

Evaporation

The process of evaporation is employed in the food industry primarily as a means of bulk and weight reduction for fluids. The process is used extensively in the dairy industry to concentrate milk, in the fruit juice industry to produce fruit juice concentrates, in the manufacture of jams, jellies, and preserves to raise the solids content necessary for gelling, and in the sugar industry to concentrate sugar solutions for crystallization. Evaporation can also be used to raise the solids content of dilute solutions prior to spray or freeze drying.

Evaporation is used to remove water from solutions with or without insoluble suspended solids. If the liquid contains only suspended solids, dewatering can be achieved by either centrifugation or filtration. The process of evaporation involves the application of heat to vaporize water at the boiling point. Its simplest form is atmospheric evaporation where the liquid in an open container is heated and the vapors driven off are dispersed into the atmosphere. Atmospheric evaporation is simple but it is slow and is not very efficient in the utilization of energy. Furthermore, because most food products are heat sensitive, prolonged exposure to high temperature in atmospheric evaporation causes off-flavors, color changes, or degradation of overall quality. In addition, because food also contains volatile compounds, vapors produced by evaporation could generate nuisance odors, therefore they must be contained by condensation. Evaporators used on food products remove water at low temperatures by heating the product in a vacuum. Efficient energy utilization can be designed into the system by using heat exchangers to extract heat from the vapors to preheat the feed or by using multiple effects where the vapors produced from one effect are used to provide heat in the succeeding effects.

Problems in evaporation involve primarily heat transfer and material and energy balances, the principles of which have been discussed earlier.

11.1 SINGLE-EFFECT EVAPORATORS

Figure 11.1 is a schematic diagram of a single-effect evaporator. The system consists of a vapor chamber where water vapor separates from the liquid, a heat exchanger to supply heat for vaporization, a condenser to draw out the vapors from the vapor chamber as rapidly as they are formed, and a steam jet ejector for removing noncondensable gases from the system. Each vapor chamber is considered an effect.

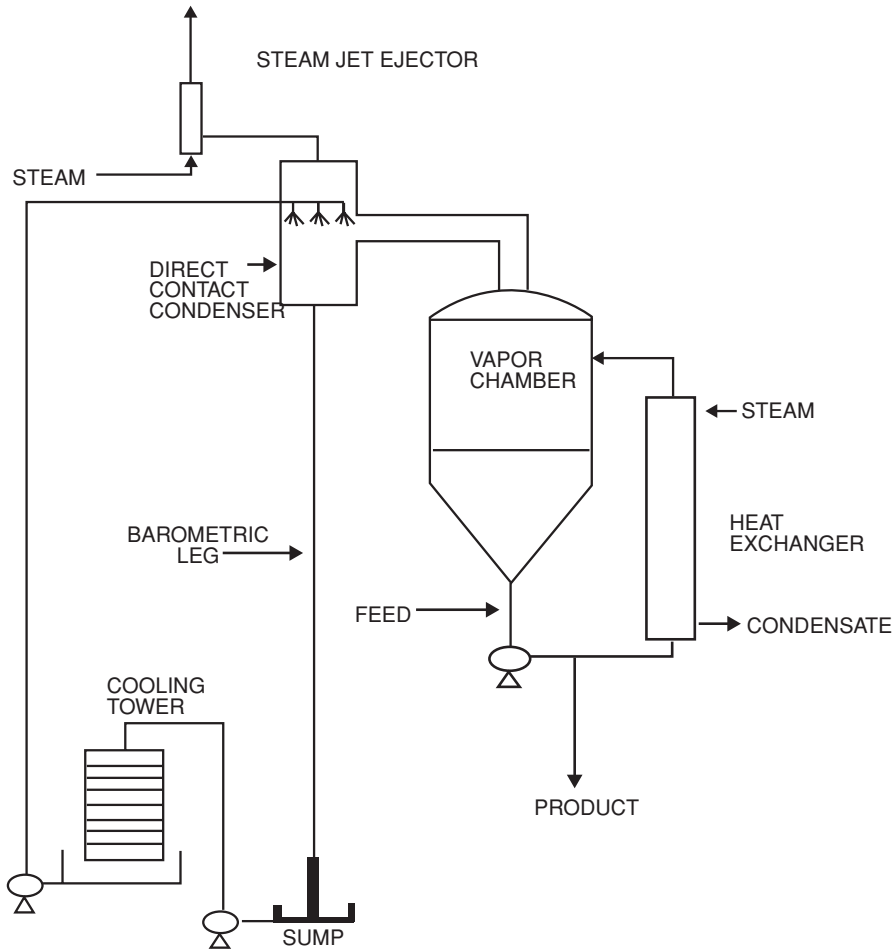


Figure 11.1 Schematic diagram of a single-effect evaporator.

11.1.1 The Vapor Chamber

This is usually the largest and most visible part of the evaporator. Its main function is to allow separation of vapor from liquid and prevent carry-over of solids by the vapor. It is also a reservoir for the product. The temperature inside an evaporator is determined by the absolute pressure in the vapor chamber. The vapor temperature is the temperature of saturated steam at the absolute pressure inside the chamber. When the liquid is a dilute solution, vapor and liquid temperatures will be the same. However, concentrated solutions exhibit a boiling point rise resulting in a higher boiling temperature than that of pure water. Thus vapors leaving the liquid will be superheated steam at the same temperature as the boiling liquid. Depending on the extent of heat loss to the surroundings around the vapor chamber, the vapor may be saturated at the absolute pressure within the vapor chamber, or superheated steam at the boiling temperature of the liquid.

In most food products the soluble solids are primarily organic compounds and the boiling point rise can be expressed as follows:

$$\Delta T_b = 0.51 m \quad (11.1)$$

where ΔT_b in $^{\circ}\text{C}$ is the increase in the boiling point of a solution with molality m , above the boiling point of pure water at the given absolute pressure. In addition to the boiling point rise due to the presence of solute, the pressure at the bottom of a liquid pool is higher than the absolute pressure of the vapor, and this pressure difference can add to the temperature of the liquid pool.. The pressure exerted by a column of liquid of height, h , and density, ρ , is

$$P = \rho(h) \frac{g}{g_c} \quad (11.2)$$

where $g_c = 1$ when using SI units.

