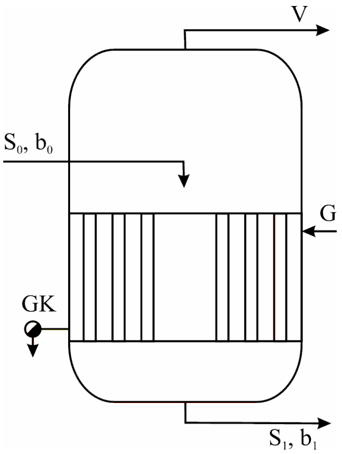
EVAPORATION

Robert evaporator



S=Solution V=Vapor G=Steam GK=Steam condensate

Balance equations

Material balance (total)

$$S_0 = S_1 + V$$

Component balance

$$S_0 \cdot b_0 = S_1 \cdot b_1$$

Heat balance

$$S_0 \cdot h_0 + G \cdot h''_G = S_1 \cdot h_1 + V \cdot h''_V + G \cdot h'_G + \dot{Q}_v$$

Merkel plot can be used for obtaining enthalpy data

Heat power consumption

Case of large evaporators (heat loss in the vapor space)

$$\dot{Q} = G \cdot \left(h''_G - h'_G\right) = G \cdot \Delta h^{vap}$$

$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V + \dot{Q}_v$$

Case of small evaporators (heat loss in the steam space)

$$\dot{Q} = G \cdot \left(h''_G - h'_G\right) - \dot{Q}_v = G \cdot \Delta h^{vap} - \dot{Q}_v$$

$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V$$

Heat transport

$$\dot{Q} = U_{virt} \cdot A \cdot \Delta T_{virt} \qquad \dot{Q} = U_{corr} \cdot A \cdot \Delta T_{corr}$$

$$\Delta T_{virt} = T_G - T_V \qquad \Delta T_{corr} = T_G - T_{S1}$$

Falling film evaporator works as a heat exchanger and logarithmic approach temperature is used.

Problem 1

100 kg/h boiling aquous NaOH solution of 30% is evaporated to 40% at 0.5 bar with 143°C steam. Heat loss is 150 kJ/h. What is the steam consumption?

Solution

Notation

S_0 = 100 kg/h

b_0 = 0.3

p = 0.5 bar

T_G = 143°C

b_1 = 0.4

$\dot{Q}_v$ = 150 kJ/h

G = ?

Output streams

$$S_0 \cdot b_0 = S_1 \cdot b_1$$

$$S_1 = S_0 \cdot \frac{b_0}{b_1} = 100 \frac{kg}{h} \cdot \frac{0.3}{0.4} = 75 \frac{kg}{h}$$

$$S_0 = S_1 + V$$

$$V = S_0 - S_1 = 100 \frac{kg}{h} - 75 \frac{kg}{h} = 25 \frac{kg}{h}$$

Enthalpy values

$$\left.\begin{array}{l} b_0 = 0{,}3 \\ p = 0.5 bar \end{array}\right\} \xrightarrow{\text{Merkel plot}} h_0 = 40 \frac{kJ}{kg}$$

$$\left.\begin{array}{l} b_1 = 0.4 \\ p = 0.5 bar \end{array}\right\} \xrightarrow{\text{Merkel plot}} h_1 = 40 \frac{kJ}{kg}$$

Heat power

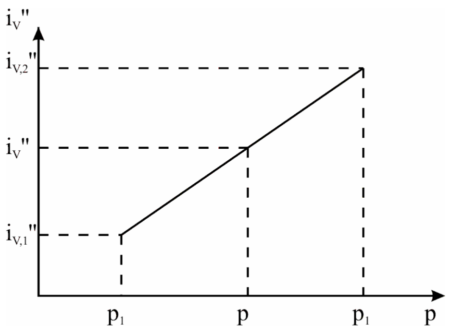
$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V + \dot{Q}_v$$

Vapor enthalpy

Inperpolation is applied because no 0.5 bar data is shown in the steam table.

