



Massey University

**Institute of Food, Nutrition and Human Health
AND
School of Engineering and Advanced Technology**

**280.371 PROCESS ENGINEERING
OPERATIONS**

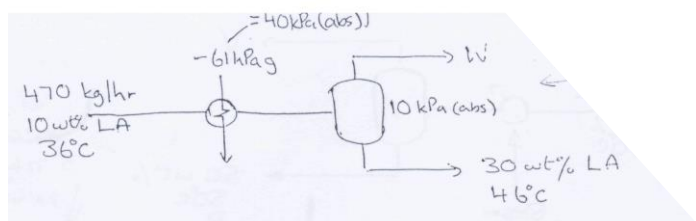
**Evaporation
Model Answers to Tutorial Problems**

**These notes are a culmination of the efforts of the following
past and present staff of Massey University:**

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EVAPORATION EXAMPLE SOLUTIONS

Example 1



Solute Balance

$$470 \times 0.1 = m_p \times 0.3 \qquad m_F x_F = m_p x_p$$

$$\Rightarrow m_p = 156.7 \text{ kg/hr}$$

$$m_F = m_p + m_v$$

Water Balance

$$470 \times 0.9 = 156.7 \times 0.7 + m_v \qquad m_F(1 - x_F) = m_p(1 - x_p)$$

$$\Rightarrow \text{water evaporated } m_v = 313.3 \text{ kg/hr}$$

$$m_v = 470 - 156.7$$

Energy Balance

$$m_F h_F + \phi = m_p h_p + m_v h_v$$

Take θ reference = 0°C (same as steam tables)

$$\Rightarrow 470 \times 4.0 \times (36 - 0) + \phi = 313.3 \times 2584.1 + 156.7 \times 4.0(46 - 0) \quad h_g - \text{steam vapour}$$

$$h = c_p \times \Delta\theta \quad \text{if } c_p @ 36^\circ\text{C} = 4.0 \quad c_p @ 46^\circ\text{C} = 4.0$$

$$\Rightarrow \phi = 770751 \text{ kJ/hr} = 214.1 \text{ kW}$$

$$\phi = UA\Delta\theta \quad \text{where at } 40 \text{ kPa (abs)} = 76^\circ\text{C}$$

$$\Delta\theta = 76 - 46$$

$$= 30$$

$$\Rightarrow A = \frac{214.1 \times 10^3}{2000 \times 30} = 3.57 \text{ m}^2$$

$$\text{Evaporator Efficiency} = \frac{m_v h_{fg}}{\phi} = \frac{313.3 \times 2392.2}{770751} \quad h_{fg} \text{ at } 46^\circ\text{C}$$

$$= 97.2\%$$

h from steam tables

$$\text{Steam economy} = \frac{m_v h_{fg \text{ steam}}}{\phi} = \frac{313.3 \times 2318.6}{770751} \quad h_{fg} \text{ at } 76^\circ\text{C}$$

$$= 0.94 \frac{\text{kg}}{\text{kg}}$$

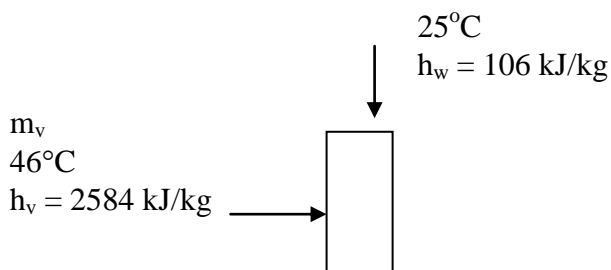
$$\text{Steam used} = \frac{m_v}{\text{steam economy}} = \frac{313.3}{0.94} = 333 \text{ kg/hour}$$

(d)

$$\phi = m_v h_{fg}$$

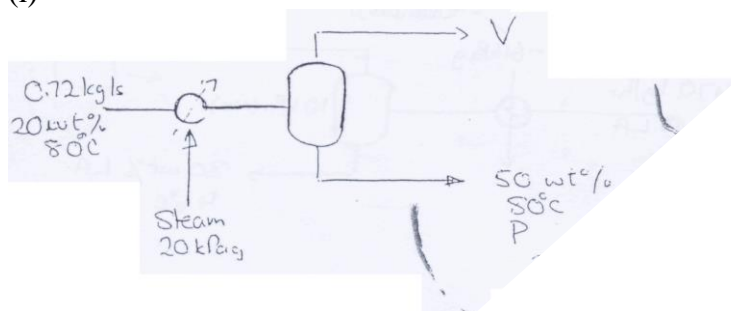
$$= 313.3 \times 2392 = 208 \text{ kW}$$

$$\phi = mc_p \Delta\theta$$



Example 2

(i)



Solids balance

$$0.72 \times 0.2 = m_p \times 0.5$$

$$\Rightarrow m_p = 0.288 \text{ kg/s}$$

Overall balance

$$m_v + 0.288 = 0.72 \Rightarrow m_v = 0.432 \text{ kg/s}$$

Heat balance (simplified because feed enters @ boiling point)

$$\phi = m_v h_{fg} \quad \text{where } h_{fg} = 2308.3 \text{ kJ/kg @ } 80^\circ\text{C}$$

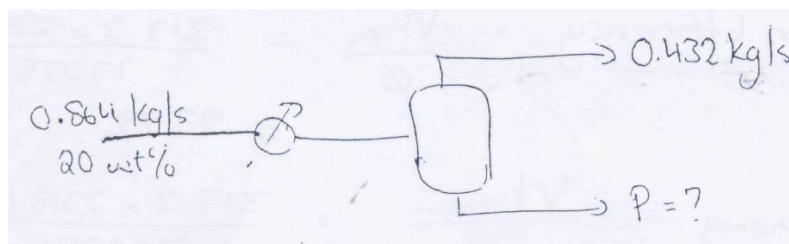
$$\Rightarrow \phi = 0.432 \times 2308.3 \\ = 997 \text{ kW}$$

$$U = \frac{\phi}{A \Delta \theta_{lm}} = \frac{997 \times 10^3}{50 \times (104.81 - 80)} \\ \uparrow 20 \text{ kPa gauge} = 121.3 \text{ kPa (abs)} \\ = 804 \text{ W/m}^2\text{K}$$