Example 11.1. Calculate the boiling temperature of liquid containing 30% soluble solids at a point 5 ft (1.524 m) below the surface inside an evaporator maintained at 20 in. Hg vacuum (33.8 kPa absolute). Assume the soluble solids are hexose sugars and the density of the liquid is 62 lb/ft³ (933 kg/m³). Atmospheric pressure is 30 in. Hg (101.5 kPa).

Solution:

The absolute pressure in lb_f/in.² corresponding to 20 in. Hg vacuum is $(30 - 20)(0.491) = 4.91$ psia. From the steam tables, the temperature corresponding to 4.91 psia is (by interpolation) 161.4°F (71.9°C). The molecular weight of a hexose sugar is 180. The molality of 30% soluble solids will be

$$m = \frac{\text{moles solute}}{1000 \text{ g solvent}} = \frac{0.3/180}{0.7/1000} = 2.38$$

Using Equation (11.1):

$$\Delta T_b = 0.51(2.38) = 1.21^{\circ}\text{C} \text{ or } 2.2^{\circ}\text{F}$$

The absolute pressure at the level considered is the sum of the absolute pressure of the vapor and the pressure exerted by the column of liquid. Expressed in lb_f/in.², this pressure is

$$P = 4.91 + \rho h \frac{g}{g_c} = 4.91 + 62 \frac{\text{lb}_m}{\text{ft}^3} (5 \text{ ft}) \cdot \frac{\text{lb}_f}{\text{lb}_m} \cdot \frac{1 \text{ ft}^2}{144 \text{ in}^2} = 7.06 \text{ psia}$$

From the steam tables, the boiling temperature corresponding to 7.06 psia is (by interpolation) 175.4°F (79.7°C).

The boiling temperature of the liquid will be $175.4 + 2.2 = 177.6^{\circ}\text{F}$ (80.9°C).

The significance of the boiling point rise is that the liquid leaving the evaporator would be at the boiling point of the liquid rather than at the temperature of the vapor. The boiling temperature at a point submerged below a pool of liquid would have the effect of reducing the ΔT available for heat transfer in the heat exchanger if the heat exchange unit is submerged far below the fluid surface.

11.1.2 The Condenser

Two general types of condensers are used. A surface condenser is used when the vapors need to be recovered. This type of condenser is actually a heat exchanger cooled by refrigerant or by cooling

water. The condensate is pumped out of the condenser. It has a high first cost and is expensive to operate. For this reason it is seldom used if an alternative is available. Condensers used on essence recovery systems fall in this category.

The other type of condenser is one where cooling water mixes directly with the condensate. This condenser may be a barometric condenser where vapors enter a water spray chamber on top of a tall column. The column full of water is called a barometric leg and the pressure of water in the column balances the atmospheric pressure to seal the system and maintain a vacuum. The temperature of the condensate-water mixture should be in the order of 5°F (2.78°C) below the temperature of the vapor in the vapor chamber to allow continuous vapor flow into the condenser. The height of the barometric leg must be sufficient to provide sufficient positive head at the base to allow the condensate and cooling water mixture to flow continuously out of the condenser at the same rate they enter. A jet condenser is one where part of the cooling water is sprayed in the upper part of the unit to condense the vapors and the rest is introduced down the throat of a venturi at the base of the unit to draw the condensed vapor and cooling water out of the condenser. The jet condenser uses considerably more water than the barometric condenser and the rate of water consumption cannot be easily controlled.

The condenser duty q_c is the amount of heat that must be removed to condense the vapor.

$$q_c = V(h_g - h_{fc}) \quad (11.3)$$

where V is the quantity of vapor to be condensed, h_g is the enthalpy of the vapor in the vapor chamber of the evaporator, and h_{fc} is the enthalpy of the liquid condensate.

For direct contact condensers, the amount of cooling water required per unit amount of vapor condensed can be determined by a heat balance:

$$W(h_{fc} - h_{fw}) = V(h_g - h_{fc}) \quad (11.4)$$

$$\frac{W}{V} = \frac{h_g - h_{fc}}{h_{fc} - h_{fw}} \quad (11.5)$$

where W is quantity of cooling water required, and h_{fw} is enthalpy of cooling water entering the condenser.

The enthalpy of the condensate-water mixture, h_{fc} , should be evaluated, in the case of barometric condensers, at a temperature 5°F (2.7°C) lower than the vapor temperature.

Example 11.2. Calculate the ratio of cooling water to vapor for a direct contact barometric condenser for an evaporator operating at a vapor temperature of 150°F (65.55°C). What would be the minimum height of the water column in the barometric leg for the evaporator to operate at this temperature? Cooling water is at 70°F (21.1°C). Atmospheric pressure is 760 mm Hg.

Solution:

At a temperature of 150°F, the absolute pressure of saturated steam is 3.7184 psia (25.6 kPa). $h_g = 1126.1$ BTU/lb or 2.619 MJ/kg. The condensate-cooling water mixture must be at 150 – 5 or 145°F (62.78°C). $h_{fc} = 112.95$ BTU/lb or 0.262 MJ/kg. The enthalpy of the cooling water $h_{fw} = 38.052$ BTU/lb or 0.088 MJ/kg. Basis: $V =$ one unit weight of vapor. Using Equation (11.5):

$$\frac{W}{V} = \frac{1126.1 - 112.95}{112.95 - 38.052} = 13.52$$

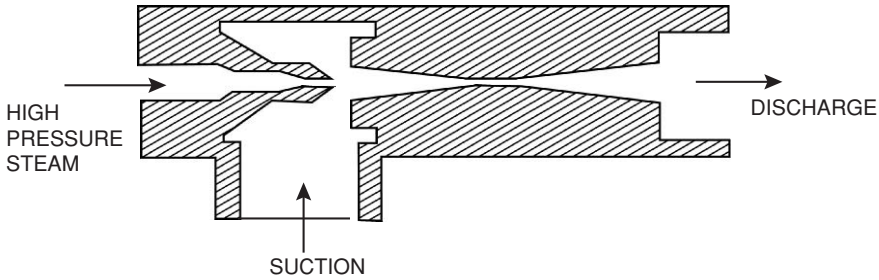


Figure 11.2 Schematic diagram of a single-stage ejector.

