280.371 Process Engineering Operations
Albany/Manawatu

Assignment 2. Evaporation
2016

Show your working for all calculations.

Question 1

A New Zealand dairy factory is considering installing a new evaporator to reduce the effluent volumes for final disposal. The daily volume of waste to be evaporated is 620 m^3, and its density is 1003 $kg.m^{-3}$; the waste is to be concentrated from 3.5 % (w/w) solids to 30 % (w/w) solids in 16 hours. Process steam is available at 220 kPa.a. The waste contains both dissolved and particulate solids and is known to be moderately fouling and viscous when heated in concentrated form. The evaporator system must be housed within the existing dairy factory building.

(a) Two second-hand falling film evaporators have been found at the back of the factory, left-over after a major refurbishment. Explain the key operating features of this type of evaporator including its advantages and disadvantages. Would they be a suitable choice for the required application?

(b) A two-effect feed-forward evaporator is proposed, using the same area in each stage. Steam evaporated in stage 1 is used as the heat source for stage 2. Boiling point elevation can be ignored and the vapour flow rates can be assumed to be the same in each stage. The evaporation temperature in the second stage is to be 105°C. The overall heat transfer coefficient, *U,* depends on the product concentration, x_{Li}, of the product leaving an evaporation stage and is given by Equation 1 below.

Calculate:

(i) The mass flow rates of feed, final product and the vapour flow rates removed in each stage.
(ii) The intermediate product concentration leaving stage 1.
(iii) The *U* values for each stage and the evaporation temperature in stage 1.
(iv) The required steam flow rate to the first stage and its steam economy ($kg.kg^{-1}$).

(c) If boiling point elevation had been significant in this case, what would the major consequence(s) be?

[Total 20 marks]

$$\boldsymbol{U = 1900\,\exp(-4\,x_{Li})} \qquad \textbf{(1)}$$

Question 2

(a) Describe the difference between forced and natural circulation evaporators using diagrams to illustrate your answer. Explain how the circulatory flow is established in each case and give one example of the type of solution for which each type of evaporator could be appropriate.

[5 marks]

(b) A triple effect feed forward evaporator is used to concentrate 5 tonne/hour of sucrose solution from 5 wt% to 40wt%. The area of each evaporator stage is 45 m^2 and the temperatures of the 1st, 2nd and 3rd effect evaporators are 100°C, 78°C and 52°C, respectively. The steam supplied to the first effect is 98 kPa.g.

(i) Estimate the amount of water removed in each stage and the flow rate of product from the evaporator. Assume that mass flow rates of vapour from each effect are equal