$$h''_{V,1}\left(p_1 = 4.931 \cdot 10^4 Pa\right) = 2644.802 \frac{kJ}{kg}$$

$$h''_{V,2}\left(p_2 = 5.133 \cdot 10^4 Pa\right) = 2646.476 \frac{kJ}{kg}$$



(i means h)

$$\frac{h''_V - h''_{V,1}}{h''_{V,2} - h''_{V,1}} = \frac{p - p_1}{p_2 - p_1}$$

$$h''_V = \frac{p - p_1}{p_2 - p_1} \cdot \left(h''_{V,2} - h''_{V,1}\right) + h''_{V,1}$$

$$h''_V = \frac{5 \cdot 10^4\,\text{Pa} - 4.931 \cdot 10^4\,\text{Pa}}{5.133 \cdot 10^4\,\text{Pa} - 4.931 \cdot 10^4\,\text{Pa}} \cdot \left(2646.476\frac{\text{kJ}}{\text{kg}} - 2644.802\frac{\text{kJ}}{\text{kg}}\right) + 2644.802\frac{\text{kJ}}{\text{kg}}$$

$$= 2645.4\frac{\text{kJ}}{\text{kg}}$$

Heat power consumption

$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V + \dot{Q}_v =$$

$$75\frac{\text{kg}}{\text{h}} \cdot 40\frac{\text{kJ}}{\text{kg}} - 100\frac{\text{kg}}{\text{h}} \cdot 40\frac{\text{kJ}}{\text{kg}} + 25\frac{\text{kg}}{\text{h}} \cdot 2645.4\frac{\text{kJ}}{\text{kg}} + 150\frac{\text{kJ}}{\text{h}}$$

$$\dot{Q} = 65285\frac{\text{kJ}}{\text{h}}$$

Steam vaporization heat

$$T_G = 143°\text{C} \xrightarrow{\text{steam table}} \Delta h^{vap} = 2136.105\frac{\text{kJ}}{\text{kg}}$$

Steam flow rate

$$\dot{Q} = G \cdot \Delta h^{vap}$$

$$G = \frac{\dot{Q}}{\Delta h^{vap}} = \frac{65285\frac{\text{kJ}}{\text{h}}}{2136.105\frac{\text{kJ}}{\text{kg}}} = 30.56\frac{\text{kg}}{\text{h}}$$

Problem 2

An atmospheric evaporator ha 5 m^2 heating area, and is heated with 165°C saturated steam. The heat loss is 4 %, and the corrected overall heat transfer coefficient is U_{corr} = 1.2 kW/m^2K. 20°C NaOH is evaporated from

a) 37%
b) 42%

to 55% concentration.

c) What is the steam consumption if the evaporation heat of the steam is 2065.7 kJ/kg?

Solution

Notation

$A = 5\ m^2$
$p = 1\ bar$
$T_0 = 20°C$
$b_1 = 0.55$
$T_G = 165°C$
$\dot{Q}_v = 0.04 \cdot \dot{Q}$
$U_{corr} = 1.2\ kW/m^2K$
$\Delta h^{vap} = 2065.7\ kJ/kg$
$S_0 = ?$
$G = ?$

a) $b_0 = 0.37$

Heat power

Dense solution temperature

$$\left.\begin{matrix} b_1 = 0.55 \\ p = 1\,bar \end{matrix}\right\} \xrightarrow{\text{Merkel plot}} T_1 = 155°C$$

Corrected approach temperature

$$\Delta T_{corr} = T_G - T_1 = 165°C - 155°C = 10°C$$

Heat power

$$\dot{Q} = U_{corr} \cdot A \cdot \Delta T_{corr} = 1.2 \frac{kW}{m^2 \cdot K} \cdot 5m^2 \cdot 10°C = 60kW$$

Enthalpy values

$$\left.\begin{matrix} b_0 = 0.37 \\ T_0 = 20°C \end{matrix}\right\} \xrightarrow{\text{Merkel plot}} h_0 = -270 \frac{kJ}{kg}$$

$$\left.\begin{matrix} b_1 = 0.55 \\ p = 1\,bar \end{matrix}\right\} \xrightarrow{\text{Merkel plot}} h_1 = 180 \frac{kJ}{kg}$$

$$p = 1\,bar\} \xrightarrow{\text{steam table}} h''_V = 2675.784 \frac{kJ}{kg}$$

Stream flow rates (balances) rearranged (S_0 in the right hand side)

$$S_0 \cdot b_0 = S_1 \cdot b_1 \quad \rightarrow \quad S_1 = S_0 \cdot \frac{b_0}{b_1}$$

$$S_0 = S_1 + V \quad \rightarrow \quad V = S_0 - S_1 = S_0 - S_0 \cdot \frac{b_0}{b_1} = S_0 \cdot \left(1 - \frac{b_0}{b_1}\right)$$