The atmospheric pressure is 760 mm Hg or 101.3 kPa. From the steam tables, the density of water at 145°F is $l/V = 61.28 \text{ lb/ft}^3$ or 981.7 kg/m^3 . The pressure that must be counteracted by the column of water in the barometric leg is the difference between barometric pressure and the absolute pressure in the system.

$$\Delta P = 101.3 - 25.6 = 75.7 \text{ kPa} = \rho gh$$

$$h = \frac{75,700 \text{ kg} \cdot \text{m}}{\text{s}^2 \cdot \text{m}^2} \frac{1}{981.7 \text{ kg} \cdot \text{m}^{-3}} \frac{1}{9.80 \text{ m} \cdot \text{s}^{-2}} = 7.868 \text{ m or } 25.8 \text{ ft}$$

11.1.3 Removal of Noncondensable Gases

A steam jet ejector is often used. Figure 11.2 is a schematic diagram of a single-stage ejector. High-pressure steam is allowed to expand through a jet, which increases its velocity. The movement of steam through the converging-diverging section at high velocity generates a zone of low pressure in the suction chamber, and noncondensable gases can be drawn into the ejector. The noncondensable gases mix with the high velocity steam and are discharged into the atmosphere. Steam jet ejectors are more effective than vacuum pumps in that water vapor present in the noncondensable gases does not interfere with its operation. If suction absolute pressures are 4 in. Hg (13.54 kPa) or lower, multistage ejectors are used. The capacity of jet ejectors is dependent on the design of the ejector, the pressure of the high-pressure steam, and the pressure differential between the suction and discharge.

Capacity charts for steam jet ejectors are usually provided by their manufacturers and the capacity is expressed as weight of air evacuated per hour as a function of suction pressure and steam pressure.

The amount of noncondensable gases to be removed from a system depends upon the extent of leakage of air into the system and the amount of dissolved air in the feed and in the cooling water. In addition to the noncondensable gases, jet ejectors also have to remove the water vapor that is present along with the noncondensable gases in the condenser. Air leakage has been estimated at 4 g air/h for every meter length of joints. The solubility of air in water at atmospheric pressure at various temperatures can be determined from Fig. 11.3. The amount of water vapor with the noncondensable gases leaving the condenser can be calculated as follows:

$$W_v = \frac{P_c(18)}{(P_v - P_c)29} \quad (11.6)$$

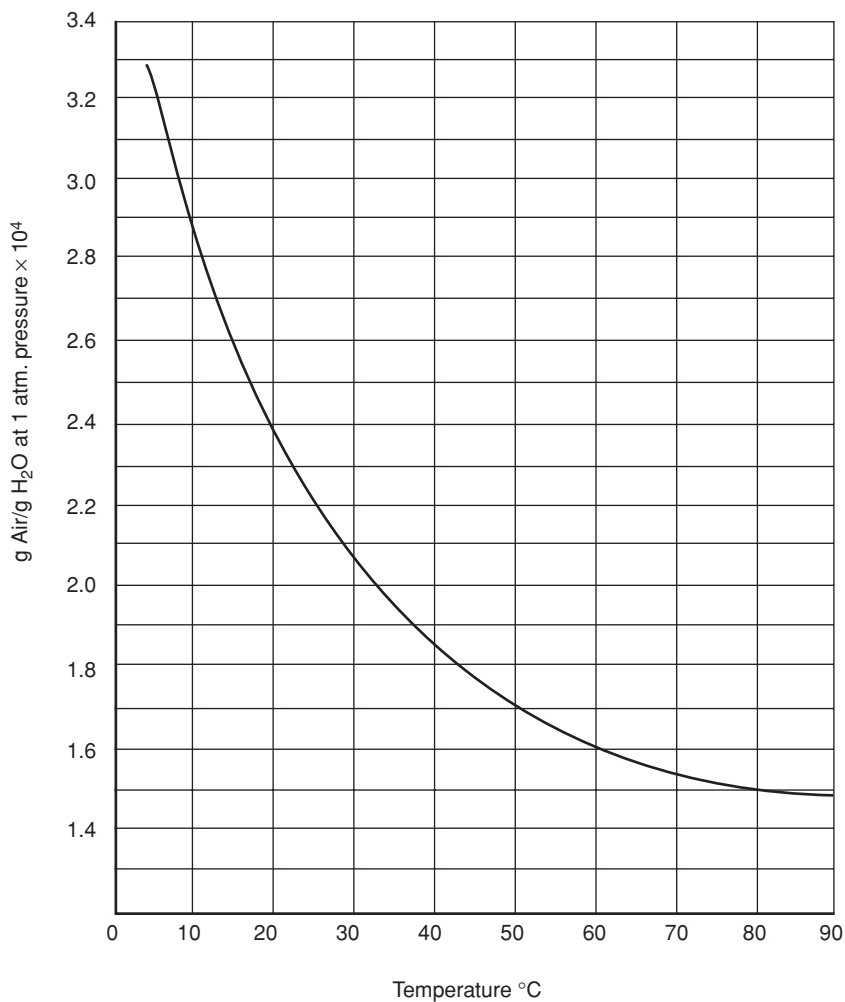


Figure 11.3 Solubility of air in water at atmospheric pressure at various temperatures. (Source: Data from Perry, et al. 1963. Chemical Engineers Handbook. McGraw-Hill, New York.)

where W_v is kg water vapor/kg air, P_c is vapor pressure of water at temperature of condensate-cooling water mixture, and P_v is absolute pressure inside the evaporator.

Example 11.3. Calculate the ejector capacity required for an evaporator that processes 100 kg/h of juice from 12% to 35% solids. The evaporator is operated at 65.6°C (150°F). Cooling water is at 21.1°C (70°F). Product enters at 35°C (89.6°F). The condenser temperature is maintained at 2.78°C (5°F) below the vapor temperature.

