

### 18.6.4 Plate Evaporators

Plate evaporators consist of a set of plates distributed in units in which vapor condenses in the channels formed between plates. The heated liquid boils on the surface of the plates, ascending and descending as a film. The liquid and vapor mixture formed goes to a centrifugal evaporator.

These evaporators are useful to concentrate heat sensitive products, since high treatment velocities are achieved, allowing good heat transfer and short residence times of the product in the evaporator. Also, plate evaporators occupy little space on the floor and are easily manipulated for cleaning, since setup and dismount are easy and quick. Plate evaporators are usually employed to concentrate coffee, soup broth, light marmalades, and citric juices.

Besides the evaporators described here, there are other types, such as expanded flow, scrape surface and those based on the functioning of the thermal pump used for evaporation of products very sensitive to heat.

### Problems

#### 18.1

A salt solution is concentrated from 5 to 40% in weight of salt. For this reason, 15,000 kg/h of the diluted solution are fed to a double-effect evaporator that operates under backward feed. The steam used in the first effect is saturated at 2.5 atm, maintaining the evaporation chamber of the second effect at a pressure of 0.20 atm. If feed is at 22°C, calculate: a) steam flow rate needed and economy of the system; b) heating area of each effect; c) temperatures and pressures of the different evaporation and condensation chambers.

Data: consider that only the 40% salt solution produces a boiling point rise of 7°C. The specific heat of the salt solutions can be calculated by the expression:  $\hat{C}_p = 4.18 - 3.34 X$  kJ/(kg·°C), where  $X$  is the mass fraction of salt in the solution. The global heat transfer coefficients of the first and second effect are, respectively, 1860 and 1280 W/(m<sup>2</sup>·°C). Specific heat of water vapor is 2.1 kJ/(kg·°C).

The diagram of the double-effect evaporator is represented in [Figure 18.P1](#).

Properties of the saturated steam:

$$P_w = 2.5 \text{ atm} = 2452 \text{ mbar} \quad T = 126.8^\circ\text{C}$$

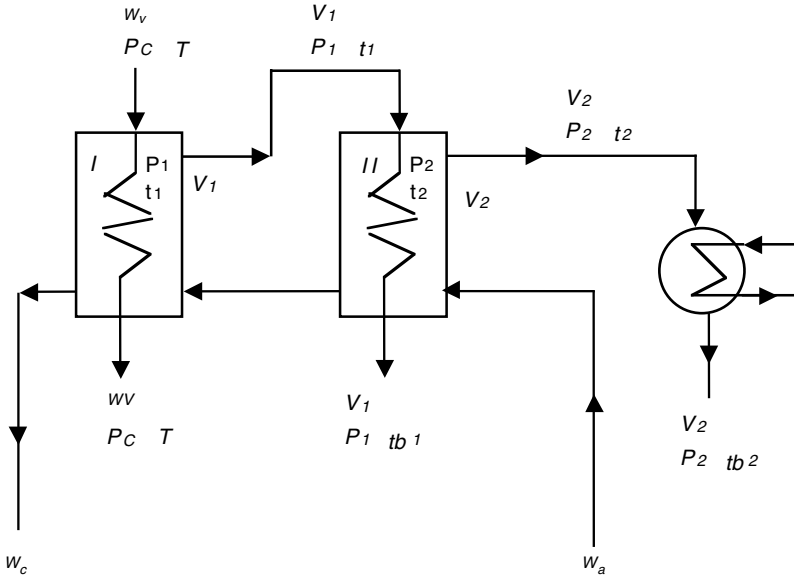
$$\hat{h}_w = 533 \text{ kJ/kg}$$

$$\hat{H}_w = 2716 \text{ kJ/kg} \quad \lambda_w = 2183 \text{ kJ/kg}$$

$$P_2 = 0.2 \text{ atm} = 196 \text{ mbar} \quad t_{b2} = 59.7^\circ\text{C}$$

$$\hat{h}_{v2} = 250 \text{ kJ/kg}$$

$$\hat{H}_{v2} = 2609 \text{ kJ/kg} \quad \lambda_{v2} = 2359 \text{ kJ/kg}$$



**FIGURE 18.P1**  
Backward feed double effect evaporator.

Global and component mass balances:

$$15,000 = w_c + V_1 + V_2$$

$$(15,000)(0.05) = w_c(0.40)$$

obtaining:

$$w_c = 1875 \text{ kg/h and } V_1 + V_2 = 13,125 \text{ kg/h}$$

Initially, it is assumed that  $V_1 = V_2 = 6562.5 \text{ kg/h}$ , supposing that the composition of the stream  $w_2$  is  $X_2 = 0.09$ .

The specific heats of each stream are obtained from the equation given in the problem statement:

- For  $X_A = 0.05$ ,  $\hat{C}_{pA} = 4.01 \text{ kJ}/(\text{kg}\cdot^\circ\text{C})$ .
- For  $X_C = 0.40$ ,  $\hat{C}_{pC} = 2.84 \text{ kJ}/(\text{kg}\cdot^\circ\text{C})$ .
- For  $X_1 = 0.09$ ,  $\hat{C}_{p1} = 3.88 \text{ kJ}/(\text{kg}\cdot^\circ\text{C})$ .

According to the statement of the problem, boiling point rise is only in the first effect, while it can be neglected in the second one, yielding that  $t_2 = t_{b2} = 59.7^\circ\text{C}$ .

In order to perform the calculation process, it is supposed that the areas and the heat flows transferred through these exchange areas are equal for the two effects, complying with (Equation 18.48):

$$\frac{\dot{Q}}{A} = \frac{T - t_{b2} - \Delta T_{b1}}{\frac{1}{U_1} + \frac{1}{U_2}} = \frac{(127.2 - 59.7 - 7)^\circ\text{C}}{\left[ \frac{1}{1860} + \frac{1}{1280} \right] \frac{\text{m}^2 \cdot ^\circ\text{C}}{\text{W}}}$$

Hence,  $\dot{Q}/A = 45,569 \text{ W/m}^2$ .

The temperature  $t_{b1}$  is obtained from the heat transfer rate equation in the second effect:

$$\dot{Q}/A = U_2(t_{b1} - t_2) \quad t_{b1} = 95.3^\circ\text{C}$$

The boiling temperature in the first effect is:

$$t_1 = t_{b1} + \Delta T_{b1} = 95.3 + 7 = 102.3^\circ\text{C}$$

It is possible to find the properties of the saturated steam from the temperature  $t_{b1} = 95.3^\circ\text{C}$  and the saturated steam tables:

$$\begin{aligned} t_{b1} &= 95.3^\circ\text{C} & P_1 &= 855 \text{ mbar} \\ \hat{h}_{v1} &= 399.3 \text{ kJ/kg} \\ \hat{H}_{v1} &= 2668 \text{ kJ/kg} & \lambda_{v1} &= 2268.7 \text{ kJ/kg} \end{aligned}$$

Enthalpy balances applied to both effects yield:

1st effect:

$$\begin{aligned} 2183 w_v &= (2268.7 + (2.1) \cdot (7)) V_1 + (2.84)(1875)(102.3 - 95.3) \\ &\quad - 3.88 w_2(59.7 - 95.3) \end{aligned}$$

2nd effect:

$$2268.7 V_1 = 2359.4 V_2 - (4.01)(15,000)(22 - 59.7)$$

Together with the following balance equations:

$$\begin{aligned} w_2 &= w_A - V_2 \\ V_1 + V_2 &= 13,125 \end{aligned}$$

A four-equation system with four unknowns is obtained, which, when solved, yields:

$$\begin{aligned}w_v &= 8102 \text{ kg/h} & w_2 &= 9056.5 \text{ kg/h} \\V_1 &= 7181.5 \text{ kg/h} & V_2 &= 5943.5 \text{ kg/h}\end{aligned}$$

The value of the areas through which heat is transferred can be obtained by means of the equations of heat transfer rate through such areas:

1st effect:

$$8102(2183/3600) = 1.86 A_1 (126.8 - 102.3)$$

2nd effect:

$$\begin{aligned}7181.5(2268.7/3600) &= 1.28 A_2 (95.3 - 59.7) \\A_1 &= 107.81 \text{ m}^2 & A_2 &= 99.32 \text{ m}^2\end{aligned}$$

The mean area is  $A_m = 105.56 \text{ m}^2$ . Since these areas differ by more than 2%, the calculation procedure should begin again, rectifying the intermediate temperatures  $t_1$  and  $t_{e1}$ , since the other temperatures remain the same:

$$\begin{aligned}t_{b1} - 59.7 &= (95.3 - 59.7)(A_2/A_m) & t_{b1} &= 93.8^\circ\text{C} \\126.8 - t_1 &= (126.8 - 102.3)(A_1/A_m) & t_1 &= 101.3^\circ\text{C}\end{aligned}$$

Hence,  $t_{b1} = 101.3 - 7 = 94.3^\circ\text{C}$ .

Since they are different, the mean value of each temperature is taken:  $t_{b1} = 94^\circ\text{C}$  and  $t_1 = 101^\circ\text{C}$ .

The new enthalpies for  $94^\circ\text{C}$  can be found in the saturated steam tables:

$$\begin{aligned}t_{b1} &= 94^\circ\text{C} & P_1 &= 815 \text{ mbar} \\ \hat{h}_{v1} &= 393.8 \text{ kJ/kg} \\ \hat{H}_{v1} &= 2666 \text{ kJ/kg} & \lambda_{v1} &= 2272.2 \text{ kJ/kg}\end{aligned}$$

The four-equation system stated above is solved again using the new value of  $\lambda_{v1}$ , yielding:

$$\begin{aligned}w_v &= 8090 \text{ kg/h} & w_2 &= 9051 \text{ kg/h} \\V_1 &= 7176 \text{ kg/h} & V_2 &= 5949 \text{ kg/h}\end{aligned}$$

The areas are recalculated from the velocity equations:

$$A_1 = 102.22 \text{ m}^2 \quad A_2 = 103.16 \text{ m}^2$$

(a) Economy of the system:

$$E = \frac{V_1 + V_2}{w_V} = \frac{13,125}{8090} = 1.62$$

(b) Area per effect:

$$A_m = 102.7 \text{ m}^2$$

(c) 1st effect:

$$P_c = 2452 \text{ mbar} \quad T = 126.8^\circ\text{C}$$

$$P_1 = 815 \text{ mbar} \quad t_1 = 101.0^\circ\text{C}$$

2nd effect:

$$P_1 = 815 \text{ mbar} \quad t_{b1} = 94.0^\circ\text{C}$$

$$P_2 = 196 \text{ mbar} \quad t_2 = 59.7^\circ\text{C}$$

## 18.2

A double-effect evaporator, operating under forward feed, is used to concentrate clarified fruit juice from 15 to 72 °Brix. The steam available from the boiler is saturated at 2.4 atm, and the vacuum pressure in the evaporation chamber of the second effect is 460 mm Hg. The diluted juice is fed into the evaporation chamber at a temperature of 50°C and a mass flow rate of 3480 kg/h. If the overall heat transfer coefficients for the first and second effects are 1625 and 1280 W/(m<sup>2</sup>·°C), respectively, determine: (a) steam flow rate from the boiler and economy of the system; (b) heating surface for each effect; and (c) temperatures and pressures in the condensation and evaporation chambers for each effect.

Data: properties of the fruit juices: the boiling point rise can be calculated according to the expression  $\Delta T_b = 0.014 C^{0.75} P^{0.1} \exp(0.034 C)^\circ\text{C}$ , where  $C$  is the soluble solids content in °Brix and  $P$  is the pressure in mbar. The specific heat is a function of the mass fraction of water according to the equation:

$$\hat{C}_p = 0.84 + 3.34X_{\text{WATER}} \text{ kJ}/(\text{kg} \cdot ^\circ\text{C})$$