280.371 Process Engineering Operations
Albany

Assignment 2. Evaporation
Due: 28th May 2015

Show your working for all calculations.

Question 1.
A milk processing factory is trialling two evaporators for the production of condensed milk. One is a single-effect falling-film evaporator, the other is a double-effect feed-forward evaporator. Note that milk is a perishable and heat sensitive product, and is stored at 7°C before being processed.

Both evaporators use steam at 96°C as the heating medium and the **same overall temperature difference** will be used in both evaporators. The milk enters each evaporator at a flow rate of 2000 kg h^{-1} and on average has a water content of 87%. The target solids concentration for the condensed milk is 26%.

(a) With the aid of diagrams, draw the single-effect falling film evaporator, labelling the major parts and flows. Describe the primary function of each part.

(b) Calculate the evaporation rate for the process.

(c) The pressure inside the single-effect evaporator is set at 30 kPa.a. Calculate the energy efficiency of the evaporator, clearly stating your assumptions. Explain the significance of your answer. Assume the specific heat of the feed and product is the same and is 4.19 kJ kg^{-1} K^{-1}.

(d) The double effect evaporator has milk entering at **its boiling point** and the pressure in the second-effect is 30 kPa.a. The heat transfer coefficients for each effect are 1750 and 1500 Wm^2K^{-1} for the first and second effects, respectively. Estimate the steam economy for the double-effect evaporator and based on this estimation calculate the heat transfer area for the first- effect, assuming the heat transfer area in each effect is the same. State your assumptions clearly.

(e) Give one reason for choosing the single-effect evaporator and one reason for choosing the double-effect evaporator for producing the condensed milk.

[20 marks]

Question 2.

Grapefruit juice is to be concentrated from 5% to 40% solids content by weight in a single effect evaporator with a heat transfer area of $20 m^3$. The overall heat transfer coefficient is $1500 W m^{-2} K^{-1}$. The feed enters the evaporator at 20°C and has a specific heat capacity of $4000 J kg^{-1}K^{-1}$. The product has a specific heat capacity of $3200 J kg^{-1}K^{-1}$. Steam is available for heating at 100 kPa.g and a vacuum of -90 kPa.g. is drawn on the product side of the evaporator.

The boiling point elevation (BPE) of concentrated grapefruit juice is significant and is given by Equation. 1 below;

$$BPE = 0.9194x^{1.285} \exp(2.227x)\, p^{0.113} \qquad \text{Equation 1}$$

Where x = solids concentration (kg solids. kg solution^{-1}), p = pressure (Pa).

(a) Determine the steam and product temperatures in the evaporator.

(b) Calculate the rate of heat transfer from steam to product across the heat exchanger.

(c) Determine the enthalpies of the feed (h_f), product (h_p) and vapour (h_v) flows. (Assume a datum at 0°C)

(d) Write down (algebraically) the following balances over the evaporator;
  a. a total flow balance
  b. a solids balance
  c. a heat balance (assuming no heat losses)

(e) Solve equations derived in (d) to calculate the feed, product and vapour generation rates.

(f) Calculate the steam utilization rate and steam efficiency.

(g) Explain the reason/s why the steam efficiency is less than 100%.

(h) Explain how a multiple effect evaporator works and the advantages gained in terms of steam efficiency compared with a single effect evaporator of the same total heat transfer area.

(i) Multiple effect evaporators can be configured as feed forward or feed backward. Describe some situations where each of these configurations might be adopted and why.

[20 marks]

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Model answers
2015

Model Answers

Question 1.

