I-Leaching

Example

In a single–stage leaching of soybean oil from flaked soybeans with hexane, 100 kg of soybean containing 20 wt% oil is leached with 100 kg of fresh hexane solvent. The mass ratio of insoluble solid to solution for the slurry underflow is essentially constant at 1.5 kg insoluble solid/kg solution. Calculate the amounts and compositions of the overflow and the underflow slurry leaving the stage.

V_N?

L_N? = 51.33

$$100 + 100 = 133.33 + V_N$$

$$V_N = 66.67 \text{ Kg}$$

$$\overset{20}{L_0} + \overset{100}{V_2} = L_1 + V_1 = M = 120$$

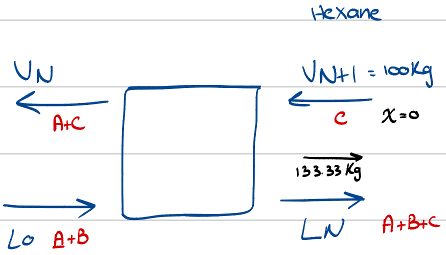
$$L_0(1) + \cancel{V_2}(0) = L_1 y_1 + V_1 x_1$$

$$20 = 51.33\, y_1 + 6667\, x_1$$

$$\boxed{x_1 = y_1 = 0.169}$$

$(y_0, N_0) \rightarrow (1, 4)$

$(x_2, N_2) \rightarrow (0, 0)$



100 Kg Soybean

$\boxed{20\text{Kg } A}$ $\boxed{B = 80\text{Kg}}$

$\boxed{y_A = 1}$

$$N_{B0} = \frac{B}{A+C} = \frac{80}{20} = 4$$

$\boxed{N_{BN} = 1.5}$

Constant

B = 80Kg

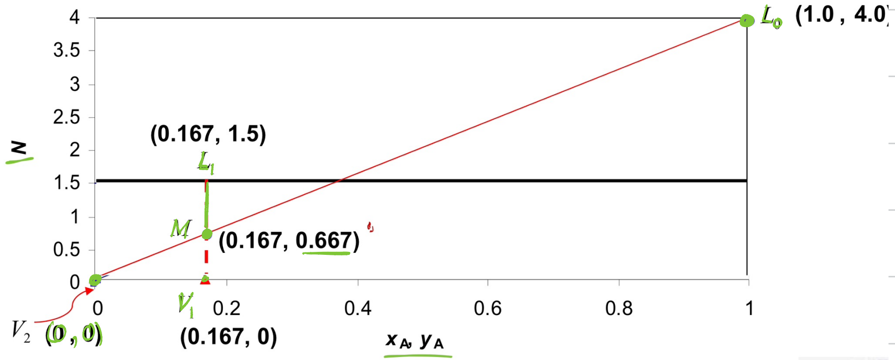
$$N_{BN} = \frac{80}{A+C}$$

$$1.5 = \frac{80}{A+C}$$

$$A+C = 53.33$$

$$\downarrow$$

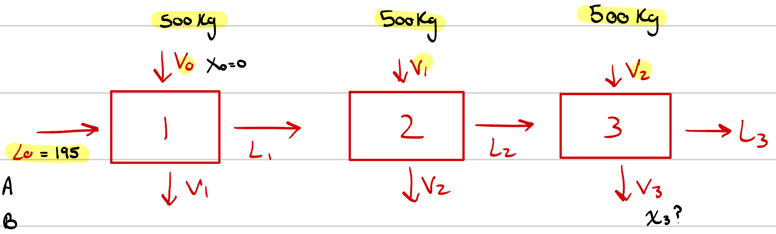
$$L_1 = 53.33$$



$$x_M = 0.167 = y_1 = x_1$$

$$N_m = ? = \frac{B}{(A+C)_M} \underset{\rightarrow 120}{} = \frac{80}{120} = \underline{0.667}$$

- In the previous task, if instead of using the solvent at one time, it is planned to carry out the leaching in three stage cross-current unit using one third of the solvent (i.e. 500 kg hexane) in each stage. Calculate the fraction of oil that can be extracted.



