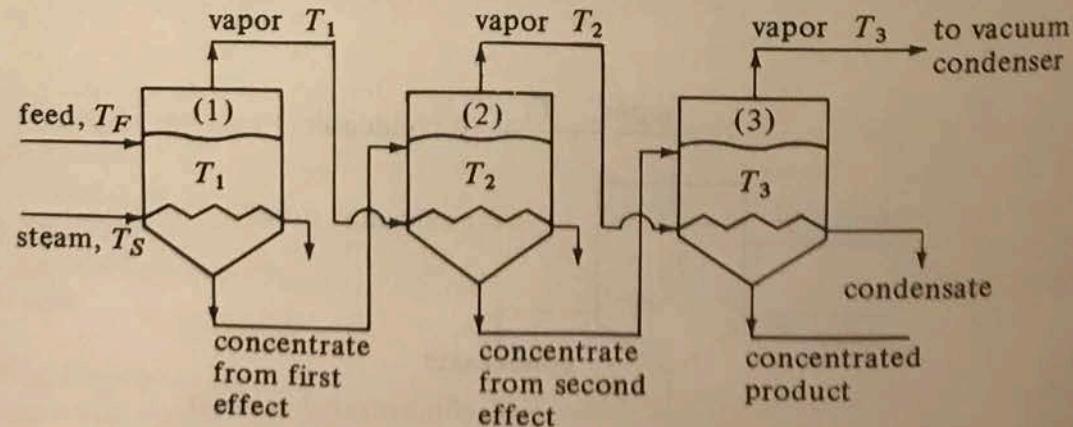


FIGURE 8.2-3. Simplified diagram of forward-feed triple-effect evaporator.

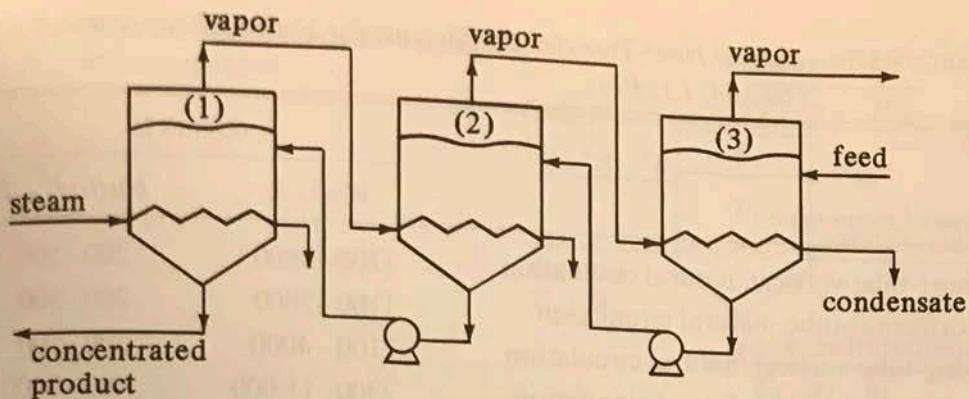


FIGURE 8.2-4. Simplified diagram of backward-feed triple-effect evaporator.

used when the feed is hot or when the final concentrated product might be damaged at high temperatures. The boiling temperatures decrease from effect to effect. This means that if the first effect is at $P_1 = 1$ atm abs pressure, the last effect will be under vacuum at a pressure P_3 .

3. Backward-feed multiple-effect evaporators. In the backward-feed operation shown in Fig. 8.2-4 for a triple-effect evaporator, the fresh feed enters the last and coldest effect and continues on until the concentrated product leaves the first effect. This method of reverse feed is advantageous when the fresh feed is cold, since a smaller amount of liquid must be heated to the higher temperatures in the second and first effects. However, liquid pumps must be used in each effect, since the flow is from low to high pressure. This reverse-feed method is also used when the concentrated product is highly viscous. The high temperatures in the early effects reduce the viscosity and give reasonable heat-transfer coefficients.

4. Parallel-feed multiple-effect evaporators. Parallel feed in multiple-effect evaporators involves the adding of fresh feed and withdrawal of concentrated product from each effect. The vapor from each effect is still used to heat the next effect. This method of operation is mainly used when the feed is almost saturated and solid crystals are the product, as in the evaporation of brine to make salt.

8.3 OVERALL HEAT-TRANSFER COEFFICIENTS IN EVAPORATORS

The overall heat-transfer coefficient U in an evaporator is composed of the steam-side condensing coefficient, which has a value of about $5700 \text{ W/m}^2 \cdot \text{K}$ ($1000 \text{ btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$); the metal wall, which has a high thermal conductivity and usually a negligible resistance; the resistance of the scale on the liquid side; and the liquid film coefficient, which is usually inside the tubes.

The steam-side condensing coefficient outside the tubes can be estimated using Eqs. (4.8-20) through (4.8-26). The resistance due to scale formation usually cannot be predicted. Increasing the velocity of the liquid in the tubes greatly decreases the rate of scale formation, which is one important advantage of forced-circulation evaporators. The scale may be salts, such as calcium sulfate or sodium sulfate, which decrease in solubility with an increase in temperature and hence tend to deposit on the hot tubes.

For forced-circulation evaporators the coefficient h inside the tubes can be predicted if there is little or no vaporization inside the tube. The liquid hydrostatic head in the tubes prevents most boiling in the tubes. The standard equations for predicting the h value of liquids

TABLE 8.3-1. *Typical Heat-Transfer Coefficients for Various Evaporators**
(B3, B4, L1, P1)

Type of Evaporator	Overall <i>U</i>	
	W/m ² · K	btu/h · ft ² · °F
Short-tube vertical, natural circulation	1100–2800	200–500
Horizontal-tube, natural circulation	1100–2800	200–500
Long-tube vertical, natural circulation	1100–4000	200–700
Long-tube vertical, forced circulation	2300–11 000	400–2000
Agitated film	680–2300	120–400

*Generally, nonviscous liquids have the higher coefficients and viscous liquids the lower coefficients in the ranges given.

inside tubes can be used. Velocities used often range from 2 to 5 m/s (7 to 15 ft/s). The heat-transfer coefficient can be predicted from Eq. (4.5-8), using a constant of 0.028 instead of 0.027 (B1). If there is some or appreciable boiling in part or all of the tubes, use of the equation assuming no boiling will give conservative safe results (P1).

For long-tube vertical natural-circulation evaporators the heat-transfer coefficient is more difficult to predict, since there is a nonboiling zone in the bottom of the tubes and a boiling zone in the top. The length of the nonboiling zone depends on the heat transfer in the two zones and the pressure drop in the boiling two-phase zone. The film heat-transfer coefficient in the nonboiling zone can be estimated using Eq. (4.5-8) with a constant of 0.028. For the boiling two-phase zone, a number of equations are given by Perry and Green (P2).

For short-tube vertical evaporators the heat-transfer coefficients can be estimated by using the same methods as for long-tube vertical natural-circulation evaporators. Horizontal-tube evaporators have heat-transfer coefficients on the same order of magnitude as short-tube vertical evaporators.

For the agitated-film evaporator, the heat-transfer coefficient may be estimated using Eq. (4.13-4) for a scraped surface heat exchanger.

The methods given above are useful for actual evaporator design and/or for evaluating the effects of changes in operating conditions on the coefficients. In making preliminary designs or cost estimates, it is helpful to have available overall heat-transfer coefficients usually encountered in commercial practice. Some preliminary values and ranges of values for various types of evaporators are given in Table 8.3-1.

8.4 CALCULATION METHODS FOR SINGLE-EFFECT EVAPORATORS

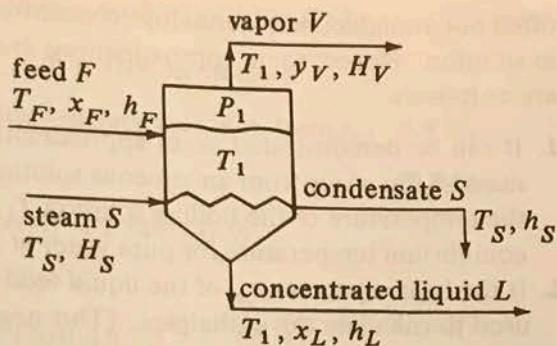
8.4A Heat and Material Balances for Evaporators

The basic equation for solving for the capacity of a single-effect evaporator is Eq. (8.2-1), which can be written as

$$q = UA \Delta T \quad (8.4-1)$$

where ΔT K ($^{\circ}$ F) is the difference in temperature between the condensing steam and the boiling liquid in the evaporator. In order to solve Eq. (8.4-1) the value of q in W (btu/h) must be determined by making a heat and material balance on the evaporator shown in Fig. 8.4-1.

FIGURE 8.4-1. Heat and mass balance for single-effect evaporator.