Heat balance

$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V + \dot{Q}_v$$

$$\dot{Q} = S_0 \cdot \frac{b_0}{b_1} \cdot h_1 - S_0 \cdot h_0 + S_0 \cdot \left(1 - \frac{b_0}{b_1}\right) \cdot h''_V + 0.04 \cdot \dot{Q}$$

$$0.96 \cdot \dot{Q} = S_0 \cdot \left[\frac{b_0}{b_1} \cdot h_1 - \cdot h_0 + \left(1 - \frac{b_0}{b_1}\right) \cdot h''_V\right]$$

$$S_0 = \frac{0.96 \cdot \dot{Q}}{\frac{b_0}{b_1} \cdot h_1 - h_0 + \left(1 - \frac{b_0}{b_1}\right) \cdot h''_V} = \frac{0.96 \cdot 60\text{kW}}{\frac{0.37}{0.55} \cdot 180\frac{\text{kJ}}{\text{kg}} - \left(-270\frac{\text{kJ}}{\text{kg}}\right) + \left(1 - \frac{0.37}{0.55}\right) \cdot 2675.784\frac{\text{kJ}}{\text{kg}}}$$

$$S_0 = 4.55 \cdot 10^{-2}\frac{\text{kg}}{\text{s}} = 163.7\frac{\text{kg}}{\text{h}}$$

b) $b_0 = 0.42$

Only the changed values have to be re-calculated.

Enthalpy

$$\left.\begin{array}{l} b_0 = 0.42 \\ T_0 = 20°C \end{array}\right\} \xrightarrow{\text{Merkel plot}} h_0 = -270\frac{\text{kJ}}{\text{kg}}$$

From the heat balance

$$S_0 = \frac{0.96 \cdot \dot{Q}}{\frac{b_0}{b_1} \cdot h_1 - h_0 + \left(1 - \frac{b_0}{b_1}\right) \cdot h''_V} = \frac{0.96 \cdot 60\text{kW}}{\frac{0.42}{0.55} \cdot 180\frac{\text{kJ}}{\text{kg}} - \left(-270\frac{\text{kJ}}{\text{kg}}\right) + \left(1 - \frac{0.42}{0.55}\right) \cdot 2675.784\frac{\text{kJ}}{\text{kg}}}$$

$$S_0 = 5.54 \cdot 10^{-2}\frac{\text{kg}}{\text{s}} = 199.4\frac{\text{kg}}{\text{h}}$$

c) What is the steam consumption if the evaporation heat of the steam is 2065.7 kJ/kg?

$$\dot{Q} = G \cdot \Delta h^{vap}$$

$$G = \frac{\dot{Q}}{\Delta h^{vap}} = \frac{60\text{kW}}{2065.7\frac{\text{kJ}}{\text{kg}}} = 0.029\frac{\text{kg}}{\text{s}} = 104.6\frac{\text{kg}}{\text{h}}$$

Problem 3

20 t/h 15% NaOH solution is to be concentrated to 25% under 1 bar pressure. Calculate steam consumption and heat transfer area if the dilute feed is fed to a Robert evaporator in a state as

a) 20°C,
b) bubble point,
c) superheated to 2 bar

The heating steam is at 133°C and constaining 5% wetness. Heat loss is 230 kW. Virtual overall heat transfer coefficient is $U_{virt} = 1\ kW/m^2K$.