Solution:

From Example 11.2, the ratio of cooling water to vapors for an evaporator operated under the identical conditions specified in this problem, was determined to be 13.52 kg of water at 21.1°C. A material balance gives:

$$\text{Wt concentrate} = \frac{100(0.12)}{0.35} = 34.28 \text{ kg/h}$$

$$\text{Wt vapors} = 100 - 34.28 = 65.71 \text{ kg/h}$$

The weight of cooling water W_c is $13.52(65.71) = 888 \text{ kg/h}$. From Fig. 11.3, the solubilities of air in water are 2.37×10^{-4} and $1.96 \times 10^{-4} \text{ kg air / kg water}$ at 21.2°C and 35°C , respectively. The amount of air, M_a , introduced with the condenser water and with the feed is:

$$M_a = 100(1.96 \times 10^{-4}) + 888(2.37 \times 10^{-4}) = 0.23 \text{ kg/h}$$

Using Equation (11.6), a vapor pressure at 62.82°C of 22.63 kPa (3.2825 psia), and a pressure of 25.63 kPa (3.7184 psia) at the vapor temperature of 65.6°C :

$$W_v = \frac{(22.63)18}{(25.63 - 22.63)(29)} = 4.68 \frac{\text{kg water}}{\text{kg air}}$$

The total ejector load excluding air leakage is equivalent to $4.68 + 0.23$ or 4.91 kg/h .

The majority of the ejector load is the water vapor that goes with the noncondensable gases.

11.1.4 The Heat Exchanger

The rate of evaporation in an evaporator is determined by the amount of heat transferred in the heat exchanger. Variations in evaporator design can be seen primarily in the manner in which heat is transferred to the product. Considerations like the stability of the product to heat, fouling of heat exchange surfaces, ease of cleaning, and whether the product could allow a rapid enough rate of heat transfer by natural convection, dictate the design of the heat exchanger for use on a given product. The schematic diagram of an evaporator shown in Fig. 11.1 shows a long tube, vertical, forced circulation evaporator. This type of design for the heat exchanger is usually used when a single effect concentrates a material that becomes very viscous at the high solids content. Because of the forced circulation, heat transfer coefficients are fairly high even at the high viscosity of the concentrate. Some evaporators would have the heat exchanger completely immersed in the fluid being heated inside the vessel that constitutes the fluid reservoir and vapor chamber. Heat is transferred by natural convection. This type of heat exchange is suitable when the product is not very viscous and is usually utilized in the first few effects of a multiple-effect-evaporator.

Heat exchangers on evaporators for food products have the food flowing inside the tubes for ease of cleaning. In very low temperature evaporation such as in fruit juice concentration, the operation has to be stopped regularly to prevent microbiological build-up and also to clean deposits of food product on the heat exchange surfaces.

The capacity of an evaporator is determined by the amount of heat transferred to the fluid by the heat exchanger. If q = the amount of heat transferred, P = mass of concentrated product, C_c = specific heat of the concentrate, V = mass of the vapor, h_g = enthalpy of the vapor, h_f = enthalpy of the

water component of the feed that is converted to vapor, T_1 = feed inlet temperature, and T_2 = liquid temperature in the evaporator, a heat balance would give:

$$q = PC_c(T_2 - T_1) + V(h_g - h_f) \quad (11.7)$$

The rate of heat transfer can be expressed as:

$$Q = U A \Delta T \quad (11.8)$$

A material balance would give:

$$P = \frac{F x_f}{x_p} \quad (11.9)$$

and

$$V = F \left(1 - \frac{x_f}{x_p} \right) \quad (11.10)$$

Equations (11.7) and (11.10) can be used to calculate the capacity of an evaporator in terms of a rate of feed F , knowing the initial solids content, x_f , the final solids content x_p , and the amount of heat transferred in the heat exchanger expressed in terms of the heat transfer coefficient U , the area available for heat transfer, A , and the temperature difference between the boiling liquid in the evaporator and the heating medium, ΔT .

In evaporators where heat transfer to the product is by natural convection, products that have tendencies to form deposits on the heat exchange surface foul the heat exchange surface and reduce the overall heat transfer coefficient, U . When evaporation rate slows down considerably such that it seriously affects production, the operation is stopped and the evaporator is cleaned. In evaporators used on tomato juice, the temperatures are high enough that microbiological build-up is not a factor, and shut-down for clean-up is usually done after about 14 days of operation. In some models of evaporators used on orange juice, on the other hand, operating time between clean-up is much shorter (2–3 days) because of the problem of microbiological build-up at the lower temperatures used.

Fouling of heat exchange surfaces is minimized with reduced ΔT across the heat exchange surface and by allowing the product to flow rapidly over the heat exchange surfaces. Although forced recirculation through the heat exchanger results in rapid heat transfer, a disadvantage is the long residence time of the product inside the evaporator.

For products that are heat sensitive and where low temperature differentials are allowable in the heat exchanger, the falling film heat exchanger is used. Figure 11.4 is a schematic diagram of a falling film type heat exchanger used extensively in the concentration of fruit juices. The product flows in a thin film down heated tubes where heat is transferred and vapor is removed. The product passes through the heat exchange tube of one effect only once, and this short time of contact with a hot surface minimizes heat induced flavor or color changes and nutrient degradation.

The coefficient of heat transfer, U , in evaporator heat exchangers is of the order 200 BTU/(h · ft² · °F) or 1136 W/(m² · K) for natural convection and 400 BTU/h(ft²) (°F) or 2272 W/(m² · K) for forced convection. The effect of increased viscosity on heat transfer can be estimated by using the relationship: heat transfer coefficient is proportional to the viscosity raised to the power -0.44 . Thus: $U_1/U_2 = (\Phi_1/\Phi_2)^{-0.44}$ where U_1 is the heat transfer coefficient corresponding to viscosity Φ_1 and U_2

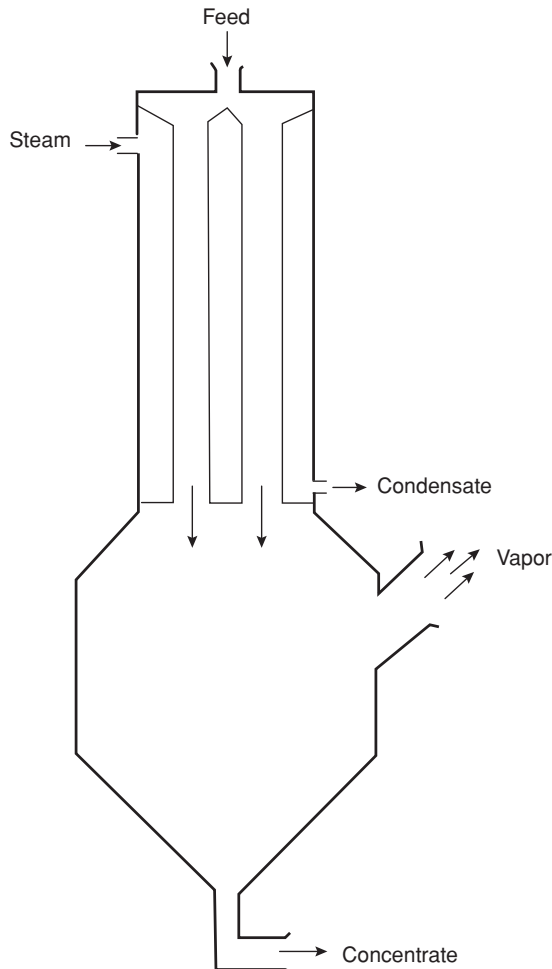


Figure 11.4 Schematic diagram of a falling film evaporator.