(ii)

If flow rate increases by 20% but U , A and $\Delta\theta$ stay the same then ϕ must stay the same and hence m_v stays the same

↑ Stays the same because the pressures are the same



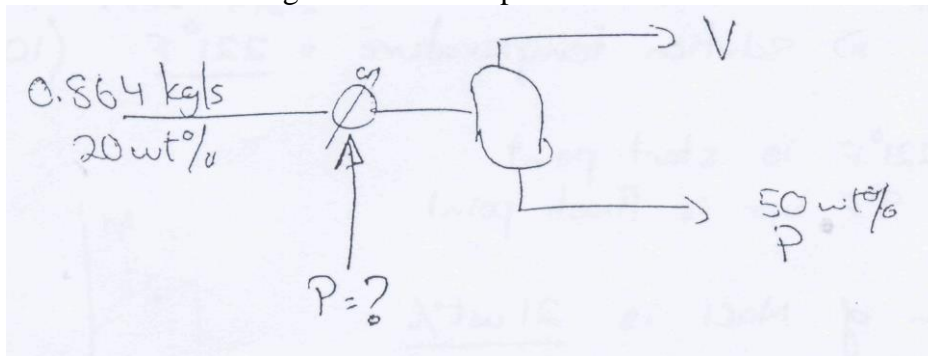
Overall balance

$$0.864 = 0.432 + m_p \Rightarrow m_p = 0.432 \text{ kg/s}$$

Solid balance

$$0.864 \times 0.2 = 0.432 \times x_p \Rightarrow x_p = 0.4$$

(iii) If we want the same product concentration, then we must increase the temperature driving force to boil off the right amount of vapour



Solids balance

$$0.864 \times 0.2 = m_p \times 0.5 \quad \Rightarrow m_p = 0.3456 \text{ kg/s}$$

Overall balance

$$0.864 = 0.3456 + m_v \quad \Rightarrow m_v = 0.5184 \text{ kg/s}$$

Heat balance

$$\phi = m_v h_{fg}$$

$$\phi = 0.5184 \times 2308.3$$

$$= 1197 \text{ kW}$$

$$\Rightarrow \Delta\theta = \frac{\phi}{UA} = \frac{1197 \times 10^3}{804 \times 50} = 29.77^\circ \text{C}$$

$$\begin{aligned} \Rightarrow \text{Steam temperature} &= 80 + 29.77 \\ &= 109.77^\circ \text{C} \end{aligned}$$

From steam tables, the steam pressure $\approx 142 \text{ kPa (absolute)}$

40.7 kPa gauge

Example 3.**(a) Low viscosity, corrosive salt solution, crystalline product**

Heat exchanger:	short vertical tube because it's relatively inexpensive and can handle crystalline product. Probably have to wear the cost of exotic materials
Separator:	Gravity separation to facilitate recirculation
Fluid moving:	propeller to ensure movement of crystalline product
Condenser:	probably indirect if solute is not suitable for discharge into the environment

(b) Concentrating fruit juice

Once through long tube vertical with forced circulation to handle crystalline product and low residence time.

Separator:	cyclone as once through, or gravity as cheap
Fluid moving:	pump upstream of heat exchanger to ensure solids are forced through and there is no thermosyphon (natural circulation) possible in once through application.
Condenser:	Spray condenser because it's cheap and discharge of natural product to the environment should be fine.

(c) Concentrating a non corrosive liquid-solution

Heat exchanger:	long to be vertical because its' cheap.
Separator:	Gravity to enable thermosyphon recirculation.
Fluid movement:	Thermosyphon because it's cheap.
Condenser:	Spray (assuming acceptable to discharge to the environment).

(d) Concentrating corrosive fluid with low head room

Heat exchanger:	horizontal tube to fit under the roof
Separator:	Gravity separation to maintain liquid level so that it doesn't cavitate the pump
Fluid movement:	recycle with pump to increase heat transfer (reduce surface area of exotic materials)
Condenser:	spray if material can be discharged to the environment

EVAPORATION

Example 4

Atmospheric pressure

$$\Rightarrow \text{boiling point of pure water} = 100^{\circ}\text{C} (212^{\circ}\text{F})$$

$$\text{boiling point elevation} = 9^{\circ}\text{F}$$

$$\Rightarrow \text{solution temperature} = \underline{221^{\circ}\text{F}} \quad 212 + 9 = 221^{\circ}\text{F} (105^{\circ}\text{C})$$