The feed to the evaporator is F kg/h (lb_m/h) having a solids content of x_F mass fraction, temperature T_F , and enthalpy h_F J/kg (btu/ lb_m). Coming out as a liquid is the concentrated liquid L kg/h (lb_m/h) having a solids content of x_L , temperature T_1 , and enthalpy h_L . The vapor V kg/h (lb_m/h) is given off as pure solvent having a solids content of $y_V = 0$, temperature T_1 , and enthalpy H_V . Saturated steam entering is S kg/h (lb_m/h) and has a temperature of T_S and enthalpy of H_S . The condensed steam leaving of S kg/h is assumed usually to be at T_S , the saturation temperature, with an enthalpy of h_S . This means that the steam gives off only its latent heat, λ , where

$$\lambda = H_S - h_S \quad (8.4-2)$$

Since the vapor V is in equilibrium with the liquid L , the temperatures of vapor and liquid are the same. Also, the pressure P_1 is the saturation vapor pressure of the liquid of composition x_L at its boiling point T_1 . (This assumes no boiling-point rise.)

For the material balance, since we are at steady state, the rate of mass in = rate of mass out. Then, for a total balance,

$$F = L + V \quad (8.4-3)$$

For a balance on the solute (solids) alone,

$$Fx_F = Lx_L \quad (8.4-4)$$

For the heat balance, since the total heat entering = total heat leaving,

$$\begin{aligned} & \text{heat in feed} + \text{heat in steam} \\ &= \text{heat in concentrated liquid} + \text{heat in vapor} + \text{heat in condensed steam} \end{aligned} \quad (8.4-5)$$

This assumes no heat lost by radiation or convection. Substituting into Eq. (8.4-5),

$$Fh_F + SH_S = Lh_L + VH_V + Sh_S \quad (8.4-6)$$

Substituting Eq. (8.4-2) into (8.4-6),

$$Fh_F + S\lambda = Lh_L + VH_V \quad (8.4-7)$$

The heat q transferred in the evaporator is then

$$q = S(H_S - h_S) = S\lambda \quad (8.4-8)$$

In Eq. (8.4-7) the latent heat λ of steam at the saturation temperature T_S can be obtained from the steam tables in Appendix A.2. However, the enthalpies of the feed and products are

often not available; these enthalpy-concentration data are available for only a few substances in solution. Hence, some approximations are made in order to make a heat balance. These are as follows:

1. It can be demonstrated as an approximation that the latent heat of evaporation of 1 kg mass of the water from an aqueous solution can be obtained from the steam tables using the temperature of the boiling solution T_1 (exposed surface temperature) rather than the equilibrium temperature for pure water at P_1 .
2. If the heat capacities c_{pF} of the liquid feed and c_{pL} of the product are known, they can be used to calculate the enthalpies. (This neglects heats of dilution, which in most cases are not known.)

EXAMPLE 8.4-1. Heat-Transfer Area in Single-Effect Evaporator

A continuous single-effect evaporator concentrates 9072 kg/h of a 1.0 wt % salt solution entering at 311.0 K (37.8°C) to a final concentration of 1.5 wt %. The vapor space of the evaporator is at 101.325 kPa (1.0 atm abs) and the steam supplied is saturated at 143.3 kPa. The overall coefficient $U = 1704 \text{ W/m}^2 \cdot \text{K}$. Calculate the amounts of vapor and liquid product and the heat-transfer area required. Assume that, since it is dilute, the solution has the same boiling point as water.

Solution: The flow diagram is the same as in Fig. 8.4-1. For the material balance, substituting into Eq. (8.4-3),

$$F = L + V \quad (8.4-3)$$

$$9072 = L + V$$

Substituting into Eq. (8.4-4) and solving,

$$Fx_F = Lx_L \quad (8.4-4)$$

$$9072(0.01) = L(0.015)$$

$$L = 6048 \text{ kg/h of liquid}$$

Substituting into Eq. (8.4-3) and solving,

$$V = 3024 \text{ kg/h of vapor}$$

The heat capacity of the feed is assumed to be $c_{pF} = 4.14 \text{ kJ/kg} \cdot \text{K}$. (Often, for feeds of inorganic salts in water, the c_p can be assumed to be approximately that of water alone.) To make a heat balance using Eq. (8.4-7), it is convenient to select the boiling point of the dilute solution in the evaporator, which is assumed to be that of water at 101.32 kPa, $T_1 = 373.2 \text{ K}$ (100°C), as the datum temperature. Then H_V is simply the latent heat of water at 373.2 K, which from the steam tables in Appendix A.2 is 2257 kJ/kg (970.3 btu/lb_m). The latent heat λ of the steam at 143.3 kPa [saturation temperature $T_s = 383.2 \text{ K}$ (230°F)] is 2230 kJ/kg (958.8 btu/lb_m).

The enthalpy of the feed can be calculated from

$$h_F = c_{pF}(T_F - T_1) \quad (8.4-9)$$

Substituting into Eq. (8.4-7) with $h_L = 0$, since it is at the datum of 373.2 K,

$$9072(4.14)(311.0 - 373.2) + S(2230) = 6048(0) + 3024(2257)$$

$$S = 4108 \text{ kg steam/h}$$

The heat q transferred through the heating surface area A is, from Eq. (8.4-8),

$$q = S(\lambda) \quad (8.4-8)$$

$$q = 4108(2230)(1000/3600) = 2544\,000 \text{ W}$$

Substituting into Eq. (8.4-1), where $\Delta T = T_s - T_1$,

$$q = 2544\,000 = UA \Delta T = 1704(A)(383.2 - 373.2)$$

Solving, $A = 149.3 \text{ m}^2$.

8.4B Effects of Processing Variables on Evaporator Operation

1. *Effect of feed temperature.* The inlet temperature of the feed has a large effect on the operation of the evaporator. In Example 8.4-1 the feed entering was at a temperature of 311.0 K, cold as compared to the boiling temperature of 373.2 K. About $\frac{1}{4}$ of the steam used for heating was used to heat the cold feed to the boiling point. Hence, only about $\frac{3}{4}$ of the steam was left for vaporization of the feed. If the feed is under pressure and enters the evaporator at a temperature above the boiling point in the evaporator, additional vaporization is obtained by flashing part of the entering hot feed. Preheating the feed can reduce the size of evaporator heat-transfer area needed.

2. *Effect of pressure.* In Example 8.4-1 a pressure of 101.32 kPa abs was used in the vapor space of the evaporator. This set the boiling point of the solution at 373.2 K and gave a ΔT for use in Eq. (8.4-1) of $383.2 - 373.2$, or 10 K. In many cases a larger ΔT is desirable, since, as ΔT increases, the heating-surface area A and cost of the evaporator decrease. To reduce the pressure below 101.32 kPa, that is, to be under vacuum, a condenser and vacuum pump can be used. For example, if the pressure were reduced to 41.4 kPa, the boiling point of water would be 349.9 K and the new ΔT would be $383.2 - 349.9$, or 33.3 K. A large decrease in heating-surface area would be obtained.

3. *Effect of steam pressure.* Using higher-pressure, saturated steam increases ΔT , which decreases the size and cost of the evaporator. However, high-pressure steam is more costly as well as often being more valuable as a source of power elsewhere. Hence, overall economic balances are really needed to determine the optimum steam pressures.

8.4C Boiling-Point Rise of Solutions

In the majority of cases in evaporation, the solutions are not dilute solutions such as those considered in Example 8.4-1. In most cases, the thermal properties of the solution being evaporated may differ considerably from those of water. The concentrations of the solutions are high enough that the heat capacity and boiling point are quite different from those for water.

For strong solutions of dissolved solutes the boiling-point rise due to the solutes in the solution usually cannot be predicted. However, a useful empirical law known as *Dühring's rule* can be applied. According to this rule, a straight line is obtained if the boiling point of a solution in °C or °F is plotted against the boiling point of pure water at the same pressure for