is the heat transfer coefficient corresponding to the viscosity Φ_2 . This relationship would be useful in estimating how much of a change in evaporator performance would be expected with a change in operating conditions that would result in variations in product viscosity.

Example 11.4. A fruit juice is to be concentrated in a single-effect forced recirculation evaporator from 10% to 45% soluble solids. The feed rate is 5500 lb/h or 2497 kg/h. Steam condensing at 250°F (121.1°C) is used for heating. The vapor temperature in the evaporator should be at 130°F (54.4°C). Assume the soluble solids are hexose sugars in calculating the boiling point rise. Use Siebel's formula for calculating the specific heat of the juice. The feed is at 125°F (51.7°C). The heat transfer coefficient, U , is 500 BTU/(h · ft² · °F) or 2839 W/(m² · K). Calculate the steam economy to be expected and the heating surface area required.

Solution:

Equations (11.7) through (11.10) will be used. The steam economy is defined as the ratio of vapor produced to steam consumed. C_c will be calculated using Siebel's formula.

$$C_c = 0.8(.55) + 0.2 = 0.64 \text{ BTU/lb}(\text{°F}) \text{ or } 2679 \text{ J/(kg.K)}.$$

$$h_g = \text{enthalpy of vapor at } 130\text{°F} = 1117.8 \text{ BTU/(lb)} = 2.679 \text{ MJ/(kg)}$$

$$h_f = \text{enthalpy of the water component of the feed at } 125\text{°F}.$$

$$= 92.96 \text{ BTU/lb or } 0.216 \text{ MJ/kg}.$$

The temperature of the concentrate leaving the evaporator, T_2 , will be the sum of the vapor temperature and the boiling point rise, ΔT_b . Using Equation (11.1), m for 45% soluble solids is

$$m = \frac{45/180}{55/1000} = 4.545 \text{ moles sugar/1000 g water}$$

$$\Delta T_b = 0.51(4.545) = 2.32\text{°C or } 4.2\text{°F}$$

$$T_2 = 130 + 4.2 = 134.2\text{°F or } 56.72\text{°C}$$

Substituting in Equation (11.10):

$$V = 5500 \left[1 - \frac{0.10}{0.45} \right] = 4278 \text{ lb/h or } 1942 \text{ kg/h}$$

Using Equation (11.9):

$$P = 5500 \left[\frac{0.10}{0.45} \right] = 1222 \text{ lb/h or } 555 \text{ kg/h}$$

Using Equation (11.7):

$$q = 1222(0.64)(134.2 - 125) + 4278(1117.8 - 92.96) = 4,391,500 \text{ BTU/h or } 1.2827 \text{ MW}$$

Equation (11.8) can be used to calculate the heat transfer surface area.

$$A = \frac{q}{U\Delta T} = \frac{4,391,500}{500(250 - 134.2)} = 75.8 \text{ ft}^2 \text{ or } 7.04 \text{ m}^2$$

Note that the liquid boiling temperature was used in determining the heat transfer ΔT rather than the vapor temperature. The enthalpy of vaporization of steam at 250°F is 945.5 BTU/lb or 2.199 MJ/kg. Steam required = $q/h_{fg} = 4,391,500/945.5 = 4645 \text{ lb/h or } 2109 \text{ kg/h}$. Steam economy = $4278/4645 = 0.92$.

11.2 IMPROVING THE ECONOMY OF EVAPORATORS

Poor evaporator economy results from wasting heat present in the vapors. Some of the techniques used to reclaim heat from the vapors include use of multiple effects such that vapors from the first effect are used to heat the succeeding effects, use of vapors to preheat the feed, and vapor recompression.

11.2.1 Vapor Recompression

Adiabatic recompression of vapor results in an increase in temperature and pressure. Figure 11.5 is a Mollier diagram for steam in the region involved in vapor recompression for evaporators. Recompression involves increasing the pressure of the vapor to increase its condensing temperature above the boiling point of the liquid in the evaporator. Compression of saturated steam would result in superheated steam at high pressure. It would be necessary to convert this vapor to saturated steam by mixing with liquid water before introducing it into the heating element of the evaporator. Superheated steam in the heat exchanger could lower the overall heat transfer coefficient. In Chapter 10, the work involved in adiabatic compression was found to be the difference in the enthalpy of the low-pressure saturated vapor and the high-pressure superheated vapor. The ratio between the latent heat of the saturated steam produced from the hot vapors and the work of compression is the coefficient of performance of the recompression system.

Example 11.5. In Example 11.4, determine the coefficient of performance for a vapor recompression system if used on the unit.

Solution:

From Fig. 11.5, the initial point for the compression is saturated vapor with an enthalpy of 1118 BTU/lb or (2.600 MJ/kg). Isentropic compression to the pressure of saturated steam at 250°F (121.1°C) would give a pressure of 29.84 psia (206 kPa) an enthalpy of 1338 BTU/lb (3.112 MJ/kg) and a temperature of 612°F (322°C). Figure 11.6 is a schematic diagram of how these numbers were obtained from Fig. 11.5.

If condensate from the heat exchanger at 250°F is used to mix with the superheated vapor after compression to produce saturated steam at 250°F, the amount of saturated steam produced will be

$$\text{Wt saturated steam} = 1 + \frac{h_{g1} - h_{g2}}{h_{fg}} = 1 + \frac{1338 - 1164}{945.5} = 1.184 \text{ lb (0.537 kg)}$$

$$\text{COP} = \frac{1.184(945.5)}{1(1338 - 1118)} = 5.09$$

The coefficient of performance in vapor recompression systems is high. COP will be higher if the ΔT is kept to a minimum. ΔT in vapor recompression systems are usually of the order 10°F (5.6°C). Although an increase in COP is achieved with the low ΔT , increased area for heat transfer in the evaporator heating unit is also required.