Using Chart – 221°F is start point

9°F bpr is finish point

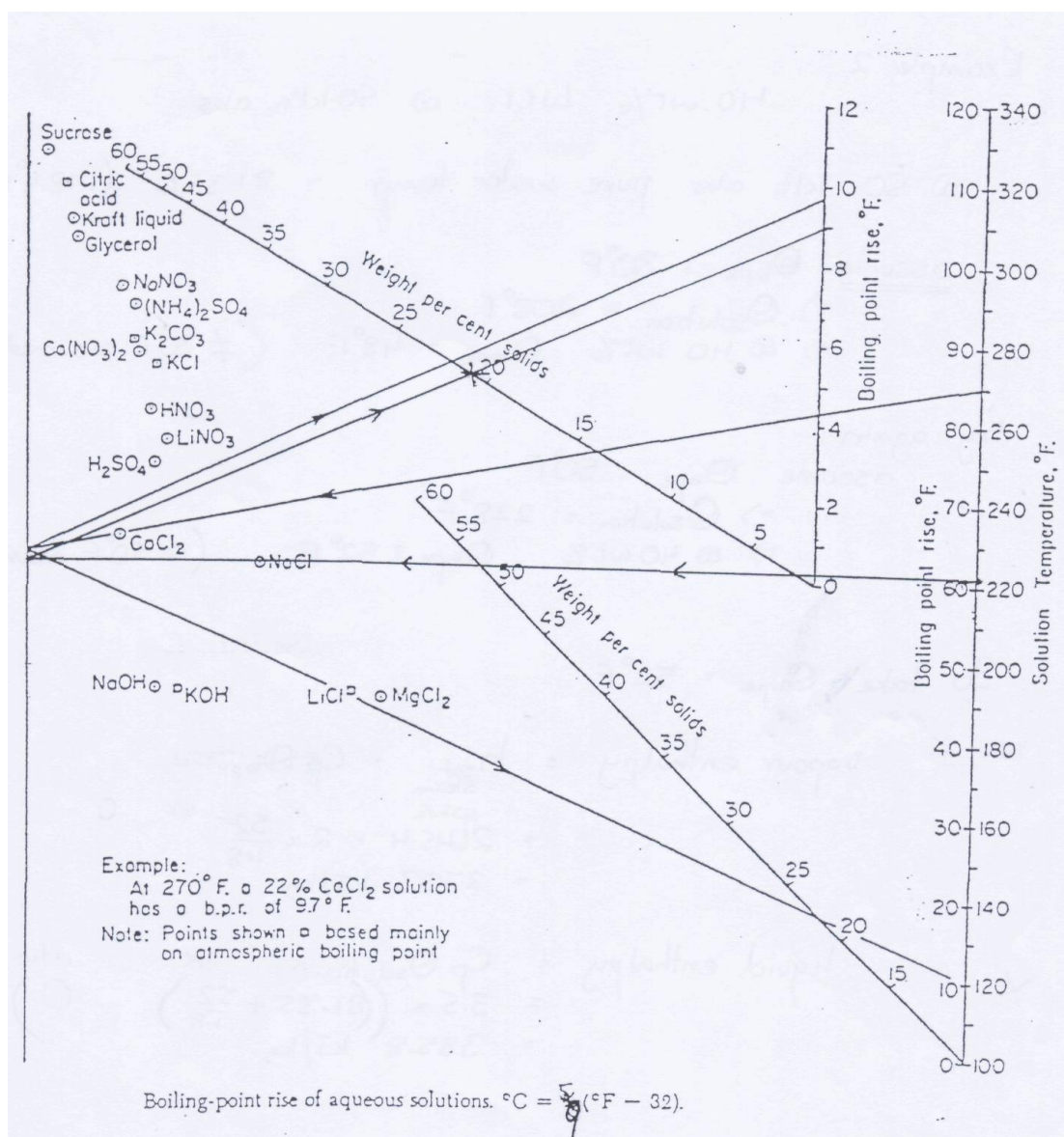
Concentration of NaCl is 21wt%

$$\text{vapour enthalpy} \left(\begin{matrix} \theta_{\text{ref}} = 0^{\circ}\text{C} \\ \text{liquid phase} \end{matrix} \right) = h_{\text{sat, steam}} + Cp\theta_{\text{bpr}} \quad \begin{matrix} @100^{\circ}\text{C} \\ 2 \text{ kJ/kg K} \end{matrix}$$

$$\begin{aligned} &= 2675.8 + 1.88 \times \frac{9}{1.8} \\ &= 2685.2 \text{ kJ / kg} \end{aligned}$$

$$\begin{aligned} \text{liquid enthalpy} \left(\begin{matrix} \theta_{\text{ref}} = 0^{\circ}\text{C} \\ \text{liquid phase} \end{matrix} \right) &= Cp(\theta_{\text{solution}} - \theta_{\text{ref}}) \\ &= 4 \times (105 - 0) \\ &= 420 \text{ kJ / kg} \end{aligned}$$

$$(^{\circ}\text{F} - 32) \frac{5}{9} = ^{\circ}\text{C}$$



Example 5

40 wt% *LiCl* @ 50 kPa (abs)

@ 50 kPa (abs) pure water temp = 81.35°C (178.4°F)

assume $\theta_{bpe} = 30^\circ F$

$$\Rightarrow \theta_{solution} = 208^\circ F$$

$$\Rightarrow @ 40 \text{ wt\% } \theta_{bpe} = 48^\circ F (\neq 30^\circ F \text{ assumed})$$

try again

assume $\theta_{bpe} = 50^\circ F$

$$\Rightarrow \theta_{solution} = 228^\circ F$$

$$\Rightarrow @ 40 \text{ wt\% } \theta_{bpe} = 52^\circ F (\neq 50^\circ F \text{ assumed})$$