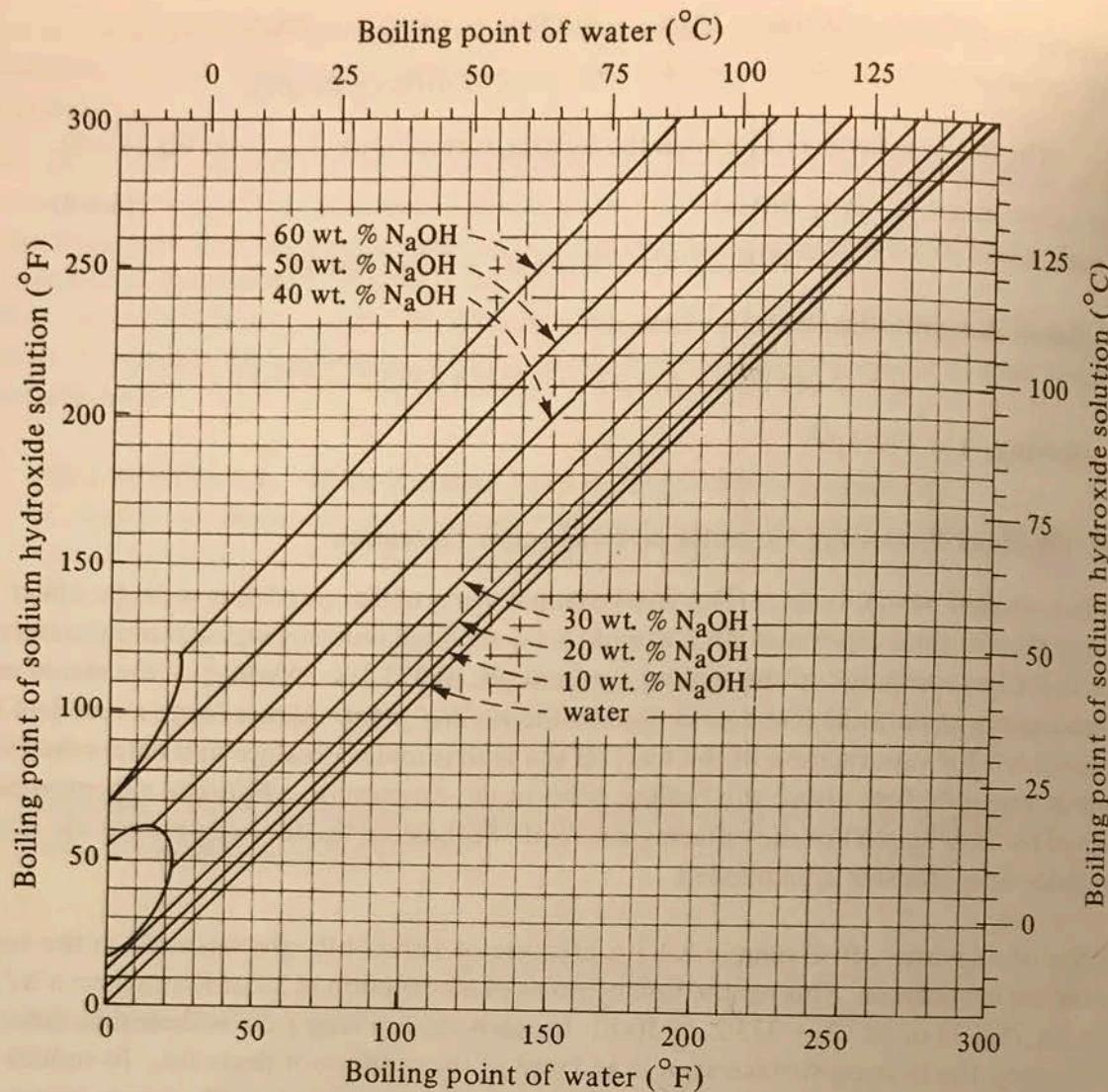


FIGURE 8.4-2. Dühring lines for aqueous solutions of sodium hydroxide.

a given concentration at different pressures. A different straight line is obtained for each given concentration. In Fig. 8.4-2 such a Dühring-line chart is given for solutions of sodium hydroxide in water. It is necessary to know the boiling point of a given solution at only two pressures to determine a line.

EXAMPLE 8.4-2. Use of Dühring Chart for Boiling-Point Rise

As an example of use of the chart, the pressure in an evaporator is given as 25.6 kPa (3.72 psia) and a solution of 30% NaOH is being boiled. Determine the boiling temperature of the NaOH solution and the boiling-point rise BPR of the solution over that of water at the same pressure.

Solution: From the steam tables in Appendix A.2, the boiling point of water at 25.6 kPa is 65.6°C. From Fig. 8.4-2 for 65.6°C (150°F) and 30% NaOH, the boiling point of the NaOH solution is 79.5°C (175°F). The boiling-point rise is $79.5 - 65.6 = 13.9^\circ\text{C}$ (25°F).

In Perry and Green (P1) a chart is given for estimating the boiling-point rise of a large number of common aqueous solutions used in chemical and biological processes. In addition to the common salts and solutes, such as NaNO_3 , NaOH , NaCl , and H_2SO_4 , the biological solutes sucrose, citric acid, kraft solution, and glycerol are given. These biological solutes have quite small boiling-point-rise values compared to those of common salts.

8.4D Enthalpy-Concentration Charts of Solutions

If the heat of solution of the aqueous solution being concentrated in the evaporator is large, neglecting it could cause errors in the heat balances. This heat-of-solution phenomenon can be explained as follows. If pellets of NaOH are dissolved in a given amount of water, it is found that a considerable temperature rise occurs; that is, heat is evolved, called *heat of solution*. The amount of heat evolved depends on the type of substance and the amount of water used. Also, if a strong solution of NaOH is diluted to a lower concentration, heat is liberated. Conversely, if a solution is concentrated from a low to a high concentration, heat must be added.

In Fig. 8.4-3 an enthalpy-concentration chart for NaOH is given (M1), where the enthalpy is in kJ/kg (btu/lb_m) solution, temperature in $^{\circ}\text{C}$ ($^{\circ}\text{F}$), and concentration in weight fraction NaOH in solution. Such enthalpy-concentration charts are usually not made for solutions having negligible heats of solution, since the heat capacities can be easily used to calculate enthalpies. Also, such charts are available for only a few solutions.

The enthalpy of the liquid water in Fig. 8.4-3 is referred to the same datum or reference state as in the steam tables, that is, liquid water at 0°C (273 K). This means that enthalpies from the figure can be used with those in the steam tables. In Eq. (8.4-7) values for h_F and h_L can be taken from Fig. 8.4-3 and values for λ and H_V from the steam tables. The uses of Fig. 8.4-3 will be better understood from the following example.

EXAMPLE 8.4-3. Evaporation of an NaOH Solution

An evaporator is used to concentrate 4536 kg/h (10 000 lb_m/h) of a 20% solution of NaOH in water entering at 60°C (140°F) to a product of 50% solids. The pressure of the saturated steam used is 172.4 kPa (25 psia) and the pressure in the vapor space of the evaporator is 11.7 kPa (1.7 psia). The overall heat-transfer coefficient is 1560 $\text{W/m}^2 \cdot \text{K}$ (275 $\text{btu}/\text{h} \cdot \text{ft}^2 \cdot {}^{\circ}\text{F}$). Calculate the steam used, the steam economy in kg vaporized/kg steam used, and the heating surface area in m^2 .

Solution: The process flow diagram and nomenclature are the same as in Fig. 8.4-1. The given variables are $F = 4536 \text{ kg/h}$, $x_F = 0.20$ wt fraction, $T_F = 60^{\circ}\text{C}$, $P_1 = 11.7 \text{ kPa}$, steam pressure = 172.4 kPa, and $x_L = 0.50$ wt fraction. For the overall material balance, substituting into Eq. (8.4-3),

$$F = 4536 = L + V \quad (8.4-3)$$

Substituting into Eq. (8.4-4) and solving (8.4-3) and (8.4-4) simultaneously,

$$\begin{aligned} Fx_F &= Lx_L \\ 4536(0.20) &= L(0.50) \\ L &= 1814 \text{ kg/h} \quad V = 2722 \text{ kg/h} \end{aligned} \quad (8.4-4)$$

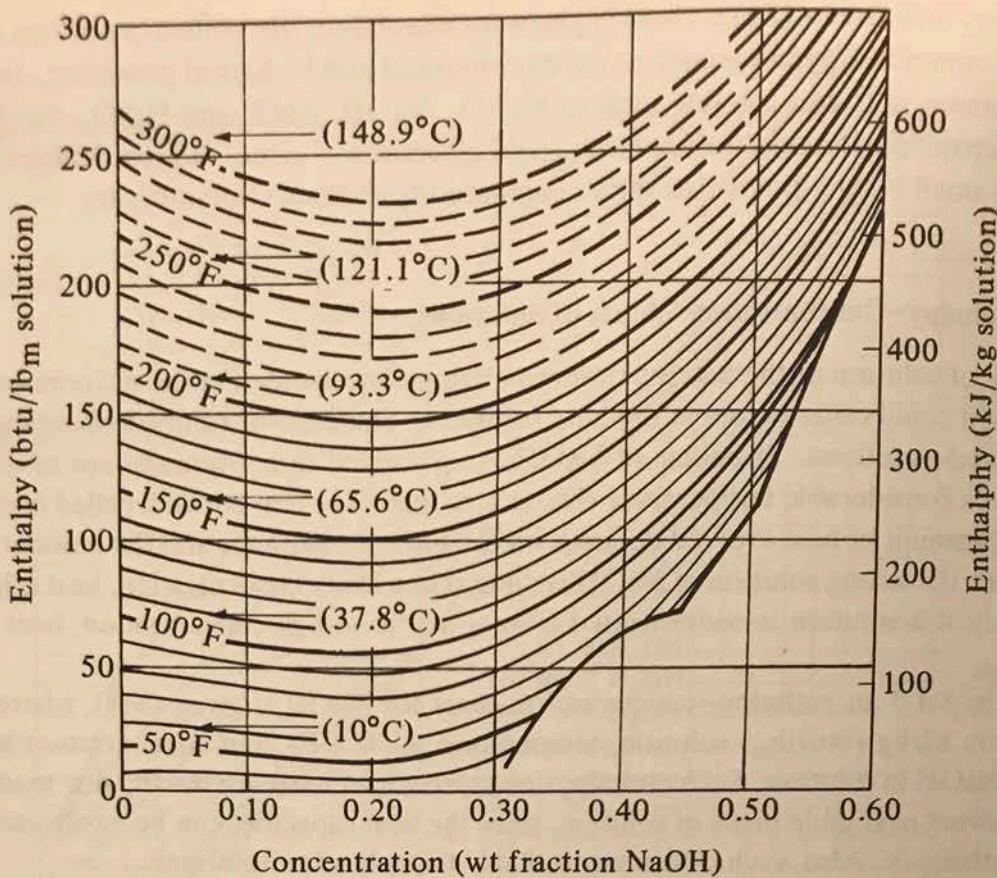


FIGURE 8.4-3. Enthalpy-concentration chart for the system NaOH -water.
[Reference state liquid water at 0°C (273 K) or 32°F .] [From W. L. McCabe, Trans. A.I.Ch.E., 31, 129 (1935). With permission.]