11.2.2 Multiple-Effect Evaporators

Steam economy can also be improved by using multiple evaporation stages and using the vapors from one effect to heat the succeeding effects. Steam is introduced only in the first effect. Figure 11.7 shows a triple effect evaporator with forward feed. This type of feeding is used when the feed is at a temperature close to the vapor temperature of the effect where it is introduced. If substantial amounts of heat are necessary to bring the feed temperature to the boiling temperature, other types of arrangements such as backward feed may be used. In a backward feed arrangement, the flow of the feed is countercurrent to the flow of vapor.

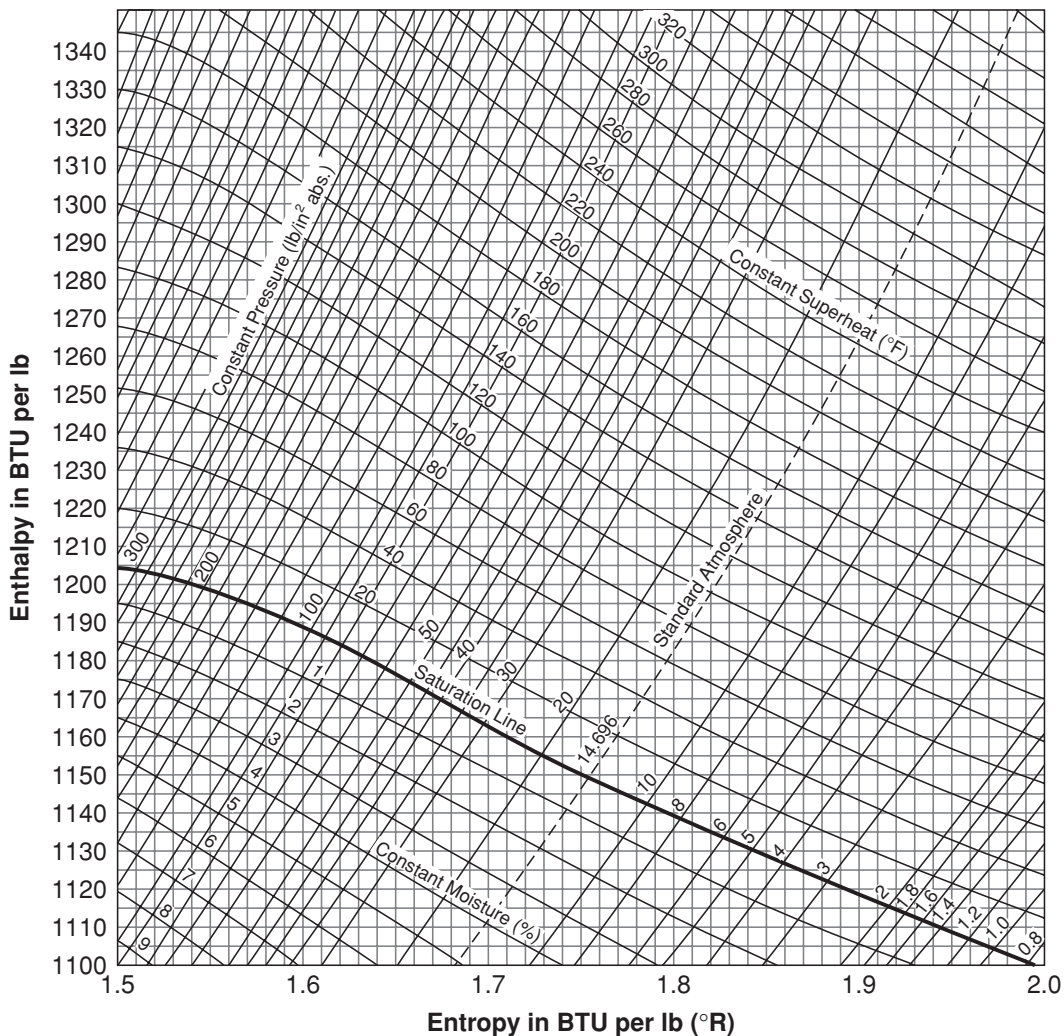


Figure 11.5 Mollier diagram for steam in the region involved in vapor recompression for evaporators. (Courtesy of Combustion Engineering Inc.)

Multiple effect evaporators are often constructed with the same heat transfer surface areas in each effect. The governing equation for evaporation rate in multiple effect evaporators is the heat transfer equation (Eq. 11.8) as in single-effect evaporators. However, the ΔT in each effect of a multiple-effect evaporator is only a fraction of the total ΔT ; therefore, for the same rate of evaporation and the same total ΔT , a multiple effect evaporator with “n” effects would require approximately “n” times the heat exchange area for a single-effect evaporator. The savings in energy costs with the improvement in steam economy is achieved only with an increase in the required heat transfer surface area.

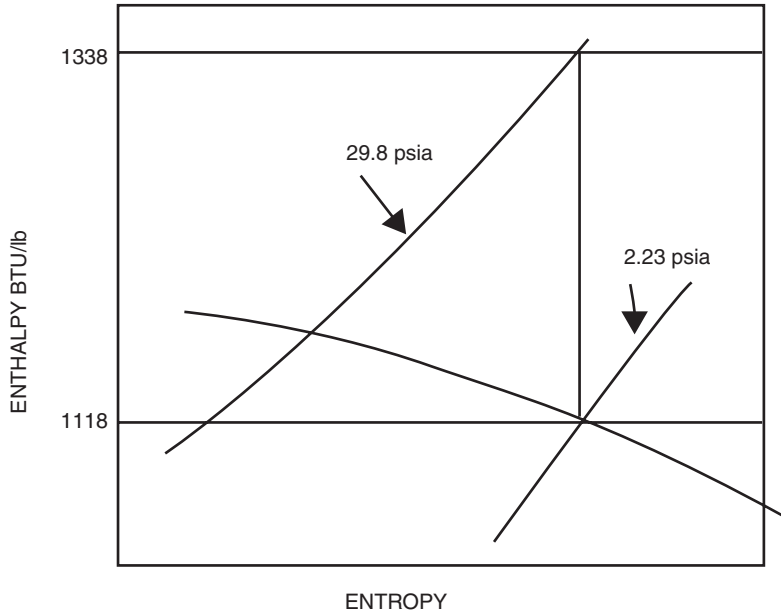


Figure 11.6 The vapor recompression process on a Mollier diagram.

