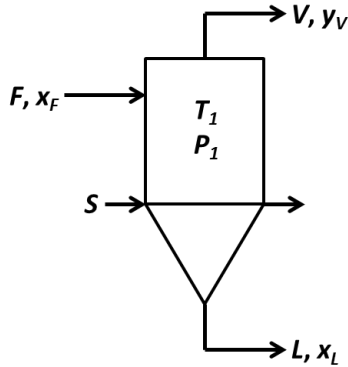


Practice problems in EVAPORATION

1.



Given: $F = 4536 \text{ kg/h}$, $x_F = 0.10$

$$x_L = 0.20$$

$$P_1 = 51.7 \text{ kPa}$$

$$T_F = 21.1^\circ\text{C}$$

$$T_S = 110^\circ\text{C}$$

$$A = 37.6 \text{ m}^2$$

Concentrated NaOH, therefore boiling point rise and heat of solution must be considered.

Solute and overall material balances to find L and V :

$$\begin{aligned} Fx_F &= Lx_L + Vy_V \\ (4536)(0.1) &= L(0.2) + V(0) \\ L &= 2268 \text{ kg/h} \end{aligned}$$

$$\begin{aligned} F &= L + V \\ 4536 &= 2268 + V \\ V &= 2268 \text{ kg/h} \end{aligned}$$

Energy balance to find S : $Fh_F + S\lambda_S = Lh_L + VH_V$

- To solve for S , we need the stream enthalpies and the latent heat of steam. We will use liquid water at 0°C as the datum so we can use the steam tables directly ($T_{\text{ref}} = 0^\circ\text{C}$).

Steam: Using the saturated steam table at $T_S = 110^\circ\text{C}$,

$$\begin{aligned} \lambda_S &= H_S - h_S \\ &= 2691.5 - 461.3 \\ &= 2230.2 \text{ kJ/kg} \end{aligned}$$

Feed: From the enthalpy-concentration chart, for 10% NaOH at 21.1°C (70°F), $h_F = 75 \text{ kJ/kg}$

For the product streams, L and V , we need to know the temperature in the evaporator, T_1 .

- From the steam table, at $P_1 = 51.7 \text{ kPa}$, $T_{\text{sat}} = 82^\circ\text{C}$
- From the Dühring chart, for 20% NaOH and $T_{\text{sat}} = 82^\circ\text{C}$, $T_1 = 90^\circ\text{C}$ and **BPR = 8°C**

Liquid: From the enthalpy-concentration chart, for 20% NaOH at 90°C (194°F), $h_L = 320 \text{ kJ/kg}$

Vapour: From the saturated steam table at $T_{\text{sat}} = 82^\circ\text{C}$, and using **BPR = 8°C** ($= 8 \text{ K}$),

$$\begin{aligned} H_V &= H_{\text{sat}} + 1.88\text{BPR} \\ &= 2647 \text{ kJ/kg} + (1.88 \text{ kJ/kg} \cdot \text{K})(8 \text{ K}) \\ &= 2662 \text{ kJ/kg} \end{aligned}$$

Substituting and solving the energy balance for S :

$$\begin{aligned} Fh_F + S\lambda_S &= Lh_L + VH_V \\ (4536)(75) + S(2230.2) &= (2268)(320) + (2268)(2662) \\ S &= 2865 \text{ kg/h} \end{aligned}$$

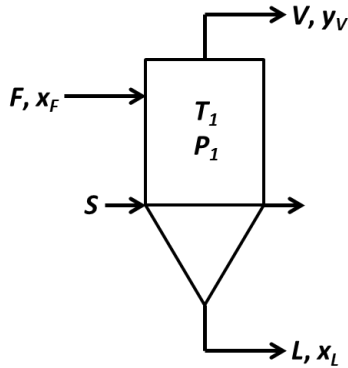
Use the heat transfer rate equation to solve for the overall heat transfer coefficient, U :

$$\begin{aligned} q &= S\lambda_S = UA\Delta T = UA(T_S - T_1) \\ U &= \frac{S\lambda_S}{A(T_S - T_1)} \\ &= \frac{(2865 \text{ kg/h})(2230.2 \text{ kJ/kg})}{(37.6 \text{ m}^2)(110 - 90) \text{ K}} \cdot \frac{1000 \text{ J/kJ}}{3600 \text{ s/h}} \\ &= 2360 \text{ W/m}^2 \cdot \text{K} \end{aligned}$$

Note:

We solved for the steam flow rate, S , because it was asked for in the problem statement. However, it was not necessary to find S (or the latent heat, λ_S) to solve for the overall heat transfer coefficient, U . We could have used the energy balance to solve for $S\lambda_S = q$, then used q directly in the rate equation to solve for U .

2.



Given: $x_F = 0.20$, $x_L = 0.50$

$$T_F = 311 \text{ K}$$

$$P_1 = 13.3 \text{ kPa abs}$$

$$T_S = 399.3 \text{ K}$$

$$U = 1420 \text{ W/m}^2 \cdot \text{K}$$

$$A = 37.6 \text{ m}^2$$

Concentrated NaOH, therefore boiling point rise and heat of solution must be considered.