So take $\theta_{bpe} = 52^\circ F$

vapour enthalpy $= h_{sat \text{ steam}} + Cp\theta_{bpr}$ 50 kPa

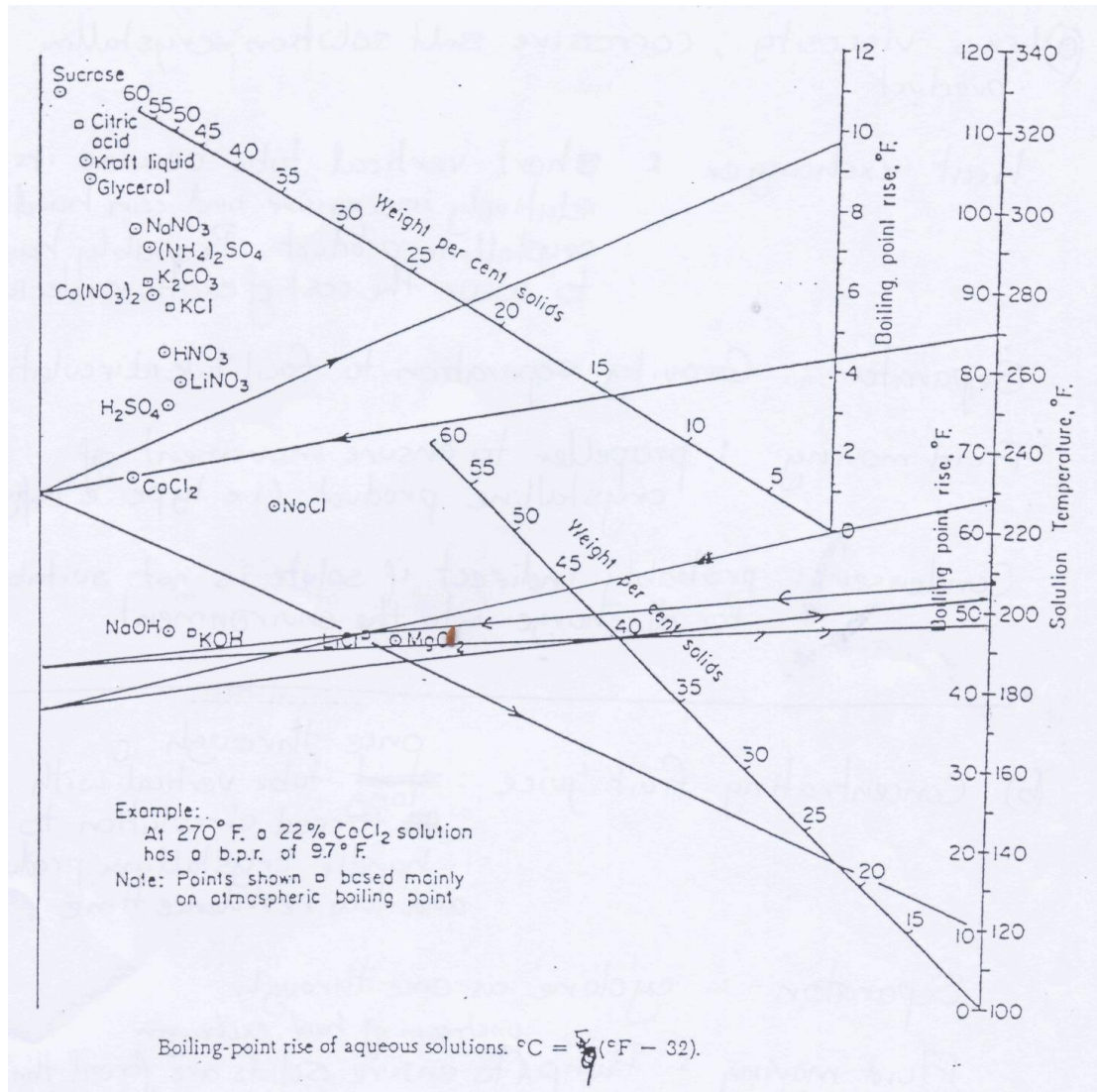
$$= 2645.4 + 2 \times \frac{52}{1.8}$$

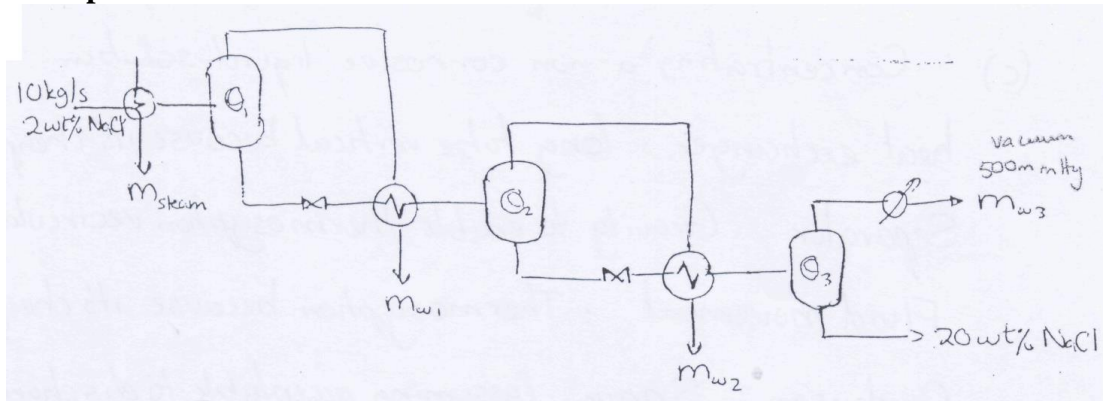
$$= 2703 \text{ kJ/kg}$$

liquid enthalpy $= Cp(\theta_{solution} - \theta_{ref})$ reference

$$= 3.5 \times \left(\left(81.35 + \frac{52}{1.8} \right) - 0 \right)$$

$$= 385.8 \text{ kJ/kg}$$



Example 6*Solute Balance*

$$10 \times 0.02 = m_p \times 0.2$$

$$\Rightarrow m_p = 1 \text{ kg/s}$$

Overall Balance

$$m_{v1} + m_{v2} + m_{v3} = 10 - 1$$

$$= 9 \text{ kg/s}$$

$$\text{Steam temperature (@ 150 kPa)} = 111.4^\circ \text{C}$$

$$\text{Steam temperature in final stage (} m_{v3} \text{ @ 260 mm Hg)} = 72.5^\circ \text{C}$$

$$P(\text{abs}) = 760 \text{ mm Hg} - 500 \text{ mm Hg}$$

$$= 260 \text{ mm Hg} = 34.7 \text{ kPa}$$

Constant area

$$\Rightarrow \theta_2 - \theta_3 = \frac{\frac{1}{U_3}}{\frac{1}{U_1} + \frac{1}{U_2} + \frac{1}{U_3}} (\theta_s - \theta_3) = \frac{\frac{1}{800}}{\frac{1}{1000} + \frac{1}{900} + \frac{1}{800}} (111.4 - 72.5)$$

$$= 14.47^\circ \text{C}$$

$$\theta_1 - \theta_2 = \frac{\frac{1}{900}}{\frac{1}{1000} + \frac{1}{900} + \frac{1}{800}} (111.4 - 72.5) = 12.86^\circ \text{C}$$