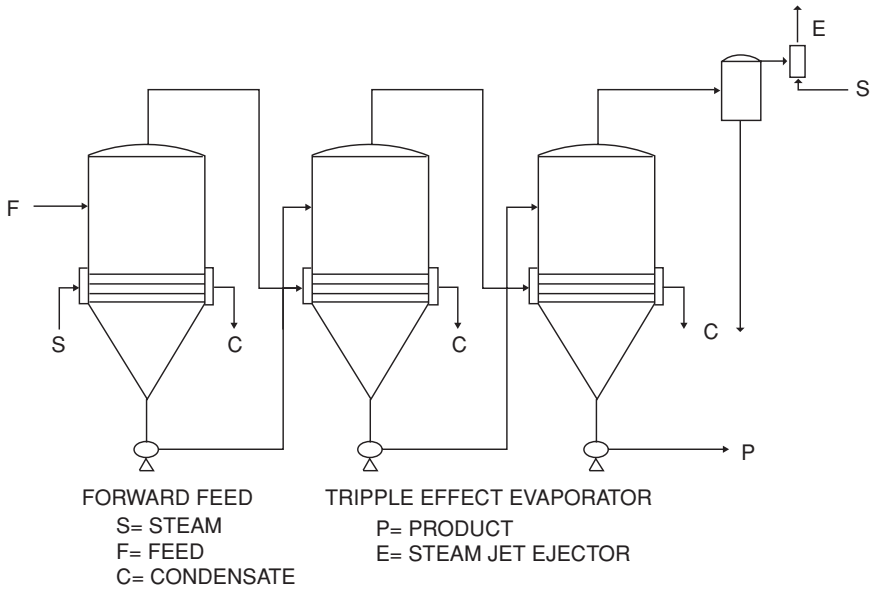


Figure 11.7 Schematic diagram of a triple effect evaporator with forward feed.

Only two parameters affecting heat transfer ΔT can be controlled in the operation of a multiple-effect evaporator. These are the temperature of the vapor in the last effect and the temperature of steam in the first effect. The vapor temperature and pressure in the first and in the intermediate effects will develop spontaneously according to the heat balance occurring within these various effects. The total ΔT in a multiple effect evaporator would be the difference between the steam temperature and the vapor temperature in the last effect. A boiling point rise would decrease the available ΔT .

$$\Delta T = T_s - T_{vn} - \Delta T_{b1} - \Delta T_{b2} - \cdots \Delta T_{bn} \quad (11.11)$$

where ΔT = the total available temperature drop for heat transfer, T_s = steam temperature, T_{vn} = vapor temperature in last effect; ΔT_{b1} , $\Delta T_{b2} \dots \Delta T_{bn}$ = boiling point rise in effects, 1, 2, \dots n.

Multiple-effect evaporator calculations are done using a trial-and-error method. A ΔT is assumed for each effect, and by making heat and material balances in each effect, the rate of heat transfer in each effect is compared with the heat input necessary to achieve the desired evaporation rate in each effect. Adjustments are then made on the assumed ΔT 's until the heat input and the heat requirement for each effect are in balance. Multiple effect evaporator calculations are tedious and time consuming. They are best done on a computer.

Reasonable approximations can be made on capacity for a given multiple effect evaporator knowing the heat transfer surface areas and the heat transfer coefficients by assuming equal evaporation in each effect and making a heat balance as if the evaporator is a single effect with a heat transfer area equal to the sum of all the areas. The overall heat transfer coefficient can be calculated as follows:

$$\frac{1}{U} = \frac{1}{U_1} + \frac{1}{U_2} + \cdots \cdots \frac{1}{U_n} \quad (11.12)$$

Example 11.6. In Example 11.4, the evaporator is a triple effect evaporator with forward feed. Assume U is the same in all effects. Calculate the approximate heat transfer surface areas in each effect and the steam economy.

Solution:

Given:

Feed rate (F) = 5500 lb/h or 2497 kg/h

Steam temperature (T_s) = 250°F (121.1°C)

Vapor temperature in last effect (T_{v3}) = 130°F (54.4°C)

Feed temperature (T_f) = 125°F (51.7°C)

$$U_1 = U_2 = U_3 = 500 \frac{\text{BTU}}{\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}} \quad \text{or} \quad 2839 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

Solids content of feed (x_f) = 10%

Solids content of product (x_p) = 45%

Molecular weight of solids (M) = 180

First, determine the overall heat transfer, ΔT , using Equation (11.11). It will be necessary to determine the boiling point rise in each effect. Using Equation (11.10):

$$\text{Total evaporation (V)} = 5500 \left[1 - \frac{0.10}{0.45} \right] = 4278 \text{ lb/h or } 1942 \text{ kg/h}$$

Assuming equal evaporation, $V_1 = V_2 = V_3 = 1426 \text{ lb/h}$ or 647.3 kg/h . The solids content in each effect can be calculated by rearranging Equation (11.10). The subscripts n on V and F refer to the feed to, and vapor from effect n.

$$x_n = \frac{x_f F_n}{F_n - V_n} \quad x_1 = \frac{0.10(5500)}{5500 - 1426} = 0.135$$

$$x_2 = \frac{0.135(5500 - 1426)}{5500 - 1426 - 1426} = \frac{0.135(4074)}{2648} = 0.208$$

$$x_3 = x_p = 0.45$$

The molalities are

$$m_1 = \frac{0.135(1000)}{(1 - 0.135)(180)} = 0.067 \text{ molal}$$

$$m_2 = \frac{0.208(1000)}{(1 - 0.208)(180)} = 1.459 \text{ molal}$$

$$m_3 = \frac{0.45(1000)}{(1 - 0.45)(180)} = 4.545 \text{ molal}$$

Using Equation (11.1), the boiling point rises are

$$\Delta T_{h1} = 0.51(0.067) = 0.0342^\circ\text{C or } 0.06^\circ\text{F}$$

$$\Delta T_{h2} = 0.51(1.459) = 0.744^\circ\text{C or } 1.34^\circ\text{F}$$

$$\Delta T_{h3} = 0.51(4.545) = 2.32^\circ\text{C or } 4.17^\circ\text{F}$$

The total ΔT for heat transfer is calculated using Equation (11.11):

$$\Delta T = 250 - 130 - 4.17 - 1.34 - 0.06 = 114.4^\circ\text{F or } 63.57^\circ\text{C}$$