$y_0 = 1$

1000 Kg → 195 Kg A

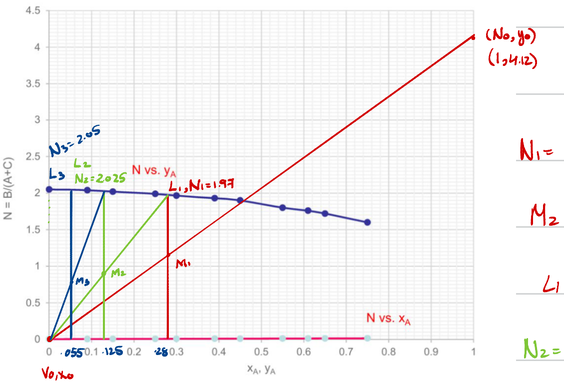
→ 805 Kg B

$N_0 = \frac{805}{195} = 4.128$

$L_0 + V_0 = 695 = M$ ✓

$L_0 y_0 + V_0 x_0 = x_M \cdot M$

$x_M = 0.28$ ✓



$N_1 = 1.97 = \frac{B}{L_1}$ $L_1 = 408.6$, $y_1 = .28 = x_1$

$M_2 = 408.6 + 500 = 908.6$

$L_1 y_1 + V_1(0) = x_{AM_2} M_2 \rightarrow x_{AM_2} = 0.126 = x_2 = y_2$

$N_2 = 2.025 = \frac{B}{L_2} \rightarrow L_2 = 397.53$

$V_1 = M - L_1 = 695 - 408.6 = 286.4$

$V_2 = 908.6 - 397.53 = 511.07$

$V_3 = 897.53 - 392.68 = 504.84$

$M_3 = 397.53 + 500 = 897.53$

$L_2 \overset{.126}{y_2} + \cancel{500(0)} = 897.53 \rightarrow x_{AM_3} = 0.056 = x_3 = y_3$