$$\Rightarrow \theta_2 = 72.5 + 14.47 = 87^\circ \text{C}$$

$$\theta_1 = 87 + 12.86 = 99.9^\circ \text{C}$$

$$h_{fg1} = 2258 \text{ kJ/kg (@ } 99.9^\circ \text{C)}$$

$$h_{fg2} = 2291 \text{ (@ } 87^\circ \text{C)}$$

$$h_{fg3} = 2325 \text{ kJ/kg (@ } 72^\circ \text{C)}$$

$$\begin{aligned}
 m_{v1} &= \frac{\frac{1}{h_{fg1}}}{\frac{1}{h_{fg1}} + \frac{1}{h_{fg2}} + \frac{1}{h_{fg3}}} (m_{v1} + m_{v2} + m_{v3}) \\
 &= \left(\frac{\frac{1}{2258}}{\frac{1}{2258} + \frac{1}{2291} + \frac{1}{2325}} \right) \times 9 \\
 &= 3.044 \text{ kg/s} \\
 m_{v2} &= \left(\frac{\frac{1}{2291}}{\frac{1}{2258} + \frac{1}{2291} + \frac{1}{2325}} \right) \times 9 = 3.000 \text{ kg/s} \\
 m_{v3} &= \left(\frac{\frac{1}{2325}}{\frac{1}{2258} + \frac{1}{2291} + \frac{1}{2325}} \right) \times 9 = 2.956 \text{ kg/s}
 \end{aligned}$$

Note: if we had just split the flow three ways (3kg/s from each stage) the error would only have been 1.5%!!

$$\phi = m_{v1} h_{fg1} = 3.044 \times 2258 = 6872 \text{ kW}$$

$$A = \frac{\phi}{U \Delta \theta} = \frac{6873 \times 10^3}{1000(\theta_s - \theta_1)} = \frac{6873 \times 10^3}{(111.4 - 99.9)1000} = 597.7 \text{ m}^2$$

(This could have been done with any of the other heat exchangers because of it's constant area)

$$\text{i.e. } A = \frac{6873 \times 10^3}{900 \times 12.86} = 593.8 \text{ m}^2 \quad (\text{close enough!})$$

Increasing pressure to 200 kPa ($\theta_s = 120.2^\circ \text{C}$)

$$\begin{aligned}
 \theta_2 - \theta_3 &= \left(\frac{\frac{1}{800}}{\frac{1}{1000} + \frac{1}{900} + \frac{1}{800}} \right) (120 - 72.5) = 17.74^\circ \text{C} \\
 (\theta_1 - \theta_2) &= \left(\frac{\frac{1}{900}}{\frac{1}{1000} + \frac{1}{900} + \frac{1}{800}} \right) (120 - 72.5) = 15.77^\circ \text{C} \\
 &\Rightarrow \theta_2 = 72.5 + 17.74 \\
 &= 90.24^\circ \text{C}
 \end{aligned}$$

$$\phi = UA \Delta \theta = 900 \times 594 \times 17.74 = 8430 \text{ kW}$$

Calculating m_{v2} (and multiply by 3 rather than calculate each one individually)

$$m_{v2} = \frac{8430 \times 10^3}{2283 \times 10^3} = 3.69 \text{ kg/s}$$

$$\Rightarrow \text{total evaporation rate} = 3 \times 3.69 = 11.08 \text{ kg/s}$$

Assuming that we are producing product of the same composition from feed of the same composition

$$\text{Product rate increase} = \frac{11.08 - 9}{9} = 23\%$$

Also calculate the increase in m_F and m_P

$$m_F = m_{v\text{total}} + m_P \quad (1)$$

$$m_F x_F = m_P x_P$$

$$m_F \times 0.02 = m_P \times 0.2 \quad (2)$$

Solve equations 1 and 2 for m_F and m_P

Substituting Equation 2 into equation 1

$$(11.08 + m_P) \times 0.02 = m_P \times 0.2$$

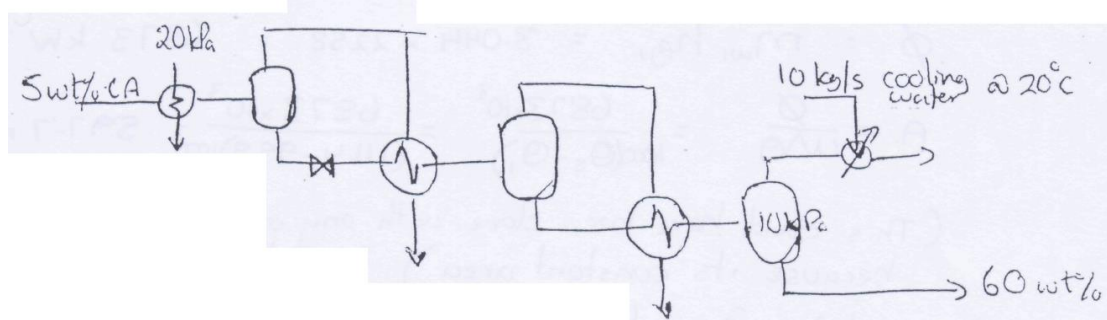
$$0.2216 + 0.02m_P = 0.2m_P$$

$$0.2216 = m_P(0.2 - 0.02)$$

$$m_P = 1.23$$

$$m_F = 11.08 + 1.23 = 12.31$$

Product rate increase = $\frac{1.23 - 1}{1} = 23\%$ the same as when calculated for the increase in vapour production.