Overall U is calculated using Equation (11.12):

$$\frac{1}{U} = \frac{1}{500} + \frac{1}{500} + \frac{1}{500} = 0.006$$

$$U = 166.67 \text{ BTU}/(\text{h} \cdot \text{ft}^2 \cdot \text{EF}) \text{ or } 946.3 \text{ W}/(\text{m}^2 \cdot \text{K})$$

From the section "The Heat Exchanger," the required heat transfer rate for this evaporator was determined to be 4,391,500 BTU/h or 1.2827 MW. Using Equation (11.8):

$$A = \frac{4,391,500}{166(114.4)} = 230.3 \text{ ft}^2 \text{ or } 21.4 \text{ m}^2$$

The heat transfer surface area for each effect will be $230.3/3 \text{ ft}^2 = 76.77 \text{ ft}^2$ or 7.13 m^2 .

Calculations of steam economy can only be done using the trial-and-error procedure necessary to establish the ΔT and the vapor temperature in each effect. The steam economy of multiple effect evaporators is a number slightly less than the number of effects.

11.3 ENTRAINMENT

When the liquid to be evaporated contains suspended solids, the liquid has a tendency to foam. The level of the foam may rise much higher than the normal liquid level resulting in carry-over of solids with the vapors. Entrainment not only results in loss of valuable food solids, but the solids in

the condensate may result in problems with condensate water treatment particularly if a direct contact condenser is used and the condensate is cooled in a cooling tower and recirculated.

11.4 ESSENCE RECOVERY

A major problem in concentration of fruit juices is the loss of essence during the evaporation process. With condensers where the cooling water directly contacts the vapor, it is not possible to recover the flavor components that are vaporized from the liquid. In the past, the problem of essence loss was solved in the orange juice industry by concentrating the juice to a higher concentration than is desired and diluting the concentrate with fresh juice to the desired solids concentration. The essence in the fresh juice gives the necessary flavor to the concentrate.

One method for essence recovery is by flashing the juice into a packed or perforated plate column maintained at a very low absolute pressure. Flash evaporation is a process where hot liquid is introduced into a chamber that is at an absolute pressure where the boiling point of the liquid is below the liquid temperature. The liquid will boil immediately upon exposure to the low pressure, vapor is released, and the liquid temperature will drop to the boiling point of the liquid at the given absolute pressure.

The feed is preheated to 120°F to 150°F (48.9°C to 65.6°C) and is introduced into a column maintained at an absolute pressure of approximately 0.5 psia (3.45 kPa). There is no heat input in the column; therefore, evaporative cooling drops the temperature of the liquid. The vapors rise up the packed column continually getting richer in the volatile components as they proceed up the column. A surface condenser cooled by a refrigeration system traps the volatile components. The essence concentrate recovered is blended with the concentrated product.

In a multiple-effect evaporator, a backward feed arrangement is used, and the vapors from the last effect are condensed using a surface condenser. The condensate containing the essence is flashed into the essence recovery unit.

PROBLEMS

- 11.1. A single-effect falling film type evaporator is used to concentrate orange juice from 14% to 45% solids. The evaporator utilizes a mechanical refrigeration cycle using ammonia as refrigerant, for heating and for condensing the vapors. The refrigeration cycle is operated at a high pressure of 200 psia (1.379 MPa) and a low side pressure of 50 psia (344.7 kPa). The evaporator is operated at a vapor temperature of 90°F (32.2°C). Feed enters at 70°F (21.1°C). The ratio of insoluble to soluble solids in the juice is 0.09 and the soluble solids may be considered as glucose and sucrose in 70:30 ratio. Consider the ΔT as the log mean ΔT between the liquid refrigerant temperature and the feed temperature at one point and the hot refrigerant gas temperature and the concentrated liquid boiling temperature at the other point. The evaporator has a heat transfer surface area of 100 ft² (9.29 m²), and an overall heat transfer coefficient of 300 BTU/(h \$ \$ ft² \$ \$ °F) or 1703 W/(m² \$ \$ K) may be expected.

Calculate:

- The evaporator capacity in weight of feed per hour.
- Tons of refrigeration capacity required for the refrigeration unit based on the heating requirement for the evaporator.
- Additional cooling required for condensation of vapors if the refrigeration unit is designed to provide all of the heating requirements for evaporation.

- 11.2. Condensate from the heating unit of one effect in a multiple effect evaporator is flashed to the pressure of the heating unit in one of the succeeding effects. If the condensate is saturated liquid at 7.511 psia (51.79 kPa) and the heating unit contains condensing steam at 2.889 psia (19.92 kPa), calculate the total available latent heat that will be in the steam produced from a unit weight of the condensate.
- 11.3. A single-effect evaporator was operating at a feed rate of 10,000 kg/h concentrating tomato juice at 160°F (71.1°C) from 15% to 28% solids. The ratio of insoluble to soluble solids is 0.168 and the soluble solids may be assumed to be hexose sugars. Condensing steam at 29.840 psia (205.7 kPa) was used for heating and the evaporator was at an absolute pressure of 5.993 psia (41.32 kPa). It is desired to change the operating conditions to enable the efficient use of a vapor recompression system. The steam pressure is to be lowered to 17.186 psia (118.37 kPa). Assume there is no change in the heat transfer coefficient because of the lowering of the heating medium temperature.

Calculate:

- The steam economy for the original operating conditions.
- The capacity in weight of feed per hour under the new operating conditions.
- The steam economy of the vapor recompression system.

Express the steam economy as the ratio of the energy required for concentration of the juice to the energy required to compress the vapor assuming a mechanical efficiency of 50% for the compressor. Assume condensate from the heating element is added to the superheated steam to reduce temperature to saturation.

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