Solution

Notation

$S_0 = 20$ t/h
$b_0 = 0.15$
p = 1 bar
$b_1 = 0.25$
$T_G = 133°C$
x = 0.95
$\dot{Q}_v = 230$ kW
$U_{virt} = 1\ kW/m^2K$
G = ?
A = ?

a) $T_0 = 20°C$

Outlet stream flow rates

$$S_0 \cdot b_0 = S_1 \cdot b_1$$

$$S_1 = S_0 \cdot \frac{b_0}{b_1} = 20\ \frac{t}{h} \cdot \frac{0.15}{0.25} = 12\frac{t}{h}$$

$$S_0 = S_1 + V$$

$$V = S_0 - S_1 = 20\frac{t}{h} - 12\frac{t}{h} = 8\frac{t}{h}$$

Enthalpy values

$$\left.\begin{array}{l} b_0 = 0.15 \\ T_0 = 20°C \end{array}\right\} \xrightarrow{\text{Merkel plot}} h_0 = -100\frac{kJ}{kg}$$

$$\left.\begin{array}{l} b_1 = 0.25 \\ p = 1 bar \end{array}\right\} \xrightarrow{\text{Merkel plot}} h_1 = 130\frac{kJ}{kg}$$

$$p = 1 bar\} \xrightarrow{\text{steam table}} h''_V = 2675.784\frac{kJ}{kg}$$

Heat power

$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V + \dot{Q}_v$$

$$\dot{Q} = 12000\frac{kg}{h} \cdot 130\frac{kJ}{kg} - 20000\frac{kg}{h} \cdot \left(-100\frac{kJ}{kg}\right) + 8000\frac{kg}{h} \cdot 2675.784\frac{kJ}{kg} + 230kW \cdot 3600\frac{s}{h}$$

$$\dot{Q} = 2.58 \cdot 10^7 \frac{kJ}{h}$$

Steam vaporization heat

$$T_G = 133°C \xrightarrow{\text{steam table}} \Delta h^{vap} = 2165.413\frac{kJ}{kg}$$

Steam consumption

Net steam consumption

$$\dot{Q} = G_{net} \cdot \Delta h^{vap}$$

$$G_{net} = \frac{\dot{Q}}{\Delta h^{vap}} = \frac{2.58 \cdot 10^7 \frac{kJ}{h}}{2165.413\frac{kJ}{kg}} = 11914.6\frac{kg}{h}$$

Wet steam consumption

$$G = \frac{G_{net}}{x} = \frac{11914.6\frac{kg}{h}}{0.95} = 12541.7\frac{kg}{h} = 12.5\frac{t}{h}$$

Heat transfer area

Vapor temperature

$$p = 1bar\} \xrightarrow{\text{steam table}} T_V = 100°C$$

Virtual approach temperature

$$\Delta T_{virt} = T_G - T_V = 133°C - 100°C = 33°C$$

Area

$$\dot{Q} = U_{virt} \cdot A \cdot \Delta T_{virt}$$

$$A = \frac{\dot{Q}}{U_{virt} \cdot \Delta T_{virt}} = \frac{2.58 \cdot 10^7 \frac{kJ}{h}}{1\frac{kW}{m^2 \cdot K} \cdot 33°C \cdot 3600\frac{s}{h}} = 217m^2$$

b) Boiling feed

Enthalpy

$$\left.\begin{array}{l} b_0 = 0.15 \\ p = 1\,\text{bar} \end{array}\right\} \xrightarrow{\text{Merkel plot}} h_0 = 220\,\frac{kJ}{kg}$$

Heat power

$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V + \dot{Q}_v$$

$$\dot{Q} = 12000\,\frac{kg}{h} \cdot 130\,\frac{kJ}{kg} - 20000\,\frac{kg}{h} \cdot 220\,\frac{kJ}{kg} + 8000\,\frac{kg}{h} \cdot 2675.784\,\frac{kJ}{kg} + 230\,kW \cdot 3600\,\frac{s}{h}$$

$$\dot{Q} = 1.94 \cdot 10^7\,\frac{kJ}{h}$$

Steam consumption

Net steam consumption

$$\dot{Q} = G_{net} \cdot \Delta h^{vap}$$

$$G = \frac{\dot{Q}}{\Delta h^{vap}} = \frac{1.94 \cdot 10^7\,\frac{kJ}{h}}{2165.413\,\frac{kJ}{kg}} = 8959\,\frac{kg}{h}$$