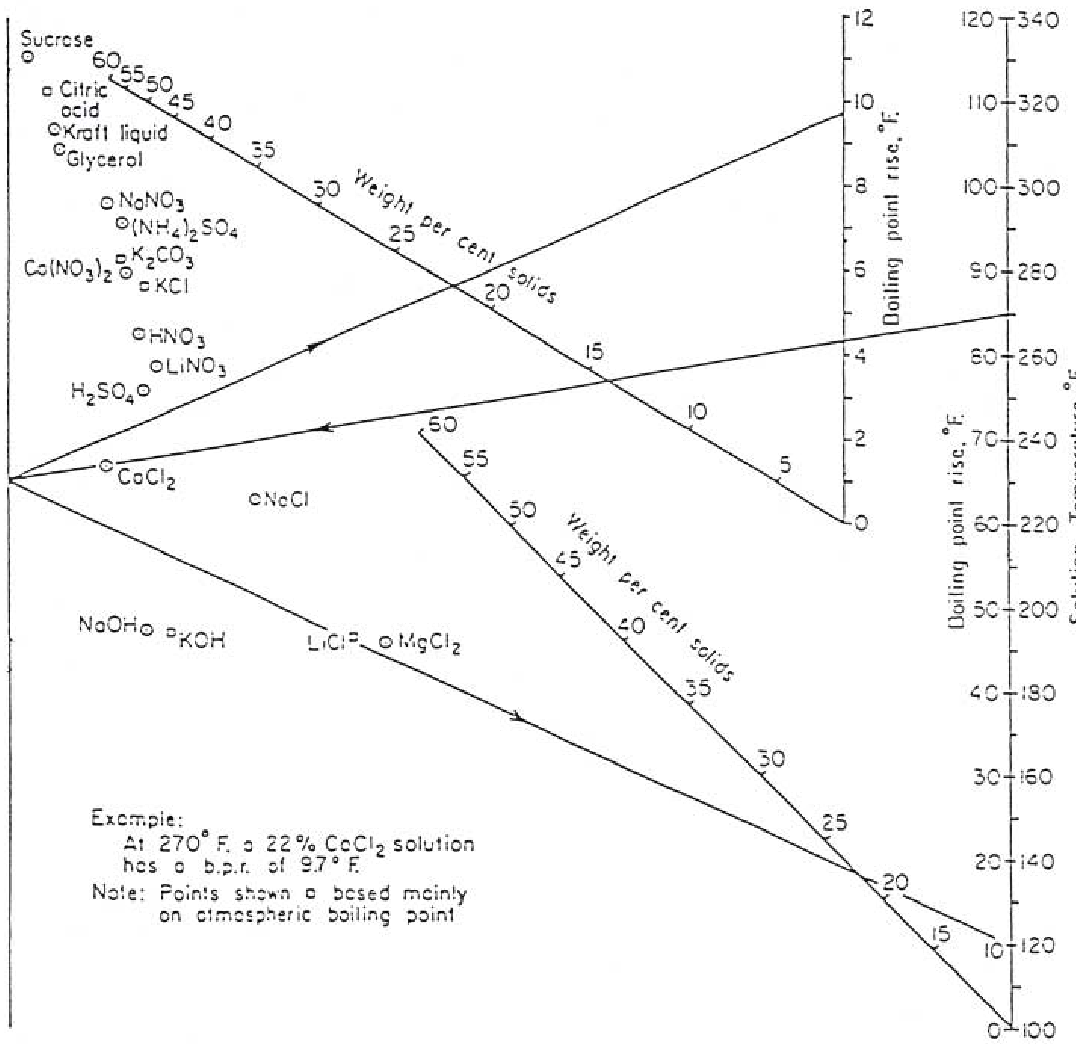
(ii) Estimate the heat transfer coefficient in the 3rd effect of the evaporator assuming negligible boiling point elevation in the 2nd effect.

(iii) Determine the pressure in the 3rd effect of the evaporator. The attached During chart should be included with your answer book.

(iv) The production rate from the evaporator must be increased by 10%. This could be achieved by increasing the flow rate of the feed to the evaporator by 10% and increasing the steam pressure to increase the rate of heat transfer.
Determine the required steam pressure assuming that, the feed and product concentrations are the same, the heat transfer coefficients are unchanged and the pressure in the final stage of the evaporator is the same.

[15 marks]

++++++++++++++



Boiling-point rise of aqueous solutions. $^\circ C = \frac{5}{9}\left(^\circ F - 32\right)$

