EVAPORATION CONT'D

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

$$q = UA\ \Delta T \qquad (8.4\text{-}1)$$

where ΔT (K, °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

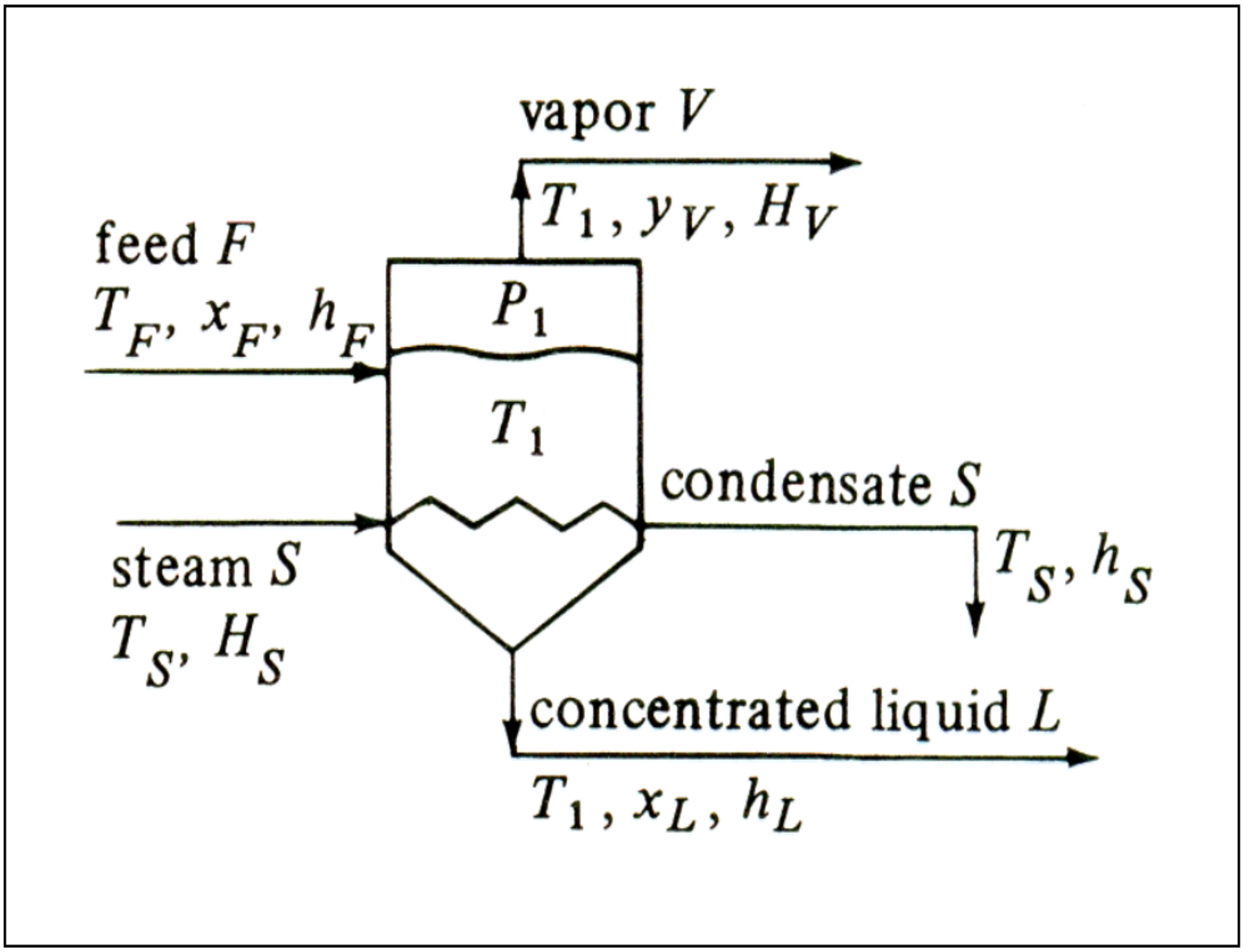

FIGURE 3.6 Heat and mass balance for single-effect evaporator

- 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 (lbm/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:

$$\lambda = H_S - h_S \qquad (8.4\text{-}2)$$

- 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,
  - $F = L + V$ (8.4-3)

- For a balance on the solute (solids) alone,
  - $F x_F = L x_L$

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

- heat in feed + heat in steam = heat in concentrated liquid + heat in vapor + heat in condensed steam (8.4-5)

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

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

- $$Fh_F + SH_S = Lh_L + VH_V + Sh_S \qquad \textbf{(8.4-6)}$$

- $$Fh_F + S\lambda = Lh_L + VH_V \qquad \textbf{(8.4-7)}$$

- The heat q transferred in the evaporator is then

- $$q = S(H_S - h_S) = S\lambda \qquad \textbf{(8.4-8)}$$

- 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.

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 W/m^2.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**.**

$F, L, V = ?$

x_F , x_L , = ?

P_1 , T_1 , = ?

P_F , T_F , h_F = ?

T_S , H_S = ?

H_V = ?