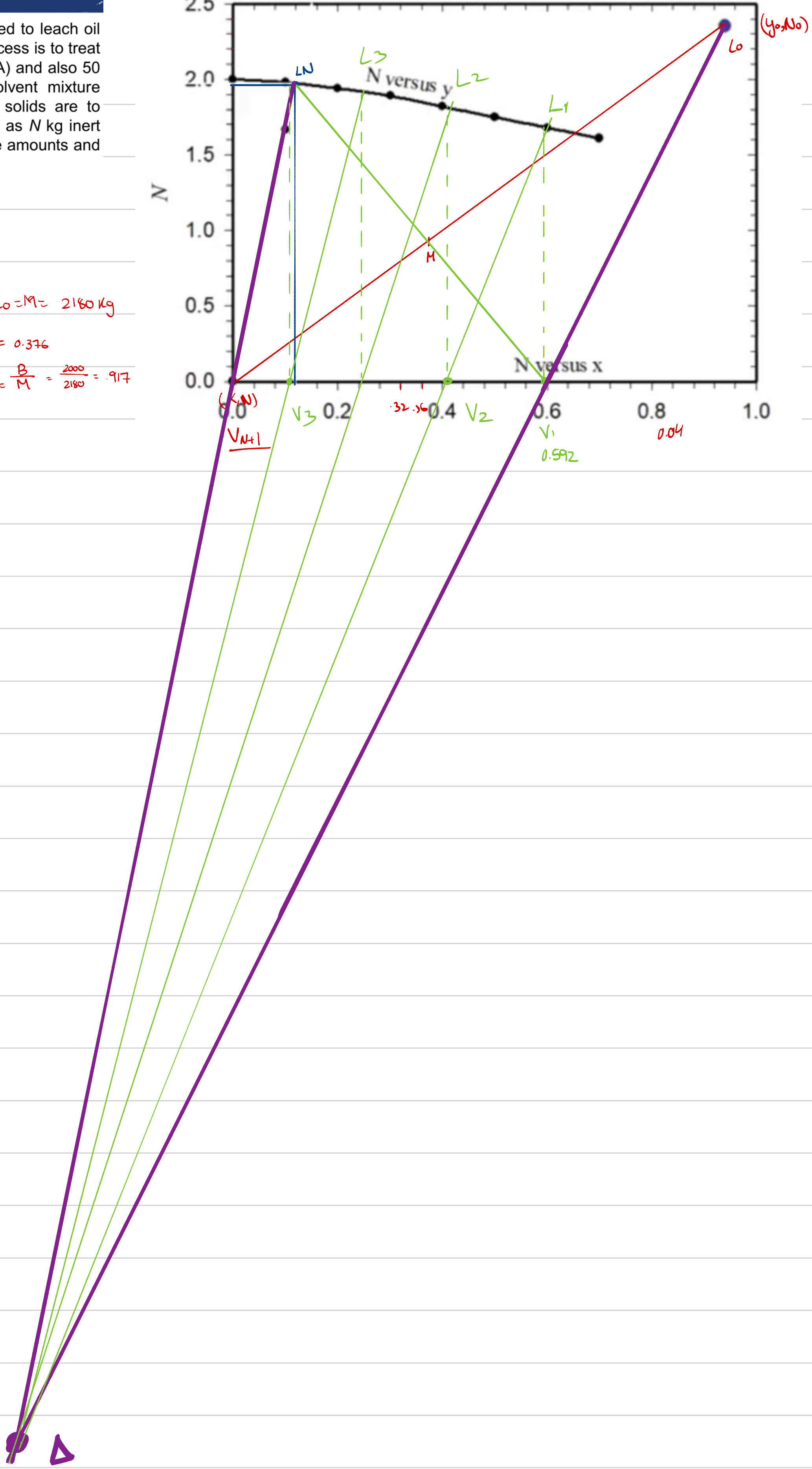
$N_3 = \frac{B}{L_3}$ $L_3 = \frac{805}{2.05} = 392.68$

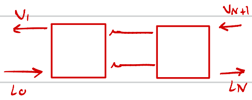
$$\text{oil extracted} = \frac{504.84(0.056) + 511.07(.126) + 286.4(0.28)}{195}$$

$$= 0.886 \simeq 88.6\,\%$$

*

A continuous countercurrent multistage system is to be used to leach oil from vegetable seed meal by benzene solvent (C). The process is to treat 2000 kg/h of inert solid meal (B) containing 800 kg/hr oil/ (A) and also 50 kg/hr benzene (C). The inlet flow per hour of fresh solvent mixture contains 1310 kg benzene and 20 kg oil. The leached solids are to contain 120 kg oil/hr. Equilibrium data are tabulated below as *N* kg inert solid B/kg solution and y_A kg oil A/kg solution. Calculate the amounts and concentrations of the stream leaving the process and the theoretical number of stages.





C=1310 Kg

VN+1 A= 20 Kg N=0 $x_o = \frac{20}{20+1310} = .015$

Lo

B = 2000 Kg

A = 800 Kg

C = 50 Kg

$N_o = \frac{2000}{850} = 2.353$

$y_o = \frac{A}{A+C} = .94$

LN

A=120Kg

B=2000

$V_{N+1} + L_o = M = 2180$ Kg

$X_M = 0.376$

$N_m = \frac{B}{M} = \frac{2000}{2180} = .917$

LN? $N = \frac{B}{LN}$, $y = \frac{A}{LN}$

$N/y = \frac{B/\cancel{LN}}{A/\cancel{LN}} = B/A = \frac{2000}{120} = 16.66$

$N = 16.667y \longrightarrow$ Draw

$y = \frac{A}{LN} \rightarrow$ LN = 1016.95 Kg

(0.188, 1.97)