To determine the boiling point T_1 of the 50% concentrated solution, we first obtain the boiling point of pure water at 11.7 kPa from the steam tables, Appendix A.2, as 48.9°C (120°F). From the Dühring chart, Fig. 8.4-2, for a boiling point of water of 48.9°C and 50% NaOH, the boiling point of the solution is $T_1 = 89.5^\circ\text{C}$ (193°F). Hence,

$$\text{boiling-point rise} = T_1 - 48.9 = 89.5 - 48.9 = 40.6^\circ\text{C} (73^\circ\text{F})$$

From the enthalpy-concentration chart (Fig. 8.4-3), for 20% NaOH at 60°C (140°F), $h_f = 214 \text{ kJ/kg}$ (92 btu/lb_m). For 50% NaOH at 89.5°C (193°F), $h_L = 505 \text{ kJ/kg}$ (217 btu/lb_m).

For the superheated vapor V at 89.5°C (193°F) and 11.7 kPa [superheated 40.6°C (73°F) since the boiling point of water is 48.9°C (120°F) at 11.7 kPa], from the steam tables, $H_V = 2667 \text{ kJ/kg}$ (1147 btu/lb_m). An alternative method for calculating the H_V is first to obtain the enthalpy of saturated vapor at 48.9°C (120°F) and 11.7 kPa of 2590 kJ/kg (1113.5 btu/lb_m). Then, using a heat capacity of $1.884 \text{ kJ/kg} \cdot \text{K}$ for superheated steam with the superheat of $(89.5 - 48.9)^\circ\text{C} = (89.5 - 48.9) \text{ K}$,

$$H_V = 2590 + 1.884(89.5 - 48.9) = 2667 \text{ kJ/kg}$$

8.5B Temperature Drops and Capacity of Multiple-Effect Evaporators

1. Temperature drops in multiple-effect evaporators. The amount of heat transferred per hour in the first effect of a triple-effect evaporator with forward feed as in Fig. 8.2-3 will be

$$q_1 = U_1 A_1 \Delta T_1 \quad (8.5-1)$$

where ΔT_1 is the difference between the condensing steam and the boiling point of the liquid, $T_s - T_1$. Assuming that the solutions have no boiling-point rise and no heat of solution and neglecting the sensible heat necessary to heat the feed to the boiling point, approximately all the latent heat of the condensing steam appears as latent heat in the vapor. This vapor then condenses in the second effect, giving up approximately the same amount of heat:

$$q_2 = U_2 A_2 \Delta T_2 \quad (8.5-2)$$

This same reasoning holds for q_3 . Since $q_1 = q_2 = q_3$, then, approximately,

$$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2 = U_3 A_3 \Delta T_3 \quad (8.5-3)$$

In commercial practice the areas in all effects are usually equal and

$$\frac{q}{A} = U_1 \Delta T_1 = U_2 \Delta T_2 = U_3 \Delta T_3 \quad (8.5-4)$$

Hence, the temperature drops ΔT in a multiple-effect evaporator are approximately inversely proportional to the values of U . Calling $\sum \Delta T$ as follows for no boiling-point rise,

$$\sum \Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 = T_s - T_3 \quad (8.5-5)$$

Note that ΔT_1 °C = ΔT_1 K, ΔT_2 °C = ΔT_2 K, and so on. Since ΔT_1 is proportional to $1/U_1$, then

$$\Delta T_1 = \sum \Delta T \frac{1/U_1}{1/U_1 + 1/U_2 + 1/U_3} \quad (8.5-6)$$

Similar equations can be written for ΔT_2 and ΔT_3 .

2. Capacity of multiple-effect evaporators. A rough estimate of the capacity of a three-effect evaporator compared to a single-effect can be obtained by adding the value of q for each evaporator:

$$q = q_1 + q_2 + q_3 = U_1 A_1 \Delta T_1 + U_2 A_2 \Delta T_2 + U_3 A_3 \Delta T_3 \quad (8.5-7)$$

If we make the assumptions that the value of U is the same in each effect and that the values of A are equal, Eq. (8.5-7) becomes

$$q = UA(\Delta T_1 + \Delta T_2 + \Delta T_3) = UA \Delta T \quad (8.5-8)$$

where $\Delta T = \sum \Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 = T_s - T_3$,

If a single-effect evaporator is used with the same area A , the same value of U , and the same total temperature drop ΔT , then

$$q = UA \Delta T \quad (8.5-9)$$

This, of course, gives the same capacity as for the multiple-effect evaporator. Hence, the increase in steam economy obtained by using multiple-effect evaporators is obtained at the expense of reduced capacity.

8.5C Calculations for Multiple-Effect Evaporators

In doing calculations for a multiple-effect evaporator system, the values to be obtained are usually the area of the heating surface in each effect, the kg of steam per hour to be supplied, and the amount of vapor leaving each effect, especially the last one. The given or known values are usually as follows: (1) steam pressure to the first effect, (2) final pressure in the vapor space of the last effect, (3) feed conditions and flow to the first effect, (4) the final concentration in the liquid leaving the last effect, (5) physical properties such as enthalpies and/or heat capacities of the liquid and vapors, and (6) overall heat-transfer coefficients in each effect. Usually, the areas of each effect are assumed equal.

The calculations are done using material balances, heat balances, and the capacity equations $q = UA \Delta T$ for each effect. A convenient way to solve these equations is by trial and error. The basic steps to follow are given as follows for a triple-effect evaporator.

8.5D Step-by-Step Calculation Methods for Triple-Effect Evaporators

1. From the known outlet concentration and pressure in the last effect, determine the boiling point in the last effect. (If a boiling-point rise is present, this can be determined from a Dühring-line plot.)
2. Determine the total amount of vapor evaporated by performing an overall material balance. For this first trial, apportion the total amount of vapor among the three effects. (Usually, equal amounts of vapor are produced in each effect, so that $V_1 = V_2 = V_3$ is assumed for the first trial.) Make a total material balance on effects 1, 2, and 3 to obtain L_1 , L_2 , and L_3 . Then calculate the solids concentration in each effect by a solids balance on each effect.
3. Using Eq. (8.5-6), estimate the temperature drops ΔT_1 , ΔT_2 , and ΔT_3 in the three effects. Any effect that has an extra heating load, such as a cold feed, requires a proportionately larger ΔT . Then calculate the boiling point in each effect.

[If a boiling-point rise (BPR) in °C is present, estimate the pressure in effects 1 and 2 and determine the BPR in each of the three effects. Only a crude pressure estimate is needed, since BPR is almost independent of pressure. Then the $\sum \Delta T$ available for heat transfer without the superheat is obtained by subtracting the sum of all three BPRs from the overall ΔT of $T_s - T_3$ (saturation). Using Eq. (8.5-6), estimate ΔT_1 , ΔT_2 , and ΔT_3 . Then calculate the boiling point in each effect.]

4. Using heat and material balances in each effect, calculate the amount vaporized and the flows of liquid in each effect. If the amounts vaporized differ appreciably from those assumed in step 2, then steps 2, 3, and 4 can be repeated using the amounts of evaporation just calculated. (In step 2 only the solids balance is repeated.)
5. Calculate the value of q transferred in each effect. Using the rate equation $q = UA \Delta T$ for each effect, calculate the areas A_1 , A_2 , and A_3 . Then calculate the average value A_m by

$$A_m = \frac{A_1 + A_2 + A_3}{3} \quad (8.5-10)$$

If these areas are reasonably close to each other, the calculations are complete and a second trial is not needed. If these areas are not almost equal, a second trial should be performed as follows.

6. To start trial 2, use the new values of L_1 , L_2 , L_3 , V_1 , V_2 , and V_3 calculated by the heat balances in step 4 and calculate the new solids concentration in each effect by a solids balance on each effect.

7. Obtain new values $\Delta T'_1$, $\Delta T'_2$, and $\Delta T'_3$ from

$$\Delta T'_1 = \frac{\Delta T_1 A_1}{A_m} \quad \Delta T'_2 = \frac{\Delta T_2 A_2}{A_m} \quad \Delta T'_3 = \frac{\Delta T_3 A_3}{A_m} \quad (8.5-11)$$

The sum $\Delta T'_1 + \Delta T'_2 + \Delta T'_3$ must equal the original $\sum \Delta T$. If not, proportionately readjust all $\Delta T'$ values so that this is so. Then calculate the boiling point in each effect.

[If a boiling-point rise is present, determine the new BPRs in the three effects using the new concentrations from step 6. To get a new value of $\sum \Delta T$ available for heat transfer, subtract the sum of all three BPRs from the overall ΔT . Calculate the new values of $\Delta T'$ by Eq. (8.5-11). The sum of the $\Delta T'$ values just calculated must be readjusted to the new $\sum \Delta T$ value. Then calculate the boiling point in each effect.] Step 7 is essentially a repeat of step 3 but using Eq. (8.5-11) to obtain a better estimate of the $\Delta T'$ values.