Wet steam consumption

$$G = \frac{G_{net}}{x} = \frac{8959\,\frac{kg}{h}}{0.95} = 9430.6\,\frac{kg}{h} = 9.43\,\frac{t}{h}$$

Heat transfer area

$$\dot{Q} = U_{virt} \cdot A \cdot \Delta T_{virt}$$

$$A = \frac{\dot{Q}}{U_{virt} \cdot \Delta T_{virt}} = \frac{1.94 \cdot 10^7\,\frac{kJ}{h}}{1\,\frac{kW}{m^2 \cdot K} \cdot 33°C \cdot 3600\,\frac{s}{h}} = 163.25\,m^2$$

c) p_0 = 2 bar

Enthalpy

$$\left.\begin{matrix} b_0 = 0.15 \\ p = 2\,\text{bar} \end{matrix}\right\} \xrightarrow{\text{Merkel plot}} h_0 = 300\frac{kJ}{kg}$$

Heat power

$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V + \dot{Q}_v$$

$$\dot{Q} = 12000\frac{kg}{h} \cdot 130\frac{kJ}{kg} - 20000\frac{kg}{h} \cdot 300\frac{kJ}{kg} + 8000\frac{kg}{h} \cdot 2675.784\frac{kJ}{kg} + 230kW \cdot 3600\frac{s}{h}$$

$$\dot{Q} = 1.78 \cdot 10^7\ \frac{kJ}{h}$$

Steam consumption

Net steam consumption

$$\dot{Q} = G_{net} \cdot \Delta h^{vap}$$

$$G = \frac{\dot{Q}}{\Delta h^{vap}} = \frac{1.78 \cdot 10^7\ \frac{kJ}{h}}{2165.413\frac{kJ}{kg}} = 8220\frac{kg}{h}$$

Wet steam consumption

$$G = \frac{G_{net}}{x} = \frac{8220\frac{kg}{h}}{0.95} = 8653\frac{kg}{h} = 8.65\frac{t}{h}$$

Heat transfer area

$$\dot{Q} = U_{virt} \cdot A \cdot \Delta T_{virt}$$

$$A = \frac{\dot{Q}}{U_{virt} \cdot \Delta T_{virt}} = \frac{1.78 \cdot 10^7\ \frac{kJ}{h}}{1\frac{kW}{m^2 \cdot K} \cdot 33°C \cdot 3600\frac{s}{h}} = 149.8m^2$$

Problem 4

One pass falling film evaporator is used to concentrate 5 t/h 20% 100°C NaOH solution to 35%, under 0.5 bar. Heat loss is 3%.
Determine:

a) Heat consumption
b) Saturation temperature of the steam to be applied if minimum approach temperature is 6°C
c) Required heat transfer area if average overall heat transfer coefficient is 0.5 kW/m^{2}K

Solution

Notation

S_0 = 5 t/h
b_0 = 0.2
b_1 = 0.35
p = 0.5 bar
T_0 = 100°C
$\dot{Q}_{loss} = 0.03 \cdot \dot{Q}$

a) Heat consumption

Output streams

$$S_0 \cdot b_0 = S_1 \cdot b_1$$
$$S_1 = S_0 \cdot \frac{b_0}{b_1} = 5\frac{t}{h} \cdot \frac{0.2}{0.35} = 2.86\frac{t}{h}$$

$$S_0 = S_1 + V$$
$$V = S_0 - S_1 = 5\frac{t}{h} - 2.86\frac{t}{h} = 2.14\frac{t}{h}$$

Enthalpy values

$$\left.\begin{matrix} b_0 = 0.2 \\ T_0 = 100°C \end{matrix}\right\} \xrightarrow{\text{Merkel plot}} h_0 = 140\frac{kJ}{kg}$$
$$\left.\begin{matrix} b_1 = 0.35 \\ p = 0.5bar \end{matrix}\right\} \xrightarrow{\text{Merkel plot}} h_1 = 35\frac{kJ}{kg}$$
$$p = 0.5bar\} \xrightarrow{\text{steam table}} h''_V = 2645.4\frac{kJ}{kg}$$