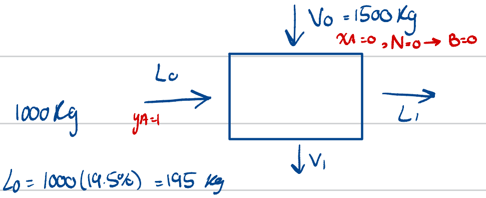
C = 896.95 Kg

Task

One thousand kilograms of crushed oil seeds (19.5% oil, 80.5% meal) is extracted with 1500 kg of 'pure' hexane in a batch extraction vessel. Calculate the fraction of the oil extracted. The equilibrium data are given as

x_A	0	0.09	0.15	0.25	0.3	0.39	0.45	0.55	0.61	0.65	0.75
N	0.003	0.0045	0.0054	0.007	0.0078	0.0092	0.01	0.012	0.013	0.013	0.015
y_A	0	0.09	0.15	0.25	0.3	0.39	0.45	0.55	0.61	0.65	0.75
N	2.05	2.04	2.02	1.99	1.965	1.93	1.9	1.8	1.76	1.72	1.6

Answer: Fraction of the oil extracted= 76.6%



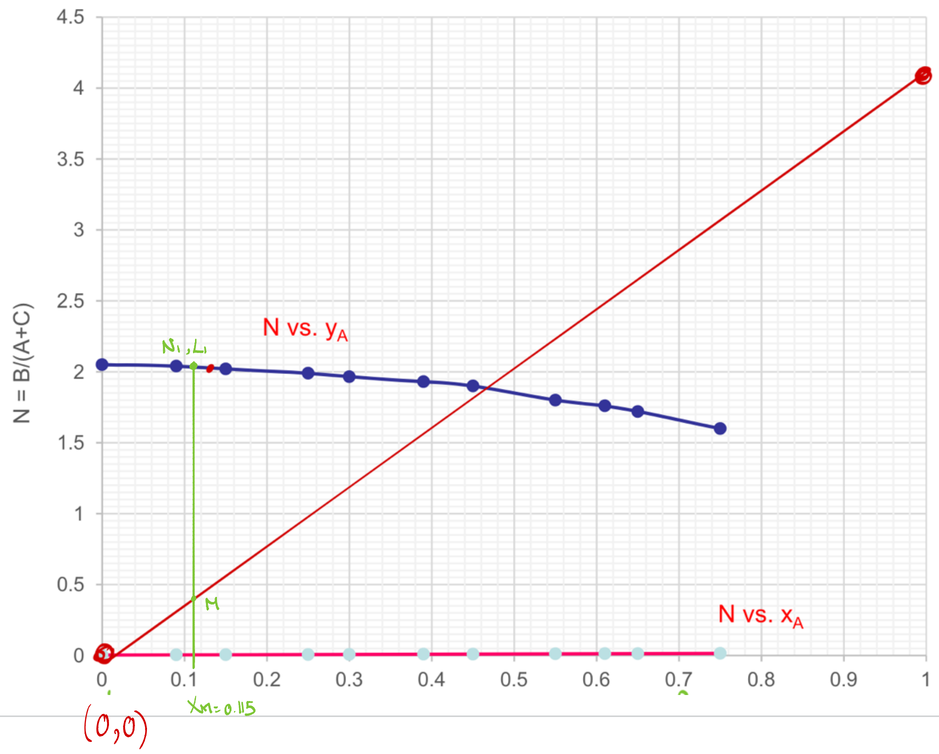
$L_0 = 1000(19.5\%) = 195$ kg

$B = 1000(80.5\%) = 805$ Kg

$N = \frac{805}{195} = 4.12$

$M = L_0 + V_0 = 1500 + 195 = 1695$ Kg

$x_M = \frac{195(1) + 0}{1695} = 0.115 = x_1 = y_1$



(1, 4.12)