(a) Marks given for a sketch of a single stage falling film evaporator show
   a. Flows
   b. Heat exchanger/calandria with long thin tubes – diagram labelled.
   c. Vapour liquid separator attached – diagram labelled
   d. Function of each section, inlet, steam, heat exchanger, vapour liquid separator and condenser

(b)

$m_F = 2000 \text{ kg/hr} = 0.56 \text{ kg/s}$

$x_F = 0.13$

$x_L = 0.26$

$m_F = m_V + m_L$ $\qquad$ $0.56 = m_V + m_L$

$m_F x_F = m_L x_L$ $\qquad$ $0.56 \times 0.13 = 0.26\, m_L$

$m_L = 0.28 \text{ kg/s}$

$m_V = 0.56 - 0.28$

$= 0.28 \text{ kg/s}$

$=$ evaporation rate

(c) Pressure inside single effect $= 30 \text{ kPa.a}$

$\Rightarrow 69.1°C$

$\therefore h_{fg} = 2336 \text{ kJ/kg}$

$\phi_{ideal} = m_V h_{fg}$

$= 0.28 \times 2336 = 654 \text{ kW}$

$m_F h_F + \phi_{actual} = m_L h_L + m_V h_V$

Feed @ 7°C $\quad c_{pF} = 4.19 \text{ kJ/kgK}$

Product @ 69.1°C $\quad c_{pF} = 4.19 \text{ kJ/kgK}$

vapour @ 69.1°C $\quad h_V = 2625 \text{ kJ/kg}$

$h_F = c_p \Delta\theta = 4.19(7-0)$
$= 29.3$ kJ/kg

$h_L = 4.19(69.1-0) = 289.5$ kJ/kg.

$\phi_{actual} = M_R h_R + M_v h_v - M_F h_F$

$= 0.28 \times 289.5 + 0.28 \times 2625 - 0.56 \times 29.3$

$= 799.65$ kW

$$\eta = \frac{\phi_{ideal}}{\phi_{actual}} = \frac{654}{799.65} = 0.817$$

Single effect evaporator efficiency is always <1.0. due to sensible heat requirements to get product to boiling point.

(d) 2 effect evaporator.

Assume steam economy $\eta = 2 = \frac{M_v}{M_s}$

$$2 = \frac{M_v}{\phi / h_{fg\,steam}}.$$

$M_v = 0.28$ kg/s

$h_{fg\,steam}$ @ 96°C $= 2267$ kJ/kg

$$\phi = \frac{M_v \times h_{fg\,steam}}{2} = \frac{0.28 \times 2267}{2}$$
$= 317$ kW

$$(\theta_i - \theta_{i+1}) = \frac{\frac{1}{U_2}}{\frac{1}{U_1} + \frac{1}{U_2}} (\theta_s - \theta_2)$$

$$(\theta_1 - \theta_2) = \frac{\frac{1}{1500}}{\frac{1}{1750} + \frac{1}{1500}} \left(96 - 69.1\right)$$

$$= 14.4$$

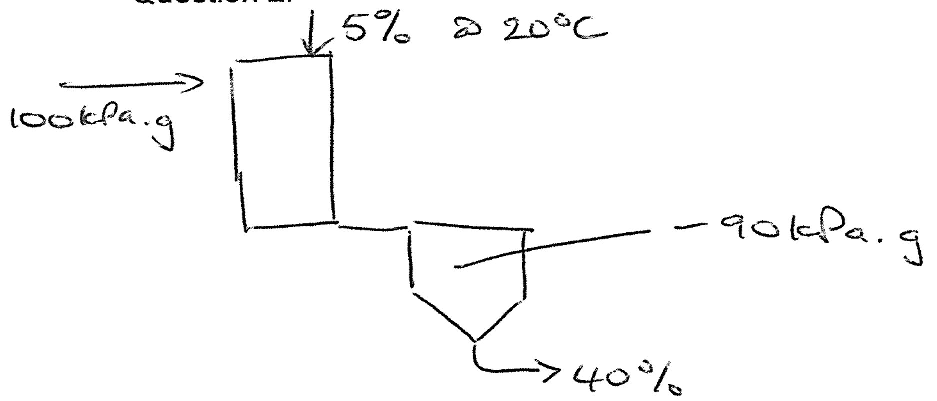
$$\therefore \theta_1 = 83.58^\circ C$$

$$\text{Area} = \frac{\phi}{U_1(\theta_1 - \theta_2)} = \frac{317 \times 10^3}{1750\,(96 - 83.58)}$$

$$= 14.58\ m^2$$

(e) single stage evaporators - cheaper, small throughput, less control required
2 stage evaporator – more cost, better steam economy, larger throughputs

Question 2.