Heat power

$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V$$
$$\dot{Q} = 2857\frac{kg}{h} \cdot 35\frac{kJ}{kg} - 5000\frac{kg}{h} \cdot 140\frac{kJ}{kg} + 2143\frac{kg}{h} \cdot 2645.4\frac{kJ}{kg}$$
$$\dot{Q} = 5.07 \cdot 10^6\frac{kJ}{h}$$

b) Saturation temperature of the steam to be applied if minimum approach temperature is 6°C

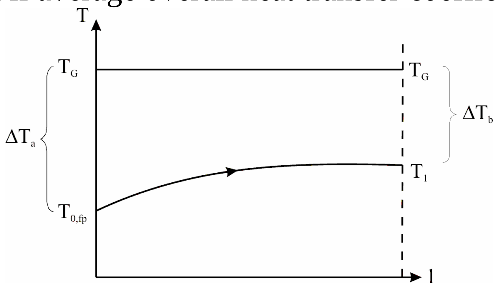
Maximum temperature amongst the process streams belongs to the dense solution.

$$\left.\begin{array}{l} b_1 = 0.35 \\ p = 0.5\text{bar} \end{array}\right\} \xrightarrow{\text{Merkel plot}} T_1 = 105°C$$

Steam temperature:

$$T_{Steam} = T_1 + \Delta T_{min} = 105°C + 6°C = 111°C$$

c) Required heat transfer area if average overall heat transfer coefficient is 0.5 kW/m^{2}K



Although the feed is of 100 C, the dilute solution reaches its bubble point in the evaporator almost at once. Therefore the boiling point is to be applied at calculating the logarithmic mean approach temperature.

$$\left.\begin{array}{l} b_0 = 0{,}2 \\ p = 0.5\text{bar} \end{array}\right\} \xrightarrow{\text{Merkel plot}} T_{0,bp} = 88°C$$

Approach temperatures at the two endpoints

$$\Delta T_a = T_{Steam} - T_{0,bp} = 111°C - 88°C = 23°C$$

$$\Delta T_b = T_{Steam} - T_1 = 111°C - 105°C = 6°C$$

Logarithmic approach temperature

$$\Delta T_{av} = \frac{\Delta T_a - \Delta T_b}{\ln\frac{\Delta T_a}{\Delta T_b}} = \frac{23°C - 6°C}{\ln\frac{23°C}{6°C}} = 12.65°C$$

Heat transfer area

$$\dot{Q} = U \cdot A \cdot \Delta T_{av}$$

$$A = \frac{\dot{Q}}{U \cdot \Delta T_{av}} = \frac{5.07 \cdot 10^6 \frac{kJ}{h}}{0.5 \frac{kW}{m^2 \cdot K} \cdot 12.65°C \cdot 3600 \frac{s}{h}} = 222.7 m^2$$

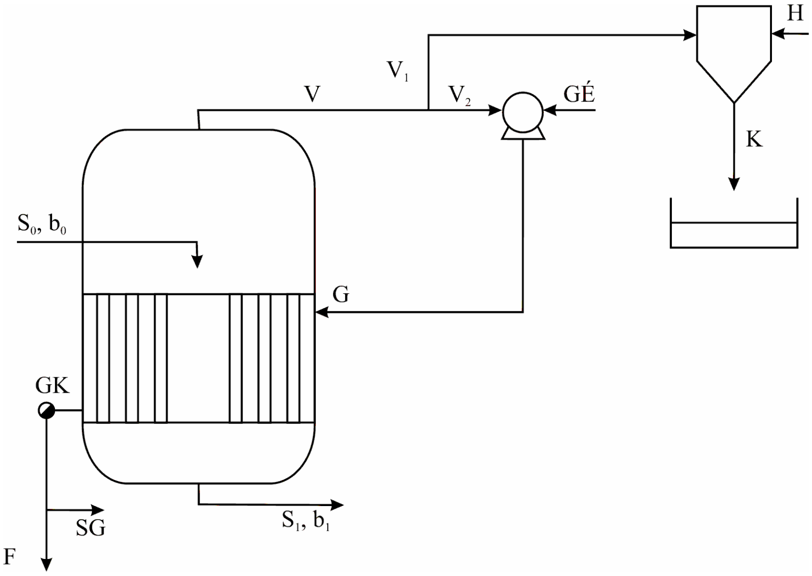
Problem 5

20 C NaOH solution is concentrated to 42 % under 0.2 bar pressure, resulting in 0.6 t dense solution and 1.5 t vapor in each hour. 1.2 bar saturated steam, obtained by mixing 1.48 bar live steam with a part of the vapor. The other part of the vapor is condensed in a mixing barometric condenser using 18 m^3/h 10°C cooling water.