From Figure

$N_1 = 2.05 = \frac{B}{L_1} = \frac{805}{L_1}$

$L_1 = 392.68$

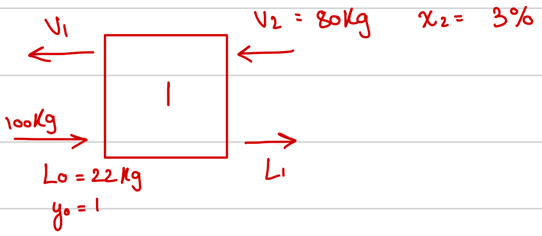
$V_2 = M - L_1 = 1695 - 392.68$

$= 1302.3$

Oil Extracted : $\frac{1302.3(0.115)}{195} = 0.768$

31.2-1. Leaching of Oil from Soybeans in a Single Stage. Repeat Example 31.2-1 for single-stage leaching of oil from soybeans. The 100 kg of soybeans contains 22 wt % oil and the solvent feed is 80 kg of solvent containing 3 wt % soybean oil.

Ans. $L_1 = 52.0$ kg, $y_{A1} = 0.239$, $V_1 = 50.0$ kg, $x_{A1} = 0.239$, $N_1 = 1.5$



$$N_o = \frac{B}{L_o} = \frac{78}{22} = 3.54$$

① $(1,\ 3.54)$
$y_o,\ N_o$

② $(3\%,\ 0)$
$x_2,\ N_2$

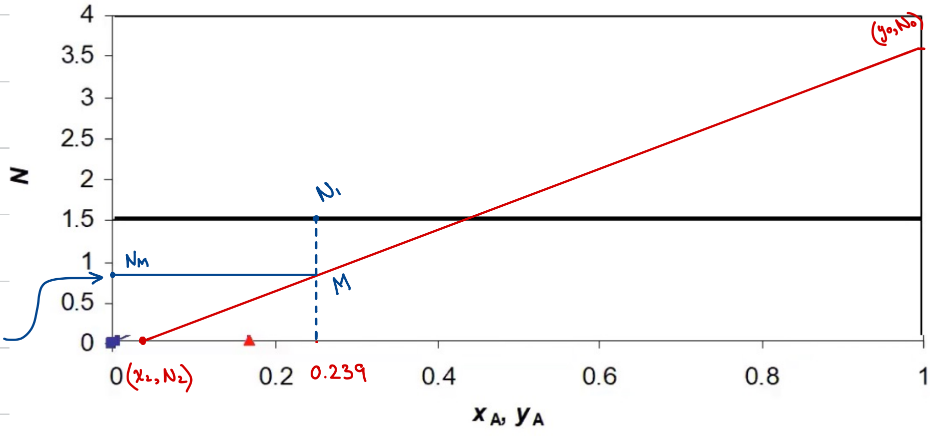
$$L_o + V_2 = M = 22 + 80 = 102 \text{ Kg}$$

$$x_M = \frac{L_o(1) + V_2(3\%)}{102} = 0.239 = x_1 = y_1$$

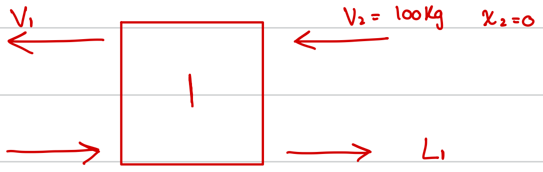
$$N_1 = 1.5 = \frac{B}{L_1} = \frac{78}{L_1} \longrightarrow L_1 = 52 \text{ Kg}$$

$$V_1 = 102 - 52 = 50 \text{ Kg}$$

$$N_M = \frac{B}{M} = \frac{78}{102} = 0.76$$



31.2-2. Leaching a Soybean Slurry in a Single Stage. A slurry of flaked soybeans weighing a total of 100 kg contains 75 kg of inert solids and 25 kg of solution with 10 wt % oil and 90 wt % solvent hexane. This slurry is contacted with 100 kg of pure hexane in a single stage so that the value of *N* for the outlet underflow is 1.5 kg insoluble solid/kg solution retained. Calculate the amounts and compositions of the overflow V_1 and the underflow L_1 leaving the stage.