Example 7

Exit water temp @ 10kPa = 45.8°C

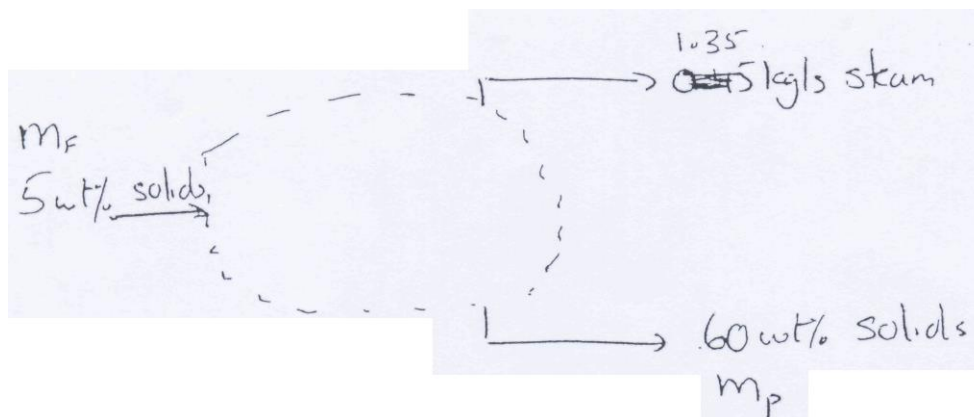
Amount of heat that can be removed with 10kg/s of cooling water assuming it is heated to 45.8°C

$$\begin{aligned}\phi_{\text{condenser}} &= 10 \times 4.186 \times (45.8 - 20) \\ &= 1080 \text{ kW}\end{aligned}$$

$$\phi = m_{\text{cond}} h_{fg3}$$

$$\begin{aligned}\Rightarrow \text{water vapour removed in front stage} &= \frac{1080 \times 10^3}{2393 \times 10^3} \\ &= 0.45 \text{ kg/s}\end{aligned}$$

$$\begin{aligned}\text{assume total water removed} &\approx 3 \times 0.45 \\ &= 1.35 \text{ kg/s}\end{aligned}$$



Solute Balance

$$m_F \times 0.05 = m_p \times 0.6 \quad \text{----- (1)}$$

Overall Balance

$$m_F = m_p + 1.35 \quad \text{----- (2)}$$

Solving eq 1 & 2 gives $m_p(0.6 - 0.05) = 1.35 \times 0.05$

$$\Rightarrow m_p = 0.123 \text{ kg/s}$$

$$\Rightarrow m_F = 1.473 \text{ kg/s}$$

$$U = 1000 \text{ W} / \text{m}^2 \text{K}$$

$$\theta_p = \theta_{\text{pure}} + \theta_{\text{bpe}}$$

$$\theta_{\text{pure}} = 45.8^\circ \text{C} \quad (114.4^\circ \text{F})$$

$$\text{assume } \theta_{\text{bpe}} = 10^\circ \text{F} \Rightarrow \theta_{\text{solution}} = 124.4^\circ \text{F}$$

$$60\text{wt\% Citric Acid gives } \theta_{\text{bpe}} = 7^\circ \text{F} (\neq 10^\circ \text{F})$$

$$\text{assume } \theta_{\text{bpe}} = 7^\circ \text{F} (\text{ends up good guess})$$

$$\Rightarrow \theta_p = 121.4^\circ \text{F} = \theta_3$$

$$= 49.7^\circ \text{C}$$

$$\begin{aligned} \theta_s @ 121 \text{ kPa} \\ = 104.8^\circ \text{C} \end{aligned}$$

$$\theta_s - \theta_3 = 104.8 - 49.7 = 55.1$$

$$\text{constant temperature difference} \Rightarrow \theta_s - \theta_1 = \theta_1 - \theta_2 = \theta_2 - \theta_3 = 18.4^\circ \text{C}$$

$$\Rightarrow \theta_2 = 49.7 + 18.4 = 68.1^\circ \text{C} \Rightarrow h_{\text{fg}2} = 2347 \text{ kJ/kg}$$

$$\Rightarrow \phi = m_{w2} h_{\text{fg}2} \approx \frac{1.35}{3} \times 2347 = 1056 \text{ kW}$$

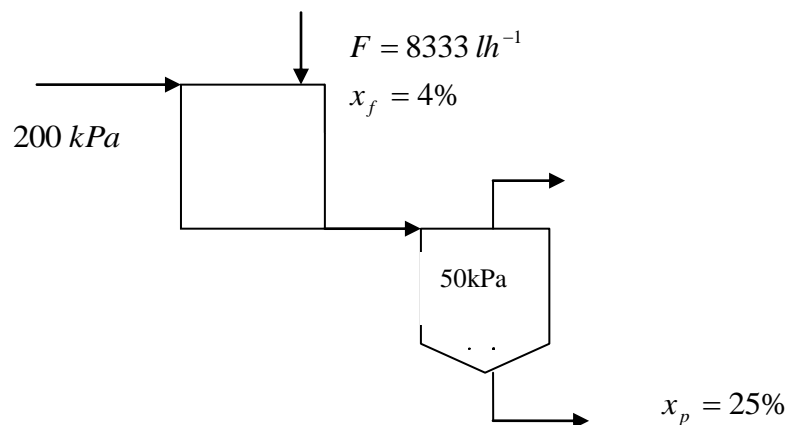
$$\phi = UA\Delta\theta$$

$$\Rightarrow A = \frac{1056 \times 10^3}{1000 \times 18.4} = 57.4 \text{ m}^2$$

Question 8: Evaporation 2006

(a) Refer to notes

(b)



(i) $Area = 68m^2$

$$F = 833 \text{ } lh^{-1} \quad \theta_f = 70^\circ C$$

$$x_f = 0.04$$

$$x_p = 0.25$$

$$P_{steam} = 200 \text{ kPa.a}$$

$$m_F = 2.4 \text{ Kgs}^{-1} \quad \left[8333 \frac{l}{h} \times \frac{m^3}{1000l} \times \frac{1040kg}{m^3} \times \frac{1hr}{3600_s} \right]$$

$$c_p = 3.8 \text{ kJ kg}^{-1} K^{-1}$$

$$m_F x_F = m_p x_p$$

$$2.4 \times 0.04 = m_p \times 0.25$$

$$\therefore m_p = 0.384 \text{ kgs}^{-1}$$

$$m_v = m_F - m_p = 2.016 \text{ kgs}^{-1}$$

(ii)

$$\begin{aligned}\theta_{soln} &= \theta_{sat} + \Delta\theta_{bpr} \\ &= 81.5 + 0.25 \times 25 \\ &= 87.75^\circ \text{C}\end{aligned}$$