Solution:

- The flow diagram is the same as in Fig. 8.4-1. For the material balance, substituting into Eq. (8.4-3),
        - $F = L + V$ (8.4-3)
    - $9072 = L + V$
- Substituting into Eq. (8.4-4) and solving,
    - $F x_F = L x_L$ (8.4-4)
    - $9072(0.01) = L(0.015)$
        - L = 6048 kg/h of liquid
    - Substituting into Eq. (8.4-3) and solving,
    - V = 3024 kg/h of vapor
- Assume c_{pF} = 4.14 kJ/kg.K
- Boiling point of dilute solution is assumed to be that of water at 101.32 kPa, T_1 = 373.2 K (100^{0}C) as datum temperature.
- Latent heat of water H_v at 373.2 K (from steam tables in Appendix A.2) is 2257 kJ/kg.
- Latent heat of the steam λ at 143.3 kPa (saturation temp., T_S = 383.2 K) is 2230 kJ/kg
- Enthalpy of the feed can be calculated from:
- T_1 = 373.2 K; h_L = 0 ; substitute into Eq. (8.4-7) gives
    - $$h_F = c_{pF}(T_F - T_1) \qquad \textbf{(8.4-9)}$$

- 9072(4.14)(311.0 - 373.2) + S(2230) = 6048(0) + 3024(2257)
    - $S = 4108$ kg steam/h
- $$Fh_F + S\lambda = Lh_L + VH_V \qquad \textbf{(8.4-7)}$$
- The heat q transferred through the heating surface area A is, from Eq. (8.4-8),
    - $q = S(\lambda)$ (8.4-8)
    - $q = (4108)(2230)(1000/3600) = 2\ 544\ 000$ W
- Substituting into Eq. (8.4-1), where $\Delta T = T_S - T_1$,
    - $q = 2\ 544\ 000 = UA\ \Delta T$
        - $= 1704(A)(383.2 - 373.2)$
- Solving, <u>$A = 149.3\ \text{m}^2$</u>
- <u>Effects of Processing Variables on Evaporator Operation</u>
- <u>. Effect of feed temperature.</u>

- The inlet temperature of the feed has a large effect on the operation of the evaporator.
- If feed enter the evaporator at 311.0 K - cold as compared to the boiling temperature of 373.2 K.
- About 1/4 of the steam used for heating is used to heat the cold feed to the boiling point.
- Hence, only about 3/4 of the steam is left for vaporization of the feed.

    - <u>Effect of pressure.</u>

- 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 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 (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
- The new ΔT would be 383.2 - 349.9 = 33.3 K.
- A large decrease in heating-surface area would be obtained.
- 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
  - 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 *Duhring'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

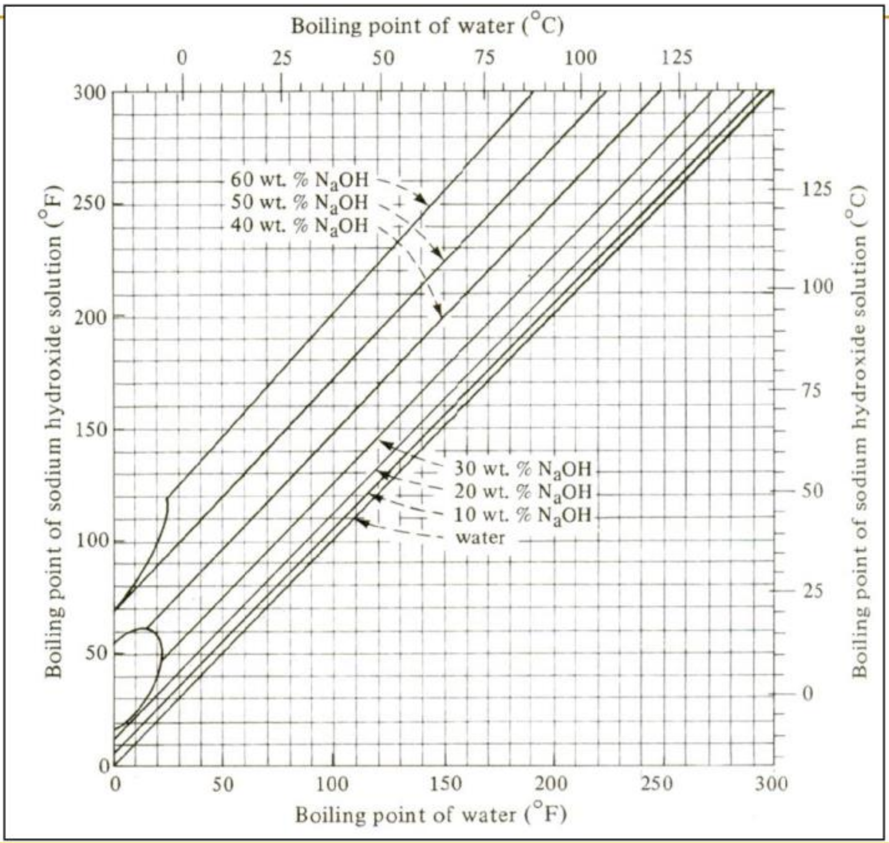

FIGURE 2. Duhring lines for aqueous solutions of sodium hydroxide.