$B = 75$ Kg

$L_0 = 25$ Kg (A+C)

$y_{A0} = 0.1$

$N = 1.5$

$$L_0 + V_2 = M = 25 + 100 = 125$$

$$x_M = \frac{25(0.1) + 100(0)}{125} = 0.02 = x_1 = y_1$$

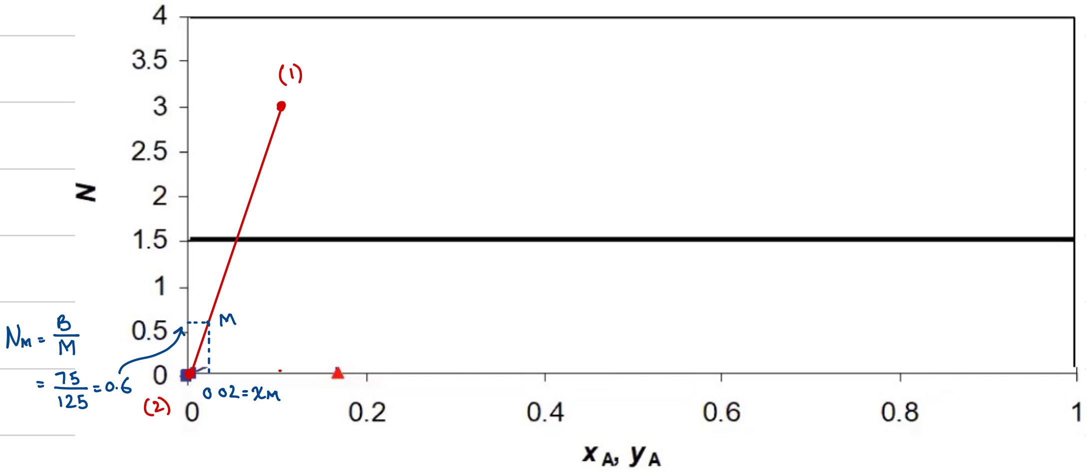
$$N_1 = 1.5 = \frac{B}{L_1} = \frac{75}{L_1} \rightarrow L_1 = 50 \text{ Kg}$$

$$V_1 = 125 - 50 = 75 \text{ Kg}$$

$$N_0 = \frac{B}{L_0} = \frac{75}{25} = 3$$

① (0.1, 3)

$N_2 = 0$, (0,0) ②

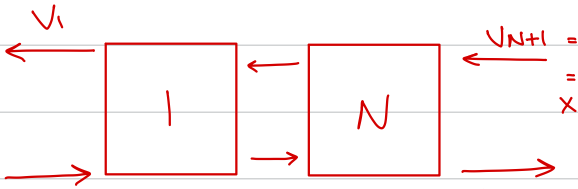


$$N_M = \frac{B}{M} = \frac{75}{125} = 0.6$$

Example 31.3-1

31.3-1. Constant Underflow in Leaching Oil from Meal. Use the same conditions as given in Example 12.10-1, but assume constant underflow of N 1.85 kg solid/kg solution. Calculate the exit flows and compositions and the number of stages required. Compare with Example 31.3-1.