(iii)

$$\begin{aligned}h_v &= 2646.4 + 1.88 \times (25 \times 0.25) \\ &= 2658 \text{ kJkg}^{-1}\end{aligned}$$

$$\phi = m_p h_p - m_f h_f + m_v h_v$$

$$\begin{aligned}&= 0.384 \times (3.8 \times 87.75) - 2.4 \times 3.8 \times 70 + 2.016 \times 2658 \\ &= \quad 128 \quad \quad \quad - 638.4 \quad \quad + \quad 5358 \\ &= 4848 \text{ kW}\end{aligned}$$

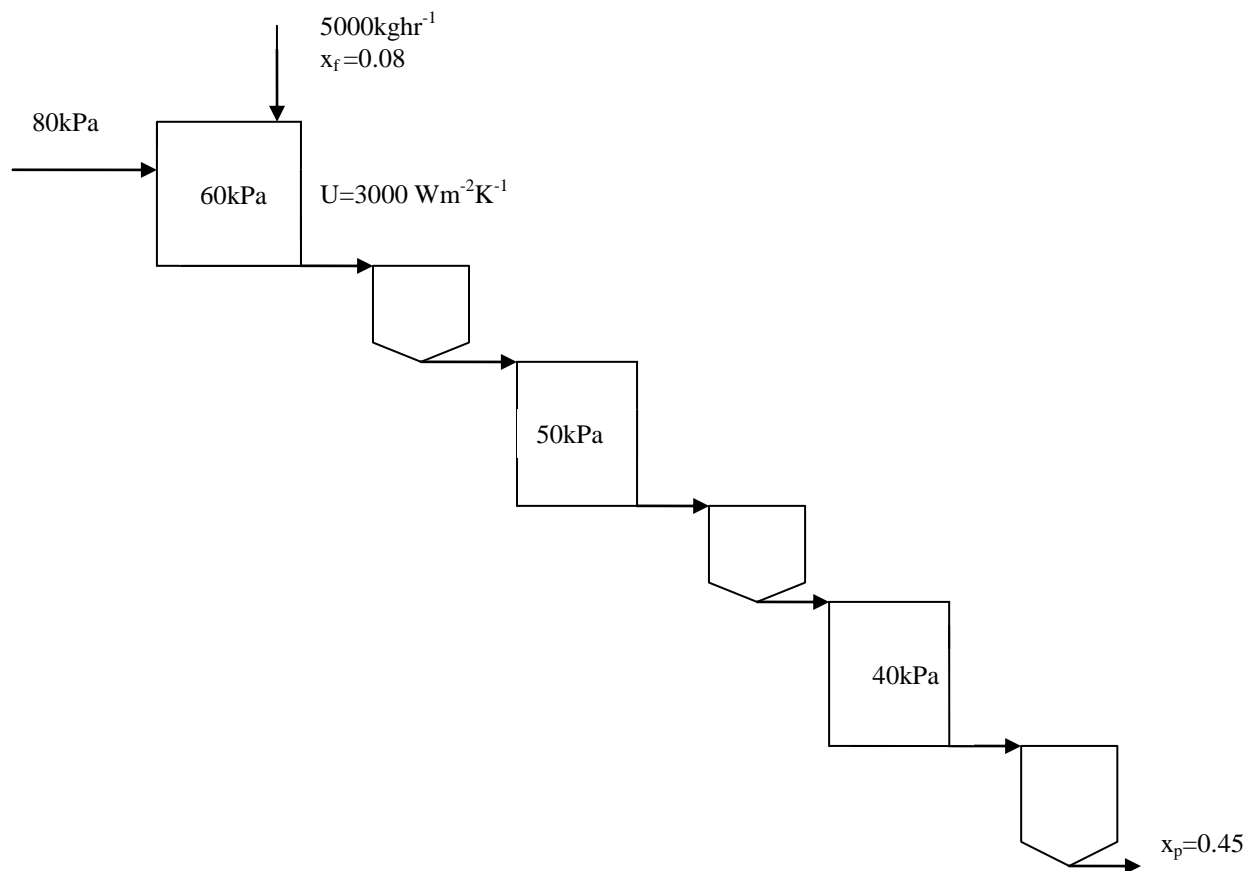
$$\begin{aligned}\phi &= m_s h_{fg \text{ steam}} \quad h_{fg \text{ steam}} = 2203 \text{ kJkg}^{-1} \\ m_s &= 2.2 \text{ kgs}^{-1}\end{aligned}$$

$$(iv) \quad \phi = UA\Delta\theta$$

$$U = \frac{4848}{68(120 - 87.75)} = 2210 \text{ Wm}^{-2}\text{K}^{-1}$$

$$\begin{aligned}\eta_s &= \frac{m_v}{m_s} = \frac{2.016}{2.2} = 0.91 \\ &= 91\%\end{aligned}$$

Question 9: Evaporation 2007



(a) $m_f x_f = m_p x_p$

$$1.39 \times 0.08 = m_p \times 0.45$$

$$m_p = 0.247 \text{ kgs}^{-1} = 890 \text{ kg h}^{-1}$$

$$\text{steam } 80 \text{ kPa absolute} = 93.5^\circ \text{C}$$

			h_{fg}
θ_1	60 kPa	86°C	2291 kJ kg ⁻¹
θ_2	40 kPa	82°C	2301 kJ kg ⁻¹
θ_3	40 kPa	76°C	2316 kJ kg ⁻¹

$$m_{v \text{ total}} = 1.39 - 0.247 = 1.143 \text{ kgs}^{-1}$$

$$m_{v1} = \frac{\frac{1}{\frac{1}{2291} + \frac{1}{2301} + \frac{1}{2316}}}{\frac{1}{2291} + \frac{1}{2301} + \frac{1}{2316}} [m_{v\text{total}}] = 0.383 \text{ kgs}^{-1}$$

$$m_{v2} = \frac{\frac{1}{\frac{1}{2291} + \frac{1}{2301} + \frac{1}{2316}}}{\frac{1}{2291} + \frac{1}{2301} + \frac{1}{2316}} (1.143) = 0.381 \text{ kgs}^{-1}$$

$$m_{v3} = \frac{\frac{1}{\frac{1}{2291} + \frac{1}{2301} + \frac{1}{2316}}}{\frac{1}{2291} + \frac{1}{2301} + \frac{1}{2316}} (1.143) = 0.379 \text{ kgs}^{-1}$$