Student ID ______________________________

Student Name ___________________________

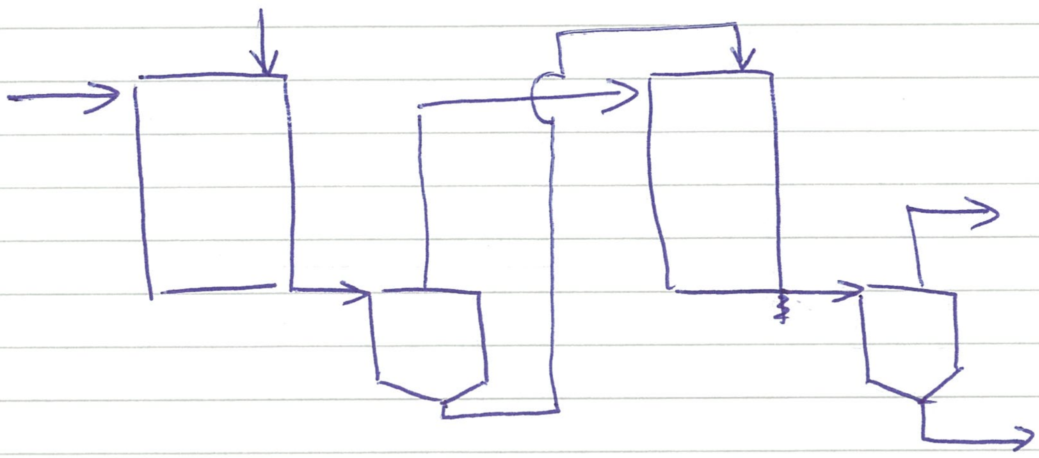
280.371 Process Engineering Operations 2016

Evaporation Assignment – Model Answers

Question 1

(a) Refer to lecture notes.

(b)



$$M_F = \frac{620}{16} \times \frac{1003}{3600} = 10.8 \text{ kg/s}$$

$$M_F x_F = M_L x_L$$

$$10.8 \times 0.035 = M_L \times 0.3$$

$$M_L = 1.26 \text{ kg/s}$$

$$M_F = M_L + M_{V_{TOTAL}}$$

$$M_{V_{TOTAL}} = 10.8 - 1.26 = 9.54 \text{ kg/s}$$

can assume $M_{V_1} = M_{V_2} = \frac{1}{2} M_{V_{TOTAL}}$

$$= \frac{1}{2}\, 9.54 \text{ kg/s} = 4.77 \text{ kg/s}$$

Stage 1 $M_F - M_{V_1} = M_{L_1}$

$$M_{L_1} = 10.8 - 4.77 = 6.03$$

$$x_{L_1} = \frac{M_F x_F}{M_{L_1}} = 0.063$$

$$= 6.3\%$$

$$U_1 = 1900\, e^{(-4 \times 0.063)}$$
$$= 1477 \quad W/m^2K$$

$$U_2 = 1900 e^{(-4 \times 0.3)}$$
$$= 572 \quad W/m^2K$$

Steam 220 kPa.a $\rightarrow \theta_s = 123.3°C$ steam tables

$$\theta_1 - \theta_2 = \frac{\frac{1}{U_2}}{\frac{1}{U_1} + \frac{1}{U_2}} (\theta_1 - \theta_2)$$

$$\theta_1 - \theta_2 = \frac{\frac{1}{572}}{\frac{1}{1477} + \frac{1}{572}} (123.3 - 105)$$

$$= 13.2°C$$
$$\theta_1 = 13.2°C + 105$$
$$= 118.2°C$$

$\phi_1 = m_{v_1} h_{fg_1}$ $\qquad h_{fg_1 @ 118.2°C} = 2208.4$ kJ/kg (steam tables)

$$= 4.77 \times 2208.4$$
$$= 10.53 \ \text{MW}$$

$$m_s = \frac{\phi}{h_{fg_s}} = \frac{10.53 \times 10^6}{2194 \times 10^3}$$
$$= 4.80 \text{ kg/s}$$