Ans. y_{AN} = 0.111, x_{A1} = 0.623, 4.3 stages



Benzene oil

$V_{N+1} = 1310\ Kg + 20\ Kg$

$= 1330\ Kg$

$X_{N+1} = \frac{20}{1330} = 0.015$

$L_0 = 800 + 50 = 850\ Kg$

$B = 2000\ Kg$

$y_0 = \frac{800}{850} = 0.94$

L_N

$N = 1.85$

$A = 120\ Kg$

$L_0 + V_{N+1} = M = 850 + 1330 = 2180\ Kg$

$x_M = \frac{850(0.94) + 1330(0.015)}{2180} = 0.375$

$N_0 = \frac{2000}{850} = 2.35$ ① $\overset{y_0}{(0.94},\overset{N_0}{2.35)}$

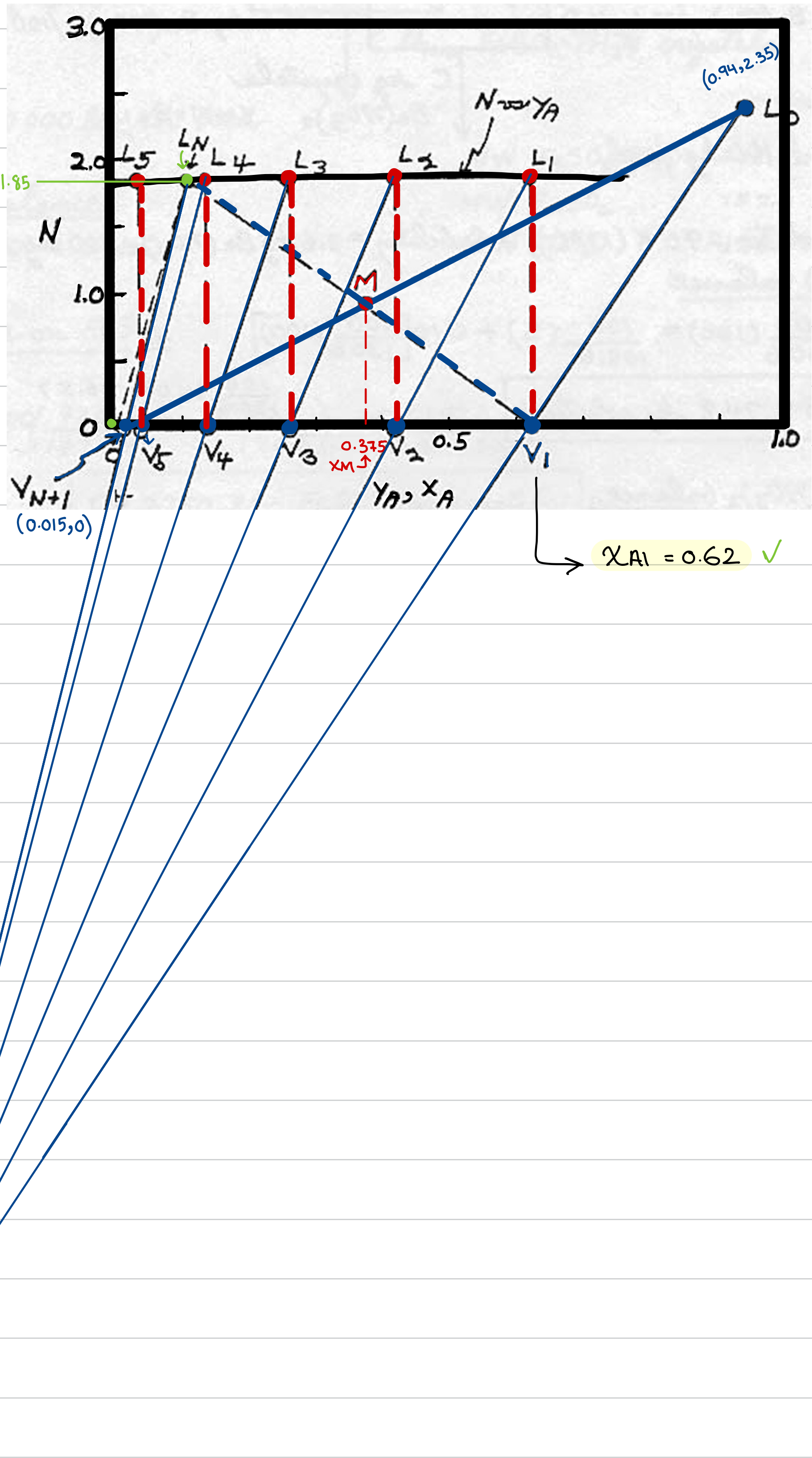
$N_2 = 0$, $x_2 = 0.015$ ② $\overset{x_2}{(0.015},\overset{N_2}{0)}$