$A = 20 m^2$

$U = 1500 \ W/m^2K$

$C_F = 4000 \ J/kgK$

$C_L = 3200 \ J/kgK$

(a) Steam

$P_{steam} = 100 \text{ kPa. gauge} = 201.3 \text{ kPa.a}$

$\Rightarrow 120.4°C$

$P_{vac} = -90 \text{ kPa.g} = 11.3 \text{ kPa.a}$

$\Rightarrow 48.23°C$

$BPE = 0.9194 \, x^{1.285} \exp(2.227 x) \, p^{0.113}$

$= 0.9194 \times 0.4^{1.285} \exp(2.227 \times 0.4)(11.3 \times 10^3)^{0.113}$

$= 1.98 \ °C$

$\theta_L = 48.23 + 1.98 = 50.21°C$

(b) $\phi = UA(\theta_s - \theta_L)$

$= 1500 \times 20 \, (120.4 - 50.21)$

$= 2105.7 \text{ kW}$

$= 2106 \text{ kW}$

(c) $h_f = c_p \Delta\theta = 4000 \times (20 - 0) = 80 \text{ kJ/kg}$

$h_L = c_p \Delta\theta = 3200 \times (50.21 - 0) = 160.7 \text{ kJ/kg}$

$h_v = h_{vsat} + c_{pv}(\Delta\theta_{BPE})$

$2588 + 1.904(1.98) = 2591 \text{ kJ/kg}$

(@ 11.3kPa)

Li

(d) $$M_F = M_V + M_L$$

$$M_F x_F = M_L x_L$$

$$M_F h_F + \phi_{actual} = M_V h_V + M_L h_L$$

(e) $$M_F = M_V + M_{\cancel{F}L}$$

$$M_F \times 0.05 = M_L \times 0.4$$

$$M_F \times 80 \times 10^3 + \overset{2106}{\cancel{2105.7}} \times 10^3 = M_V\, 2591 \times 10^3 + M_L\, 160.7 \times 10^3$$

$$0.05\, M_V \cancel{+} 0.05\, M_L = 0.4 M_L$$

$$0.05\, M_V = 0.35 M_L$$

$$M_V = 7 M_L$$

$$80 \times 10^3 M_V + 80 \times 10^3 M_L + 2106 \cancel{.7} \times 10^3 = 2591 \times 10^3 M_V + 160.7 \times 10^3 M_L$$

$$2106 \times 10^3 = 2511 \times 10^3\, M_V + 81 \times 10^3 M_L$$

$$2106 \times 10^3 = 17657\, 10^3\, M_L$$

$$M_L = 0.119 \text{ kg/s}$$

$$M_V = 0.835 \text{ kg/s}$$

$$M_F = 0.954 \text{ kg/s}$$

(f) $$M_S = \frac{\phi}{h_{fg\,steam}} = \frac{2106 \times 10^3}{2201.8 \times 10^3} = 0.956 \text{ kg/s}$$

$$\eta_S = \frac{M_V}{M_S} = \frac{0.835}{0.956} \times 100 = 87.3\%.$$

(g)
1. Some heat is used to heat feed from 20°C to boiling point, heat not used for evaporation.
2. h_{fg} at 50°C is 2383 kJ/kg compared with h_{fg} at 120.4°C which is 2205 kJ/kg. It takes more heat to boil 1 kg of water at 50°C than 1 kg of steam has available when condensing at 120°C.

(h) main idea is that vapour is produced in 1st effect and used to heat the next effect. This is achieved by operating the next effect at a lower pressure to maintain a temperature difference across the heat exchangers. In this way the amount of evaporation achieved is roughly the number of effects x steam consumption rate.

(i) Feed forward – has feed entering at the hottest effect and most concentrated material is at lowest temperature. Because reactions are generally faster at higher concentrations it makes sense to have the most concentrated material at the lower temperature.
Feed backwards – has highest concentration at highest temperature. This might be good if viscosity limits heat transfer as highest concentration is the highest viscosity but is offset somewhat by reducing viscosity at the higher temperature.