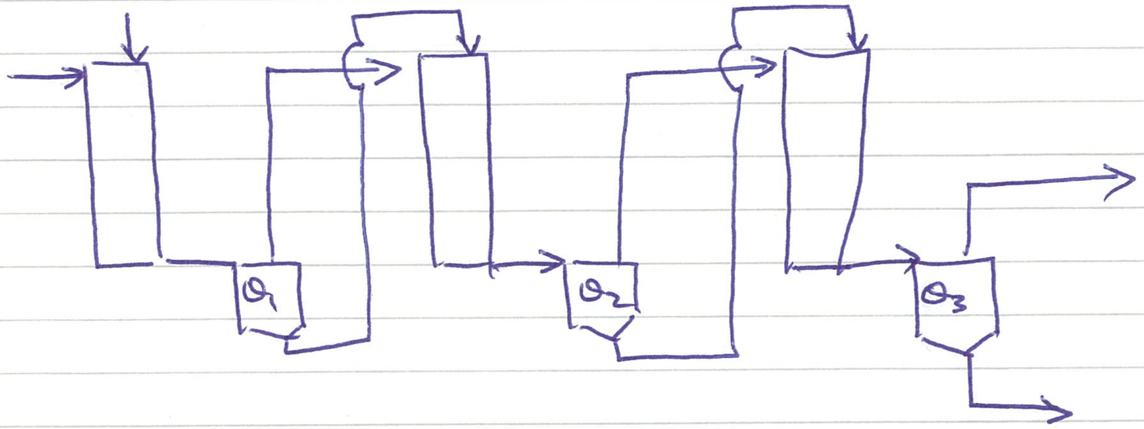
$$\eta_s = \frac{m_v}{m_s} = \frac{4.77}{4.80} = 0.99$$

BPE is significant ∴ evaporation temperature in each stage increases ∴ in each stage $\Delta\theta$ decreases ∴ area required for each stage to achieve desired evaporation rate must increase

Question 2

(a) Refer to lecture notes

(b)



$M_F = 5\times10^3$ kg/hr $\qquad A_1 = A_2 = A_3 = 45\,m^2$

$X_F = 0.05$

$X_L = 0.40$

$\theta_1 = 100°C \qquad \theta_{steam}$ @ 98 kPa.g

$\theta_2 = 78°C \qquad = 199.3$ kPa.a

$\theta_3 = 52°C \qquad \rightarrow \theta_{steam} = 120.1°C$

(i) $M_F X_F = M_L X_L$

$$M_L = \frac{5\times10^3 \times 0.05}{40} = 625 \text{ kg/hr}$$
$$= 0.174 \text{ kg/s}$$

$$M_{v_{TOTAL}} = 5\times10^3 - 625 = 4375 \text{ kg/hr}$$
$$= 1.215 \text{ kg/s}$$

$$M_{v_1} = M_{v_2} = M_{v_3} = \frac{1}{3} M_{v_{TOTAL}} = \frac{1}{3}\,4375$$
$$= 1458.3 \text{ kg/hr}$$
$$= 0.405 \text{ kg/s}$$

(ii) 3rd effect

@ 52°C $\qquad h_{fg_3} = 2377.8$ kJ/kg

$$\phi = M_{v_3} h_{fg_3} = \frac{1458.3}{3600} \times 2377.8$$
$$= 963.2 \text{ kW}$$

$\phi = UA(\theta_2 - \theta_3)$

$U = \frac{963.2 \times 10^3}{45(78-52)} = 823.2 \ W/m^2K$

(iii) Determine BPE

Sucrose solution 40%

$\theta_{solution} = 52°C$

$= 125.6°F$

From Duhring chart. BPE = 2°F

$\therefore \theta_{pure} = 125.6 - 2 = 123.6°F$

$= 50.88°C$

Pressure $= 12.94$ kPa

(iv) $\Delta\theta_{overall} = \theta_5 - \theta_3 \Rightarrow$ must increase by 10%

old $\Delta\theta = 120.1 - 52 = 68.1°C$

new $\Delta\theta = 68.1 \times 1.1 = 74.91°C$

$\theta_{steam} = 74.91 + 52 = 126.91$

$\text{Pressure}_{steam} = 248$ kPa.a. (steam tables)

remember $\phi = \underbrace{UA}_{\text{constant}} \Delta\theta$

for ϕ to $\uparrow$

$\Delta\theta$ must $\uparrow$