Energy balance: $Fh_F + S\lambda_S = Lh_L + VH_V$

We can solve the energy balance for F with the following information and substitutions:

- Temperature in the evaporator, T_1
- Stream enthalpies h_F , h_L and H_V . We will use liquid water at 0°C as the datum so we can use the steam tables directly ($T_{\text{ref}} = 0^\circ\text{C}$).
- Heat transfer rate equation to get $q = S\lambda$
- Overall mass balance and solute balance to get $L = f(F)$ and $V = f(F)$

Evaporator temperature and stream enthalpies:

Evaporator:

- From the steam table, at $P_1 = 13.3 \text{ kPa}$, $T_{\text{sat}} = 51.4^\circ\text{C}$
- From the Dühring chart, for 50% NaOH and $T_{\text{sat}} = 51.4^\circ\text{C}$, $T_1 = 88^\circ\text{C}$ and **BPR = 36.6°C**

Feed: From the enthalpy-concentration chart, for 20% NaOH at 311 K (100°F), $h_F = 125 \text{ kJ/kg}$

Liquid: From the enthalpy-concentration chart, for 50% NaOH at 88°C (190°F), $h_L = 500 \text{ kJ/kg}$

Vapour: From the saturated steam table at $T_{\text{sat}} = 51.4^\circ\text{C}$, and using BPR = 36.6°C (= 36.6 K),

$$\begin{aligned} H_v &= H_{\text{sat}} + 1.88\text{BPR} \\ &= 2594.6\text{kJ/kg} + (1.88\text{kJ/kg}\cdot\text{K})(36.6\text{K}) \\ &= 2663.4\text{kJ/kg} \end{aligned}$$

Heat transfer rate equation: $q = S\lambda_s = UA\Delta T = UA(T_s - T_1)$

$$S\lambda_s = (1420\text{W/m}^2 \cdot \text{K})(86.4\text{m}^2)(399.3\text{K} - 361\text{K}) \frac{3600\text{s/h}}{1000\text{J/kJ}}$$

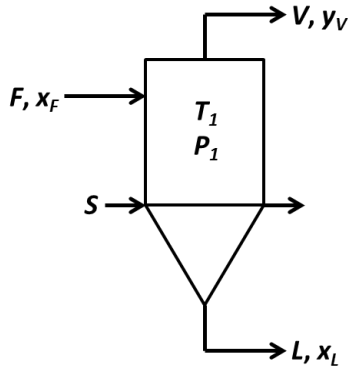
Solute and overall material balances:

$$\begin{aligned} Fx_F &= Lx_L + Vy_v & F &= L + V \\ F(0.2) &= L(0.5) + V(0) & F &= 0.4F + V \\ L &= 0.4F & V &= 0.6F \end{aligned}$$

Substitute and solve the energy balance to find F :

$$\begin{aligned} Fh_F + S\lambda_s &= Lh_L + VH_v \\ F(125) + (1420)(86.4)(399.3 - 361) \frac{3600}{1000} &= 0.4F(500) + 0.6F(2663.4) \\ F &= 10111\text{kg/h} \end{aligned}$$

3.



Given: $x_F = 0.05$, $x_L = 0.50$

$$V = 4536 \text{ kg/h}$$

$$P_1 = 15.3 \text{ kPa}$$

$$T_F = 15.6^\circ\text{C}$$

$$P_S = 101.32 \text{ kPa}$$

$$U = 1988 \text{ W/m}^2 \text{ K}$$

Organic colloids, $C_{PF} = 4.06 \text{ kJ/kg K}$; negligible boiling point rise. Product is quite concentrated, so we cannot assume that C_P is the same as for the feed.

Solute and overall material balances to find F and L :

$$F = L + V \rightarrow L = F - V$$

$$Fx_F = Lx_L + Vy_V = (F - V)x_L + Vy_V$$

$$F(0.05) = F(0.5) - (4536)(0.5) + (4536)(0)$$

$$F = 5040 \text{ kg/h}$$

$$L = F - V$$

$$= 5040 - 4536$$

$$= 504 \text{ kg/h}$$

Energy balance to find S :

$$Fh_F + S\lambda_S = Lh_L + VH_V$$

$$FC_{PF}(T_F - T_{ref}) + S\lambda_S = LC_{PL}(T_1 - T_{ref}) + VH_V$$

- To solve for S , we need the stream enthalpies and the latent heat of steam. We can use the heat capacity of the feed, but we do not know the heat capacity of the liquid product (or have enthalpy-concentration data). Instead, we will use liquid at T_1 as the datum ($T_{ref} = T_1$ and $T_1 - T_{ref} = 0$) for all three process streams. Note that this does not affect the calculation of the latent heat of the steam. (Why not?)
- From the steam table, at $P_1 = 15.3 \text{ kPa}$, $T_1 = T_{sat} = 54.3^\circ\text{C}$

Steam: Using the saturated steam table at $P_S = 101.32 \text{ kPa}$ ($T_S = 110^\circ\text{C}$), $\lambda_s = H_s - h_s$

$$= 2676.1 - 419.04$$

$$= 2257.06 \text{ kJ/kg}$$

Vapour: From the saturated steam table at $T_I = 51.4^\circ\text{C}$,

$$H_V = H_{sat,T1} - h_{sat,T1}$$

$$= 2599.67 - 227.30$$

$$= 2372.4 \text{ kJ/kg}$$

Substituting and solving the energy balance for S :

$$FC_{PF}(T_F - T_{ref}) + S\lambda_s = LC_{PL}(T_1 - T_{ref}) + VH_V$$

$$(5040)(4.06)(15.6 - 54.3) + S(2257.06) = (504)C_{PL}(54.3 - 54.3) + (4536)(2372.4)$$

$$S = 5119 \text{ kg/h}$$

Use the heat transfer rate equation to solve for the area of the evaporator, A :

$$q = S\lambda_s = UA\Delta T = UA(T_S - T_1)$$

$$A = \frac{S\lambda_s}{U(T_S - T_1)}$$

$$= \frac{(5119 \text{ kg/h})(2257.06 \text{ kJ/kg})}{(1988 \text{ W/m}^2 \cdot \text{K})(100 - 54.3) \text{ K}} \cdot \frac{1000 \text{ J/kJ}}{3600 \text{ s/h}}$$

$$= 35.3 \text{ m}^2$$