8. Using the new $\Delta T'$ values from step 7, repeat the calculations starting with step 4. Two trials are usually sufficient so that the areas are reasonably close to being equal.

EXAMPLE 8.5-1. Evaporation of Sugar Solution in a Triple-Effect Evaporator

A triple-effect forward-feed evaporator is being used to evaporate a sugar solution containing 10 wt % solids to a concentrated solution of 50%. The boiling-point rise of the solutions (independent of pressure) can be estimated from $BPR^{\circ}\text{C} = 1.78x + 6.22x^2$ ($BPR^{\circ}\text{F} = 3.2x + 11.2x^2$), where x is wt fraction of sugar in solution (K1). Saturated steam at 205.5 kPa (29.8 psia) [121.1°C (250°F) saturation temperature] is being used. The pressure in the vapor space of the third effect is 13.4 kPa (1.94 psia). The feed rate is 22 680 kg/h (50 000 lb_m/h) at 26.7°C (80°F). The heat capacity of the liquid solutions is (K1) $c_p = 4.19 - 2.35x$ kJ/kg · K ($1.0 - 0.56x$ btu/lb_m · °F). The heat of solution is considered to be negligible. The coefficients of heat transfer have been estimated as $U_1 = 3123$, $U_2 = 1987$, and $U_3 = 1136 \text{ W/m}^2 \cdot \text{K}$, or 550, 350, and 200 btu/h · ft² · °F. If each effect has the same surface area, calculate the area, the steam rate used, and the steam economy.

Solution: The process flow diagram is given in Fig. 8.5-1. Following the eight steps outlined, the calculations are as follows:

Step 1. For 13.4 kPa (1.94 psia), the saturation temperature is 51.67°C (125°F) from the steam tables. Using the equation for BPR for evaporator number 3 with $x = 0.5$,

$$BPR_3 = 1.78x + 6.22x^2 = 1.78(0.5) + 6.22(0.5)^2 = 2.45^{\circ}\text{C}$$
 (4.4°F)

$$T_3 = 51.67 + 2.45 = 54.12^{\circ}\text{C}$$
 (129.4°F)

Step 2. Making an overall and a solids balance to calculate the total amount vaporized ($V_1 + V_2 + V_3$) and L_3 ,

$$F = 22\ 680 = L_3 + (V_1 + V_2 + V_3)$$

$$Fx_F = 22\ 680(0.1) = L_3(0.5) + (V_1 + V_2 + V_3)(0)$$

$$L_3 = 4536 \text{ kg/h}$$
 ($10\ 000 \text{ lb}_m/\text{h}$)

$$\text{total vaporized} = (V_1 + V_2 + V_3) = 18\ 144 \text{ kg/h}$$
 ($40\ 000 \text{ lb}_m/\text{h}$)

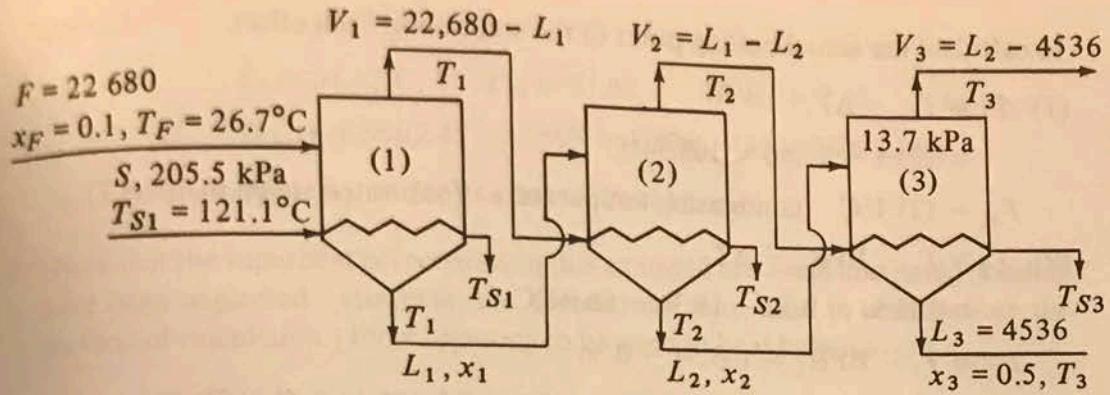


FIGURE 8.5-1. Flow diagram for triple-effect evaporation for Example 8.5-1.

Assuming equal amount vaporized in each effect, $V_1 = V_2 = V_3 = 6048 \text{ kg/h}$ (13 333 lb_m/h). Making a total material balance on effects 1, 2, and 3 and solving,

$$(1) \quad F = 22,680 = V_1 + L_1 = 6048 + L_1, \quad L_1 = 16,632 \text{ kg/h} (33,667 \text{ lb}_m/\text{h})$$

$$(2) \quad L_1 = 16,632 = V_2 + L_2 = 6048 + L_2, \quad L_2 = 10,584 \text{ (23,334)}$$

$$(3) \quad L_2 = 10,584 = V_3 + L_3 = 6048 + L_3, \quad L_3 = 4536 \text{ (10,000)}$$

Making a solids balance on effects 1, 2, and 3 and solving for x ,

$$(1) \quad 22,680(0.1) = L_1 x_1 = 16,632(x_1), \quad x_1 = 0.136$$

$$(2) \quad 16,632(0.136) = L_2 x_2 = 10,584(x_2), \quad x_2 = 0.214$$

$$(3) \quad 10,584(0.214) = L_3 x_3 = 4536(x_3), \quad x_3 = 0.500 \text{ (check balance)}$$

Step 3. The BPR in each effect is calculated as follows:

$$(1) \quad \text{BPR}_1 = 1.78x_1 + 6.22x_1^2 = 1.78(0.136) + 6.22(0.136)^2 = 0.36^\circ\text{C} (0.7^\circ\text{F})$$

$$(2) \quad \text{BPR}_2 = 1.78(0.214) + 6.22(0.214)^2 = 0.65^\circ\text{C} (1.2^\circ\text{F})$$

$$(3) \quad \text{BPR}_3 = 1.78(0.5) + 6.22(0.5)^2 = 2.45^\circ\text{C} (4.4^\circ\text{F})$$

$$\begin{aligned} \sum \Delta T \text{ available} &= T_{S1} - T_3(\text{saturation}) - (\text{BPR}_1 + \text{BPR}_2 + \text{BPR}_3) \\ &= 121.1 - 51.67 - (0.36 + 0.65 + 2.45) = 65.97^\circ\text{C} (118.7^\circ\text{F}) \end{aligned}$$

Using Eq. (8.5-6) for ΔT_1 and similar equations for ΔT_2 and ΔT_3 ,

$$\begin{aligned} \Delta T_1 &= \sum \Delta T \frac{1/U_1}{1/U_1 + 1/U_2 + 1/U_3} = \frac{(65.97)(1/3123)}{(1/3123) + (1/1987) + (1/1136)} \\ \Delta T_1 &= 12.40^\circ\text{C} \quad \Delta T_2 = 19.50^\circ\text{C} \quad \Delta T_3 = 34.07^\circ\text{C} \end{aligned}$$

However, since a cold feed enters effect number 1, this effect requires more heat. Increasing ΔT_1 and lowering ΔT_2 and ΔT_3 proportionately as a first estimate,

$$\Delta T_1 = 15.56^\circ\text{C} = 15.56 \text{ K} \quad \Delta T_2 = 18.34^\circ\text{C} = 18.34 \text{ K}$$

$$\Delta T_3 = 32.07^\circ\text{C} = 32.07 \text{ K}$$

To calculate the actual boiling point of the solution in each effect,

$$(1) \quad T_1 = T_{S1} - \Delta T_1 \\ = 121.1 - 15.56 = 105.54^\circ\text{C}$$

$T_{S1} = 121.1^\circ\text{C}$ (condensing temperature of saturated steam to effect 1)

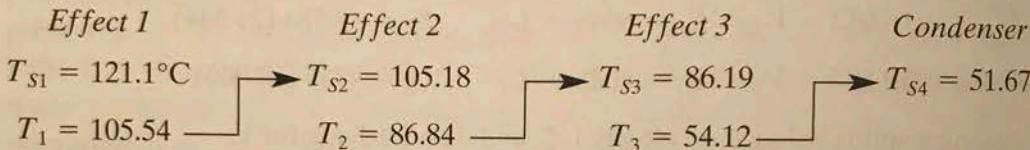
$$(2) \quad T_2 = T_1 - \text{BPR}_1 - \Delta T_2 \\ = 105.54 - 0.36 - 18.34 = 86.84^\circ\text{C}$$

$$T_{S2} = T_1 - \text{BPR}_1 = 105.54 - 0.36 \\ = 105.18^\circ\text{C} \quad (\text{condensing temperature of steam to effect 2})$$

$$(3) \quad T_3 = T_2 - \text{BPR}_2 - \Delta T_3 \\ = 86.84 - 0.65 - 32.07 = 54.12^\circ\text{C}$$

$$T_{S3} = T_2 - \text{BPR}_2 \\ = 86.84 - 0.65 = 86.19^\circ\text{C} \quad (\text{condensing temperature of steam to effect 3})$$

The temperatures in the three effects are as follows:



Step 4. The heat capacity of the liquid in each effect is calculated from the equation $c_p = 4.19 - 2.35x$:

$$F: \quad c_p = 4.19 - 2.35(0.1) = 3.955 \text{ kJ/kg} \cdot \text{K}$$

$$L_1: \quad c_p = 4.19 - 2.35(0.136) = 3.869$$

$$L_2: \quad c_p = 4.19 - 2.35(0.214) = 3.684$$

$$L_3: \quad c_p = 4.19 - 2.35(0.5) = 3.015$$

The values of the enthalpy H of the various vapor streams relative to water at 0°C as a datum are obtained from the steam table as follows:

Effect 1:

$$T_1 = 105.54^\circ\text{C}, \quad T_{S2} = 105.18 \text{ (221.3°F)}, \quad \text{BPR}_1 = 0.36, \quad T_{S1} = 121.1 \text{ (250°F)}$$

$$H_1 = H_{S2}(\text{saturation enthalpy at } T_{S2}) + 1.884(0.36^\circ\text{C superheat}) \\ = 2684 + 1.884(0.36) = 2685 \text{ kJ/kg}$$

$$\lambda_{S1} = H_{S1}(\text{vapor saturation enthalpy}) - h_{S1}(\text{liquid enthalpy at } T_{S1}) \\ = (2708 - 508) = 2200 \text{ kJ/kg latent heat of condensation}$$

Effect 2:

$$T_2 = 86.84^\circ\text{C}, \quad T_{S3} = 86.19, \quad \text{BPR}_2 = 0.65$$

$$H_2 = H_{S3} + 1.884(0.65) = 2654 + 1.884(0.65) = 2655 \text{ kJ/kg}$$

$$\lambda_{S2} = H_1 - h_{S2} = 2685 - 441 = 2244 \text{ kJ/kg}$$

Effect 3:

$$T_3 = 54.12^\circ\text{C}, \quad T_{S4} = 51.67, \quad \text{BPR}_3 = 2.45$$

$$H_3 = H_{S4} + 1.884(2.45) = 2595 + 1.884(2.45) = 2600 \text{ kJ/kg}$$

$$\lambda_{S3} = H_2 - h_{S3} = 2655 - 361 = 2294 \text{ kJ/kg}$$

(Note that the superheat corrections in this example are small and could possibly have been neglected. However, the corrections were used to demonstrate the method of calculation.) Flow relations to be used in heat balances are

$$V_1 = 22680 - L_1, \quad V_2 = L_1 - L_2, \quad V_3 = L_2 - 4536, \quad L_3 = 4536$$

Write a heat balance on each effect. Using 0°C as a datum, since the values of H of the vapors are relative to 0°C (32°F), and noting that $(T_F - 0)^\circ\text{C} = (T_F - 0) \text{ K}$ and $(T_1 - 0)^\circ\text{C} = (T_1 - 0) \text{ K}$,

$$(1) \quad Fc_p(T_F - 0) + S\lambda_{S1} = L_1 c_p(T_1 - 0) + V_1 H_1$$

Substituting the known values,

$$22680(3.955)(26.7 - 0) + S(2200)$$

$$= L_1(3.869)(105.54 - 0) + (22680 - L_1)(2685)$$

$$(2) \quad L_1 c_p(T_1 - 0) + V_1 \lambda_{S2} = L_2 c_p(T_2 - 0) + V_2 H_2$$

$$L_1(3.869)(105.54 - 0) + (22680 - L_1)(2244)$$

$$= L_2(3.684)(86.84 - 0) + (L_1 - L_2)(2655)$$

$$(3) \quad L_2 c_p(T_2 - 0) + V_2 \lambda_{S3} = L_3 c_p(T_3 - 0) + V_3 H_3$$

$$L_2(3.684)(86.84 - 0) + (L_1 - L_2)(2294)$$

$$= 4536(3.015)(54.12 - 0) + (L_2 - 4536)(2600)$$

Solving the last two equations simultaneously for L_1 and L_2 and substituting into the first equation,

$$L_1 = 17078 \text{ kg/h} \quad L_2 = 11068 \quad L_3 = 4536$$

$$S = 8936 \quad V_1 = 5602 \quad V_2 = 6010 \quad V_3 = 6532$$

The calculated values of V_1 , V_2 , and V_3 are close enough to the assumed values that steps 2, 3, and 4 do not need to be repeated. If the calculation were repeated, the calculated values of V_1 , V_2 , and V_3 would be used starting with step 2 and a solids balance in each effect would be made.

Step 5. Solving for the values of q in each effect and area,

$$q_1 = S\lambda_{S1} = \left(\frac{8936}{3600}\right)(2200 \times 1000) = 5.460 \times 10^6 \text{ W}$$

$$q_2 = V_1 \lambda_{S2} = \left(\frac{5602}{3600}\right)(2244 \times 1000) = 3.492 \times 10^6 \text{ W}$$

$$q_3 = V_2 \lambda_{S3} = \left(\frac{6010}{3600}\right)(2294 \times 1000) = 3.830 \times 10^6 \text{ W}$$

$$A_1 = \frac{q_1}{U_1 \Delta T_1} = \frac{5.460 \times 10^6}{3123(15.56)} = 112.4 \text{ m}^2$$

$$A_2 = \frac{q_2}{U_2 \Delta T_2} = \frac{3.492 \times 10^6}{1987(18.34)} = 95.8 \text{ m}^2$$

$$A_3 = \frac{q_3}{U_3 \Delta T_3} = \frac{3.830 \times 10^6}{1136(32.07)} = 105.1 \text{ m}^2$$

The average area $A_m = 104.4 \text{ m}^2$. The areas differ from the average value by less than 10% and a second trial is not really necessary. However, a second trial will be made starting with step 6 to demonstrate the calculation methods used.

Step 6. Making a new solids balance on effects 1, 2, and 3, using the new $L_1 = 17\ 078$, $L_2 = 11\ 068$, and $L_3 = 4536$, and solving for x ,

$$(1) \quad 22\ 680(0.1) = 17\ 078(x_1), \quad x_1 = 0.133$$

$$(2) \quad 17\ 078(0.133) = 11\ 068(x_2), \quad x_2 = 0.205$$

$$(3) \quad 11\ 068(0.205) = 4536(x_3), \quad x_3 = 0.500 \quad (\text{check balance})$$

Step 7. The new BPR in each effect is then

$$(1) \quad \text{BPR}_1 = 1.78x_1 + 6.22x_1^2 = 1.78(0.133) + 6.22(0.133)^2 = 0.35^\circ\text{C}$$

$$(2) \quad \text{BPR}_2 = 1.78(0.205) + 6.22(0.205)^2 = 0.63^\circ\text{C}$$

$$(3) \quad \text{BPR}_3 = 1.78(0.5) + 6.22(0.5)^2 = 2.45^\circ\text{C}$$

$$\sum \Delta T \text{ available} = 121.1 - 51.67 - (0.35 + 0.63 + 2.45) = 66.00^\circ\text{C}$$

The new values for ΔT are obtained using Eq. (8.5-11):

$$\Delta T'_1 = \frac{\Delta T_1 A_1}{A_m} = \frac{15.56(112.4)}{104.4} = 16.77 \text{ K} = 16.77^\circ\text{C}$$

$$\Delta T'_2 = \frac{\Delta T_2 A_2}{A_m} = \frac{18.34(95.8)}{104.4} = 16.86^\circ\text{C}$$

$$\Delta T'_3 = \frac{\Delta T_3 A_3}{A_m} = \frac{32.07(105.1)}{104.4} = 32.34^\circ\text{C}$$

$$\sum \Delta T = 16.77 + 16.86 + 32.34 = 65.97^\circ\text{C}$$

These $\Delta T'$ values are readjusted so that $\Delta T'_1 = 16.77$, $\Delta T'_2 = 16.87$, $\Delta T'_3 = 32.36$, and $\sum \Delta T = 16.77 + 16.87 + 32.36 = 66.00^\circ\text{C}$. To calculate the actual boiling point of the solution in each effect,

$$(1) \quad T_1 = T_{S1} - \Delta T'_1 = 121.1 - 16.77 = 104.33^\circ\text{C}, \quad T_{S1} = 121.1^\circ\text{C}$$

$$(2) \quad T_2 = T_1 - \text{BPR}_1 - \Delta T'_2 = 104.33 - 0.35 - 16.87 = 87.11^\circ\text{C}$$

$$T_{S2} = T_1 - \text{BPR}_1 = 104.33 - 0.35 = 103.98^\circ\text{C}$$

$$(3) \quad T_3 = T_2 - \text{BPR}_2 - \Delta T'_3 = 87.11 - 0.63 - 32.36 = 54.12^\circ\text{C}$$

$$T_{S3} = T_2 - \text{BPR}_2 = 87.11 - 0.63 = 86.48^\circ\text{C}$$

Step 8. Following step 4, the heat capacity of the liquid is $c_p = 4.19 - 2.35x$:

$$F: \quad c_p = 3.955 \text{ kJ/kg} \cdot \text{K}$$

$$L_1: \quad c_p = 4.19 - 2.35(0.133) = 3.877$$

$$L_2: \quad c_p = 4.19 - 2.35(0.205) = 3.708$$

$$L_3: \quad c_p = 3.015$$

The new values of the enthalpy H are as follows in each effect:

$$(1) \quad H_1 = H_{S2} + 1.884(\text{°C superheat}) = 2682 + 1.884(0.35) = 2683 \text{ kJ/kg}$$

$$\lambda_{S1} = H_{S1} - h_{S1} = 2708 - 508 = 2200 \text{ kJ/kg}$$

$$(2) \quad H_2 = H_{S3} + 1.884(0.63) = 2654 + 1.884(0.63) = 2655 \text{ kJ/kg}$$

$$\lambda_{S2} = H_1 - h_{S2} = 2683 - 440 = 2243 \text{ kJ/kg}$$

$$(3) \quad H_3 = H_{S4} + 1.884(2.45) = 2595 + 1.884(2.45) = 2600 \text{ kJ/kg}$$

$$\lambda_{S3} = H_2 - h_{S3} = 2655 - 362 = 2293 \text{ kJ/kg}$$

Writing a heat balance on each effect,

$$(1) \quad 22\,680(3.955)(26.7 - 0) + S(2200) \\ = L_1(3.877)(104.33 - 0) + (22\,680 - L_1)(2683)$$

$$(2) \quad L_1(3.877)(104.33 - 0) + (22\,680 - L_1)(2243) \\ = L_2(3.708)(87.11 - 0) + (L_1 - L_2)(2655)$$

$$(3) \quad L_2(3.708)(87.11 - 0) + (L_1 - L_2)(2293) \\ = 4536(3.015)(54.12 - 0) + (L_2 - 4536)(2600)$$

Solving,

$$L_1 = 17\,005 \text{ kg/h} \quad L_2 = 10\,952 \quad L_3 = 4536 \quad S = 8960 \text{ (steam used)}$$

$$V_1 = 5675 \quad V_2 = 6053 \quad V_3 = 6416$$

Note that these values from trial 2 differ very little from the trial 1 results. Following step 5, and solving for q in each effect and A ,

$$q_1 = S\lambda_{S1} = \frac{8960}{3600}(2200 \times 1000) = 5.476 \times 10^6 \text{ W}$$

$$q_2 = V_1\lambda_{S2} = \frac{5675}{3600}(2243 \times 1000) = 3.539 \times 10^6 \text{ W}$$

$$q_3 = V_2\lambda_{S3} = \frac{6053}{3600}(2293 \times 1000) = 3.855 \times 10^6 \text{ W}$$

$$A_1 = \frac{q_1}{U_1 \Delta T'_1} = \frac{5.476 \times 10^6}{3123(16.77)} = 104.6 \text{ m}^2$$

$$A_2 = \frac{q_2}{U_2 \Delta T'_2} = \frac{3.539 \times 10^6}{1987(16.87)} = 105.6 \text{ m}^2$$

$$A_3 = \frac{q_3}{U_3 \Delta T'_3} = \frac{3.855 \times 10^6}{1136(32.36)} = 104.9 \text{ m}^2$$

The average area to use in each effect is $A_m = 105.0 \text{ m}^2$. Note that this value of 105.0 m^2 is quite close to the average value of 104.4 m^2 from the first trial.

$$\text{steam economy} = \frac{V_1 + V_2 + V_3}{S} = \frac{5675 + 6053 + 6416}{8960} = 2.025$$

8.6 CONDENSERS FOR EVAPORATORS

8.6A Introduction

In multiple-effect evaporators the vapors from the last effect are usually leaving under vacuum, that is, at less than atmospheric pressure. These vapors must be condensed and discharged as a liquid at atmospheric pressure. This is done by using cooling water to condense the vapors. The condenser can be a surface condenser, where the vapor to be condensed and the cooling liquid are separated by a metal wall, or a direct-contact condenser, where the vapor and cooling liquid are mixed directly.

8.6B Surface Condensers

Surface condensers are employed where actual mixing of the condensate with condenser cooling water is not desired. In general, they are shell-and-tube condensers, with the vapor on the shell side and cooling water in multipass flow on the tube side. Noncondensable gases such as air, CO_2 , N_2 , or another gas are usually present in the vapor stream. They may have entered as dissolved gases in the liquid feed or occur because of decomposition in the solutions. These noncondensable gases may be vented from any well-cooled point in the condenser. If the vapor being condensed is below atmospheric pressure, the condensed liquid leaving the surface condenser can be removed by pumping and the noncondensable gases by using a vacuum pump. Surface condensers are much more expensive and use more cooling water, so they are usually not used in cases where a direct-contact condenser is suitable.

8.6C Direct-Contact Condensers

In *direct-contact condensers* cooling water directly contacts and condenses the vapors. One of the most common types of direct-contact condenser is the countercurrent barometric condenser shown in Fig. 8.6-1. The vapor enters the condenser and is condensed by rising upward against a shower of cooling water droplets. The condenser is located on top of a long discharge tailpipe. The condenser is high enough above the discharge point in the tailpipe that the water column established in the pipe more than compensates for the difference in pressure between the low absolute pressure in the condenser and the atmosphere. The water can then discharge by gravity through a seal pot at the bottom. A height of about 10.4 m (34 ft) is used.

The barometric condenser is inexpensive and economical of water consumption. It can maintain a vacuum corresponding to a saturated vapor temperature within about 2.8 K (5°F) of the water temperature leaving the condenser. For example, if the discharge water is at 316.5 K (110°F), the pressure corresponding to $316.5 + 2.8$ or 319.3 K is 10.1 kPa (1.47 psia).

The water consumption can be estimated by a simple heat balance for a barometric condenser. If the vapor flow to the condenser is $V \text{ kg/h}$ at temperature T_s and the water flow is

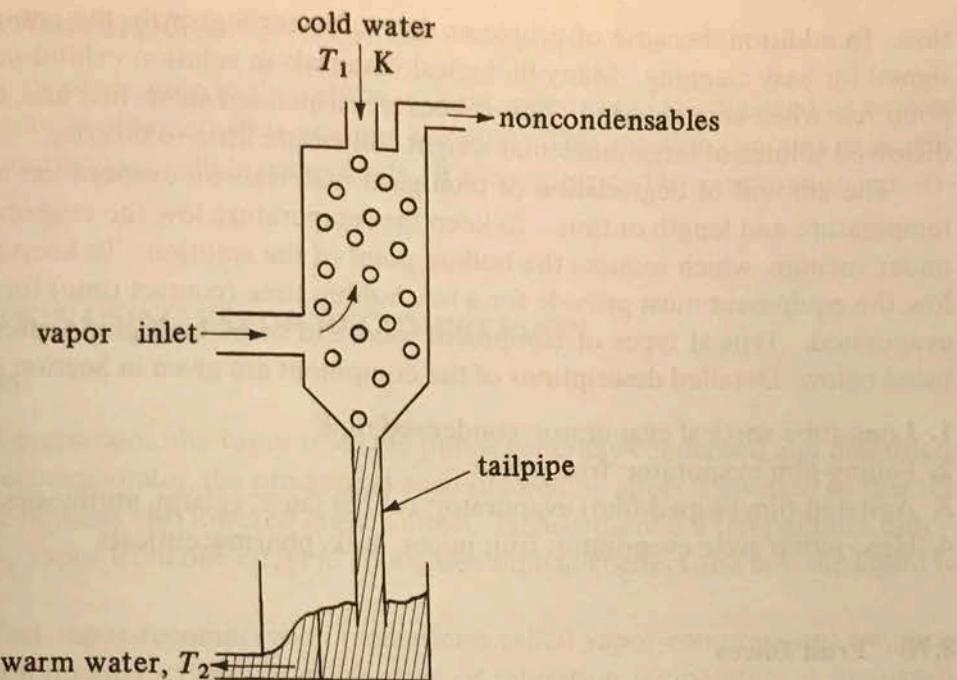


FIGURE 8.6-1. Schematic of barometric condenser.

$W \text{ kg/h}$ at an entering temperature of T_1 and a leaving temperature of T_2 , the derivation is as follows:

$$VH_S + Wc_p(T_1 - 273.2) = (V + W)c_p(T_2 - 273.2) \quad (8.6-1)$$

where H_S is the enthalpy from the steam tables of the vapor at T_S K and the pressure in the vapor stream. Solving,

$$\frac{W}{V} = \frac{\text{kg water}}{\text{kg vapor}} = \frac{H_S - c_p(T_2 - 273.2)}{c_p(T_2 - T_1)} \quad (8.6-2)$$

The noncondensable gases can be removed from the condenser by a vacuum pump, either a mechanical pump or a steam-jet ejector. In the ejector high-pressure steam enters a nozzle at high speed and entrains the noncondensable gases from the space under vacuum.

Another type of direct-contact condenser is the jet barometric condenser. High-velocity jets of water act as both a vapor condenser and an entrainer of the noncondensables out of the tail pipe. Jet condensers usually require more water than the more-common barometric condensers and are more difficult to throttle at low vapor rates.

8.7 EVAPORATION OF BIOLOGICAL MATERIALS

8.7A Introduction and Properties of Biological Materials

The evaporation of many biological materials frequently differs from the evaporation of inorganic materials such as NaCl and NaOH and organic materials such as ethanol and acetic acid. Biological materials such as pharmaceuticals, milk, citrus juices, and vegetable extracts are usually quite heat-sensitive and often contain fine particles of suspended matter in solu-

tion. In addition, because biological materials are often suspended solids, a small boiling-point rise when concentrated. This is because suspended solids in a fine, dispersed form and dissolved solutes of large molecular weight contribute little to this rise.