(b) Stage 1 $\phi = m_v h_{fg1} = 0.383 \times 2291 \times 10^3$
 $= 877 \text{ kW}$

$$\frac{\phi}{h_{fg\text{steam}}} = m_{\text{steam}} = \frac{877 \times 10^3}{2273 \times 10} = 0.386 \text{ kgs}^{-1} = 1390 \text{ kg h}^{-1}$$

(c) $\phi = U_1 A (\theta_{\text{steam}} - \theta_{\text{soln}})$

$$A = \frac{877 \times 10^3}{3000(93.5 - 86)} = 39 \text{ m}^2$$

$$\phi = U_2 A (\theta_1 - \theta_2)$$

$$U_2 = \frac{877 \times 10^3}{39(86 - 82)} = 5621 \text{ W m}^{-2} \text{ K}^{-1}$$

$$\phi = U_3 A (\theta_2 - \theta_3)$$

$$U_3 = \frac{877 \times 10^3}{39(82 - 76)} = 3758 \text{ W m}^{-2} \text{ K}^{-1}$$

(d) $m_v = 1.143 \text{ kgs}^{-1}$

@ 40 kPa, 76°C $h_g = 2637 \text{ kJ kg}^{-1}$

$$m_v h_v + m_w h_w = (m_v + m_w) h_{vw}$$

$$\begin{array}{ll}
 \text{water @ } 10^0 \text{ C} & \text{if temperature of condensed water} = 30^0 \text{ C} \\
 h_w = 42 \text{ kJkg}^{-1} & h_{vw} = 2556 \text{ kJkg}^{-1}
 \end{array}$$

$$1.143 \times 2637 + m_w \times 42 = (1.143 + m_w) 2556$$

$$3014 + 42m_w = 292105 + 2556m_w$$

$$m_w = 0.04 \text{ kg s}^{-1}$$

$$= 132 \text{ kg h}^{-1}$$

Question 5 – Evaporation 2008

(a)

$$m_v = 1500 \text{ kg h}^{-1}$$

$$= 0.417 \text{ kg s}^{-1}$$

$$\phi = m_v h_{fg} \quad h_{fg} @ 100^\circ \text{C} = 2257 \text{ kJ kg}^{-1}$$

$$= 0.417 \times 2257 \times 10^3 = 941.2 \text{ kW}$$

$$\theta_s @ 100 \text{ kPag} \quad 0.2013 \text{ MPa.a}$$

$$\therefore \theta_s = 120^\circ \text{C}$$

$$U = \frac{\phi}{A(\theta_{\text{steam}} - \theta_s)}$$

$$= \frac{941.2 \times 10^3}{20(120 - 100)} = 23\,53 \text{ Wm}^{-2} \text{ K}^{-1}$$

(b)

20m³ cleaning solution

assume density = 1000 kg m⁻³

$$\text{mass} = 20 \times 10^3 \text{ kg}$$

concentrated in 16 hrs

$$M_f = \frac{20 \times 10^3}{16 \times 3600} = 0.347 \text{ kg s}^{-1}$$

$$m_p = \frac{m_f x_f}{x_p} = \frac{0.347 \times 0.005}{0.15} = 0.0116 \text{ kg s}^{-1}$$

From During chart determine $\Delta\theta_{bpr}$

$$100^\circ \text{C} = 212^\circ \text{F}$$

Guess $\Delta\theta_{bpr}$ 6° F confirmed on During chat

$$\Delta\theta_{bpr} = 3.33^\circ \text{C}$$

$$\theta_{soln} = 103.33^{\circ}C$$

$$h_v = h_{vsat} + c_{pg} (\Delta\theta_{bpr})$$

$$= 2676 + 2.04(3.33)$$

$$= 2683 \text{ kJ kg}^{-1}$$

$$h_f = 4200 \times 60 = 252 \text{ kJ kg}^{-1}$$

$$h_p = 431.6 \text{ kJ kg}^{-1}$$

$$\phi = m_p h_p + m_v h_v - m_f h_f$$

$$= 0.0116 \times 431.6 + 0.3354 \times 2683 - 0.347 \times 252$$

$$= 817.4 \text{ kW}$$

$$A = \frac{817.4 \times 10^{-3}}{2353(120 - 103.33)} = 20.8 \text{ m}^2$$

Evaporator has insufficient area to do job required as evaporator is only 20m²

(C)

$$x_f = 0.1$$

$$x_f = 0.2$$

$$m_f \times 0.1 = m_p \times 0.2$$

$$m_f = m_p + m_v$$

$$= m_p + 0.417$$

$$0.1(m_p + 0.417) = 0.2m_p$$

$$m_p = 0.417 \text{ kg s}^{-1}$$

$$m_f = 0.834$$

$$h_f = 252 \text{ kJ kg}^{-1}$$

$$h_p = 419.2 \text{ kJ kg}^{-1} @ 100^\circ \text{C no BPR}$$

$$h_v = 2676 \text{ kJ kg}^{-1} @ 100^\circ \text{C}$$

$$\phi = m_p h_p + m_v h_v - m_f h_f$$

$$= 0.417 \times 419.2 + 0.417 \times 2676 - 0.834 \times 252$$

$$= 1080.5 \text{ kW}$$

$$\eta = \frac{m_v h_{fg} @ 100^\circ \text{C}}{\phi}$$

$$= \frac{0.417 \times 2257}{1080.5}$$

$$= 0.87$$

$$= 87\%$$

(ii) Refer to notes