Calculate:

a) Live steam consumption
b) Fraction of the vapor used in the steam
c) Temperature of the barometric condenser outlet stream
d) Flow rate of the flash steam obtained from the steam condensate

Solution



H: cooling water K: vapor condensate
GÉ: live steam G: steam
GK: steam condensate SG: flash steam
F: exhaust

Notation

$b_1 = 0.42$
$p = 0.2$ bar
$T_0 = 20$°C
$S_1 = 0.6$ t/h
$V = 1.5$ t/h

$p_G = 1.2$ bar
$p_{GÉ} = 1.48$ bar
$\dot{V}_H = 18\ m^3/h$
$T_H = 10$°C

a) Live steam consumption

Fead stream flow rate

$$S_0 = S_1 + V = 0.6\frac{t}{h} + 1.5\frac{t}{h} = 2.1\frac{t}{h}$$

Feed stream concentration

$$S_0 \cdot b_0 = S_1 \cdot b_1$$

$$b_0 = \frac{S_1}{S_0} \cdot b_1 = \frac{0.6\frac{t}{h}}{2.1\frac{t}{h}} \cdot 0.42 = 0.12$$

Enthalpy values

$$\left.\begin{matrix} b_0 = 0.12 \\ T_0 = 20°C \end{matrix}\right\} \xrightarrow{\text{Merkel plot}} h_0 = -65\frac{kJ}{kg}$$

$$\left.\begin{matrix} b_1 = 0.42 \\ p = 0.2 bar \end{matrix}\right\} \xrightarrow{\text{Merkel plot}} h_1 = -30\frac{kJ}{kg}$$

$$p = 0.2 bar\} \xrightarrow{\text{steam table}} h''_V = 2609.214\frac{kJ}{kg}$$

Heat power

$$\dot{Q} = S_1 \cdot h_1 - S_0 \cdot h_0 + V \cdot h''_V$$

$$\dot{Q} = 600\frac{kg}{h} \cdot \left(-30\frac{kJ}{kg}\right) - 2100\frac{kg}{h} \cdot \left(-65\frac{kJ}{kg}\right) + 1500\frac{kg}{h} \cdot 2609.214\frac{kJ}{kg}$$

$$\dot{Q} = 4.03 \cdot 10^6 \frac{kJ}{h}$$

Steam consumption

Steam vaporization heat

$$p_G = 1.2 bar\} \xrightarrow{\text{steam table}} \Delta h^{vap} = 2243.287\frac{kJ}{kg}$$

Steam mass flow rate

$$\dot{Q} = G \cdot \Delta h^{vap}$$

$$G = \frac{\dot{Q}}{\Delta h^{vap}} = \frac{4,03 \cdot 10^6 \frac{kJ}{h}}{2243.287\frac{kJ}{kg}} = 1797.5\frac{kg}{h}$$

b) Fraction of the vapor utilized in the steam

Material balance around the compressor

$$V_2 + GÉ = G$$

Heat balance around the compressor

$$V_2 \cdot h''_V + GÉ \cdot h''_{GÉ} = G \cdot h''_G$$

(The vapor looses it superheated value as it leaves the evaporator; its saturated state is taken into account)

Enthalpy values

$$p_G = 1.2 bar\} \xrightarrow{\text{steam table}} h''_G = 2683.320 \frac{kJ}{kg}$$

$$p_{GÉ} = 1.48 bar\} \xrightarrow{\text{steam table}} h''_{GÉ} = 2692.95 \frac{kJ}{kg}$$