The amount of degradation of biological materials on evaporation is a function of the temperature and length of time. To keep the temperature low, the evaporation must be done under vacuum, which reduces the boiling point of the solution. To keep the time of contact low, the equipment must provide for a low holdup time (contact time) for the material being evaporated. Typical types of equipment used and some biological materials processed are listed below. Detailed descriptions of the equipment are given in Section 8.2.

1. Long-tube vertical evaporator: condensed milk
2. Falling-film evaporator: fruit juices
3. Agitated-film (wiped-film) evaporator: rubber latex, gelatin, antibiotics, fruit juices
4. Heat-pump cycle evaporator: fruit juices, milk, pharmaceuticals

8.7B Fruit Juices

In the evaporation of fruit juices, such as orange juice, problems arise that are quite different from those associated with the evaporation of a typical salt such as NaCl. The fruit juices are heat-sensitive and the viscosity increases greatly as concentration increases. Also, solid suspended matter in fruit juices has a tendency to cling to the heating surface, thus causing overheating which leads to burning and spoilage of the matter (B2).

To reduce this tendency to stick and to reduce residence time, high rates of circulation over the heat-transfer surface are necessary. Since the material is heat-sensitive, low-temperature operation is also necessary. Hence, a fruit juice concentration plant usually employs a single and not a multiple evaporation unit. Vacuum is used to reduce the temperature of evaporation.

A typical fruit juice evaporation system using the heat-pump cycle is shown in the literature (P1, C1); it employs low-temperature ammonia as the heating fluid. A frozen concentrated citrus juice process is described by Charm (C1). The process uses a multistage falling-film evaporator. A major fault of concentrated orange juice is a flat flavor due to the loss of volatile constituents during evaporation. To overcome this, a portion of the fresh pulpy juice bypasses the evaporation cycle and is blended with the evaporated concentrate.

8.7C Sugar Solutions

Sugar (sucrose) is obtained primarily from sugarcane and sugar beets. Sugar tends to caramelize if kept at high temperatures for long periods (B2). The general tendency is to use short-tube evaporators of the natural circulation type. In the evaporation process for sugar solutions, a clear solution of sugar having a concentration of 10–13° Brix (10–13 wt %) is evaporated to 40–60° Brix (K1, S1).

The feed is first preheated by exhaust steam and then typically enters a six-effect forward-feed evaporator system. The first effect operates at a pressure in the vapor space of the evaporator of about 207 kPa (30 psia) [121.1°C (250°F) saturation temperature] and the last effect under vacuum at about 24 kPa (63.9°C saturation). Examples of the relatively small boiling-point rise of sugar solutions and the heat capacity are given in Example 8.5-1.

8.7D Paper-Pulp Waste Liquors

In the manufacture of paper pulp in the sulfate process, wood chips are digested or cooked and spent black liquor is obtained after washing the pulp. This solution contains primarily sodium carbonate and organic sulfide compounds. It is concentrated by evaporation in a six-effect system (K1, S1).

8.8 EVAPORATION USING VAPOR RECOMPRESSION

8.8A Introduction

In the single-effect evaporator, the vapor from the unit is generally condensed and discarded. In the multiple-effect evaporator, the pressure in each succeeding effect is lowered so that the boiling point of the liquid is also lowered in each effect. Hence, there is a temperature difference created for the vapor from one effect to condense in the next effect and boil the liquid to form vapor.

In a single-effect vapor-recompression (sometimes called vapor-compression) evaporator, the vapor is compressed so that its condensing or saturation temperature is increased. This compressed vapor is returned back to the heater of steam chest and condenses so that vapor is formed in the evaporator (B5, W1, Z1). In this manner the latent heat of the vapor is used and not discarded. The two types of vapor-recompression units are the mechanical and the thermal type.

8.8B Mechanical Vapor-Recompression Evaporator

In a mechanical vapor-recompression evaporator, a conventional single-effect evaporator similar to that in Fig. 8.2-2 is used, as shown in Fig. 8.8-1. The cold feed is preheated by exchange with the hot outlet liquid product and then flows to the unit. The vapor coming overhead does not go to a condenser but is sent to a centrifugal or positive-displacement compressor driven by an electric motor or steam. This compressed vapor or steam is sent back to the heat exchanger or steam chest. The compressed vapor condenses at a temperature higher than the boiling point of the hot liquid in the effect, and a temperature difference is set up. Vapor is again generated and the cycle repeated.

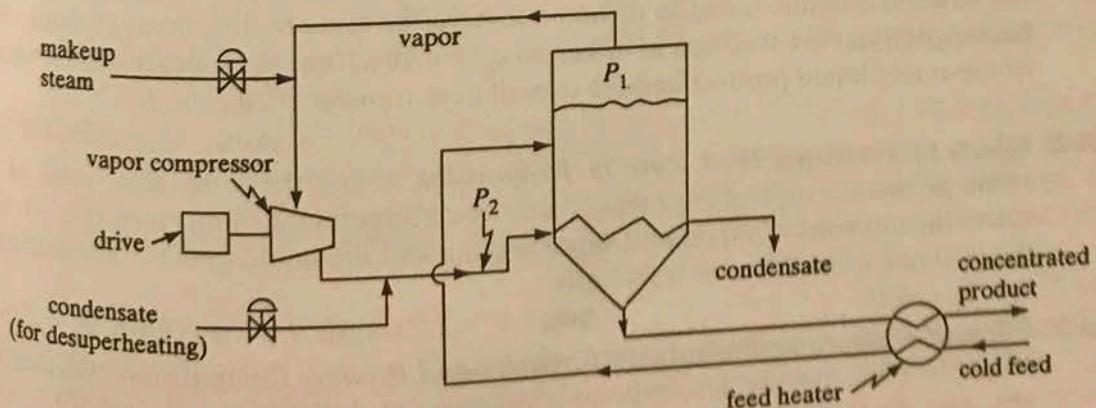


FIGURE 8.8-1. Simplified process flow for mechanical vapor recompression evaporator.

Sometimes it is necessary to add a small amount of makeup steam to the vapor line before the compressor (B5, K2). Also, a small amount of condensate may be added to the compressed vapor to remove any superheat, if present.

Vapor-recompression units generally operate at low optimum-temperature differences of 5–10°C. Hence, large heat-transfer areas are needed. These units usually have higher capital costs than multiple-effect units because of the larger area and the costs of the relatively expensive compressor and drive unit. The main advantage of vapor-recompression units is their lower energy costs. Using the steam equivalent of the power to drive the compressor, the steam economy is equivalent to a multiple-effect evaporator of up to 10 or more units (Z1).

Some typical applications of mechanical vapor-recompression units are evaporation of seawater to give distilled water, evaporation of kraft black liquor in the paper industry (L2), evaporation of heat-sensitive materials such as fruit juices, and crystallization of salts having inverse solubility curves, where the solubility decreases with increasing temperature (K2, M3).

Falling-film evaporators are well suited for vapor-recompression systems (W1) because they operate at low-temperature-difference values and have very little entrained liquid which can cause problems in the compressor. Vapor recompression has been used in distillation towers where the overhead vapor is recompressed and used in the reboiler as the heating medium (M2).

8.8C Thermal Vapor-Recompression Evaporator

A steam jet can also be used to compress the vapor, in what is called a thermal vapor-recompression evaporator. Its main disadvantages are the low efficiency of the steam jet, necessitating the removal of this excess heat, and the lack of flexibility to changes in process variables (M3). Steam jets are cheaper and more durable than mechanical compressors and can more easily handle large volumes of low-pressure vapors.

PROBLEMS

- 8.4-1. Heat-Transfer Coefficient in Single-Effect Evaporator.** A feed of 4535 kg/h of a 2.0 wt % salt solution at 311 K enters continuously a single-effect evaporator and is being concentrated to 3.0%. The evaporation is at atmospheric pressure and the area of the evaporator is 69.7 m². Saturated steam at 383.2 K is supplied for heating. Since the solution is dilute, it can be assumed to have the same boiling point as water. The heat capacity of the feed can be taken as $c_p = 4.10 \text{ kJ/kg} \cdot \text{K}$. Calculate the amounts of vapor and liquid product and the overall heat-transfer coefficient U .

$$\text{Ans. } U = 1823 \text{ W/m}^2 \cdot \text{K}$$

- 8.4-2. Effects of Increased Feed Rate in Evaporator.** Using the same area, value of U , steam pressure, evaporator pressure, and feed temperature as in Problem 8.4-1, calculate the amounts of liquid and vapor leaving and the liquid outlet concentration if the feed rate is increased to 6804 kg/h.

$$\text{Ans. } V = 1256 \text{ kg/h}, L = 5548 \text{ kg/h}, x_L = 2.45\%$$

- 8.4-3. Effect of Evaporator Pressure on Capacity and Product Composition.** Recalculate Example 8.4-1 but use an evaporator pressure of 41.4 kPa instead of 101.32 kPa abs. Use the same steam pressure, area A , and heat-transfer coefficient U in the calculations.