Mass flow rate of live steam and of utilized vapor (from balance)

$$V_2 \cdot h''_V + GÉ \cdot h''_{GÉ} = G \cdot h''_G$$

$$(G - GÉ) \cdot h''_V + GÉ \cdot h''_{GÉ} = G \cdot h''_G$$

$$G \cdot h''_V - GÉ \cdot h''_V + GÉ \cdot h''_{GÉ} = G \cdot h''_G$$

$$GÉ \cdot (h''_{GÉ} - h''_V) = G \cdot (h''_G - h''_V)$$

$$GÉ = \frac{G \cdot (h''_G - h''_V)}{h''_{GÉ} - h''_V} = \frac{1797.5 \frac{kg}{h} \cdot \left(2683.320 \frac{kJ}{kg} - 2609.214 \frac{kJ}{kg}\right)}{2692.95 \frac{kJ}{kg} - 2609.214 \frac{kJ}{kg}} = 1590 \frac{kg}{h}$$

$$V_2 = G - GÉ = 1797.5 \frac{kg}{h} - 1590 \frac{kg}{h} = 207.5 \frac{kg}{h}$$

c) Temperature of the barometric condenser outlet stream

Remaining vapor

$$V_1 = V - V_2 = 1500 \frac{kg}{h} - 207.5 \frac{kg}{h} = 1292.5 \frac{kg}{h}$$

Cooling water mass flow rate

$$H = \dot{V}_H \cdot \rho_H = 18 \frac{m^3}{h} \cdot 1000 \frac{kg}{m^3} = 18000 \frac{kg}{h}$$

Vapor mixed condensate mass flow rate

$$K = V_1 + H = 1292.5 \frac{kg}{h} + 18000 \frac{kg}{h} = 19292.5 \frac{kg}{h}$$

Cooling water enthalpy value

$$T_H = 10°C\} \xrightarrow{\text{steam table}} h'_H = 42.035 \frac{kJ}{kg}$$

Heat balance of the barometric mixing condenser

$$V_1 \cdot h''_V + H \cdot h'_H = K \cdot h'_K$$

Mixed vapor condensate enthalpy

$$h'_K = \frac{V_1 \cdot h''_V + H \cdot h'_H}{K} = \frac{1292.5\,\frac{kg}{h} \cdot 2609.214\,\frac{kJ}{kg} + 18000\,\frac{kg}{h} \cdot 42.035\,\frac{kJ}{kg}}{19292.5\,\frac{kg}{h}} = 214\,\frac{kJ}{kg}$$

Mixed vapor condensate temperature

$$\left. h'_K = 214\,\frac{kJ}{kg} \right\} \xrightarrow{\text{steam table}} T_K \approx 51°C$$

d) Flow rate of the flash steam obtained from the steam condensate

Mass balance

$$GK = SG + F$$

Enthalpy values

$$\left. p_{GK} = 1.2 bar \right\} \xrightarrow{\text{steam table}} h'_{GK} = 440.2\,\frac{kJ}{kg}$$

$$\left. p_{SG} = 1 bar \right\} \xrightarrow{\text{steam table}} h''_{SG} = 2675.784\,\frac{kJ}{kg}$$

$$\left. p_F = 1 bar \right\} \xrightarrow{\text{steam table}} h'_F = 419.099\,\frac{kJ}{kg}$$

(Exhaust is considered as liquid)

Steam condensate mass flow rate

$$GK = G = 1797.5\,\frac{kg}{h}$$

Flash steam mass flow rate

Heat balance

$$GK \cdot h'_{GK} = SG \cdot h''_{SG} + F \cdot h'_F$$

$$GK \cdot h'_{GK} = SG \cdot h''_{SG} + (GK - SG) \cdot h'_F$$

$$GK \cdot (h'_{GK} - h'_F) = SG \cdot (h''_{SG} - h'_F)$$

$$SG = \frac{GK \cdot (h'_{GK} - h'_F)}{h''_{SG} - h'_F} = \frac{1797.5\,\frac{kg}{h} \cdot \left(440.2\,\frac{kJ}{kg} - 419.099\,\frac{kJ}{kg}\right)}{2675.784\,\frac{kJ}{kg} - 419.099\,\frac{kJ}{kg}} = 16.8\,\frac{kg}{h}$$