L_N :-

$N_N = 1.8 = \frac{B \rightarrow 2000}{L_N}$

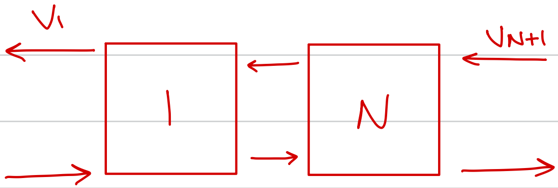
$L_N = 1081.08$

$y_N = \frac{120}{1081.1} = 0.11$



$X_{A1} = 0.62$ ✓

31.3-2. Effect of Less Solvent Flow in Leaching Oil from Meal. Use the same conditions as given in Example 31.3-1, but the inlet fresh-solvent-mixture flow rate per hour is decreased by 10%, to 1179 kg of benzene and 18 kg of oil. Calculate the number of stages needed.



Benzene oil

$V_{N+1} = 1179\ kg + 18\ kg$

$= 1197\ kg$

$X_{N+1} = \frac{18}{1197}$

$= 0.015$

$L_0 = 800 + 50 = 850\ kg$

$B = 2000\ kg$

$y_0 = \frac{800}{850} = 0.94$

L_N

$N = 1.85$

$A = 120\ kg$

$L_0 + V_{N+1} = M = 850 + 1197 = 2047\ kg$

$$X_M = \frac{850(0.94) + 1197(0.015)}{2047} = 0.4$$

$N_0 = \frac{2000}{850} = 2.35$ ① $\begin{array}{c} y_0 \quad N_0 \\ (0.94, 2.35) \end{array}$

$N_2 = 0$, $x_2 = 0.015$ ② $\begin{array}{c} x_2 \quad N_2 \\ (0.015, 0) \end{array}$

$\boxed{\text{More Stages are required}}$

31.3-3. Countercurrent Multistage Washing of Ore. A treated ore containing inert solid gangue and copper sulfate is to be leached in a countercurrent multistage extractor using pure water to leach the $CuSO_4$. The solid charge rate per hour consists of 10 000 kg of inert gangue (*B*), 1200 kg of $CuSO_4$ (solute *A*), and 400 kg of water (*C*). The exit wash solution is to contain 92 wt % water and 8 wt % $CuSO_4$. A total of 95% of the $CuSO_4$ in the inlet ore is to be recovered. The underflow is constant at *N* = 0.5 kg inert gangue solid/kg aqueous solution. Calculate the number of stages required.

A: $CuSO_4$

C: water

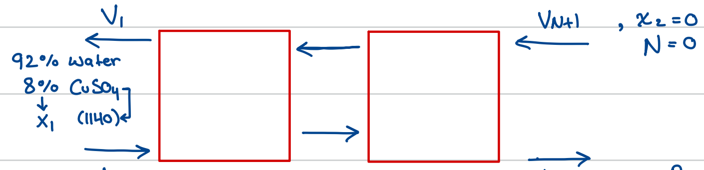
B: gangue

$8\% \times V_1 = 95\%(1200) \rightarrow V_1 = 14250$

A in LN = 5% × 1200 = 60 Kg

5% $CuSO_4$ underflow

95% $CuSO_4$ overflow



$L_o = 1200 + 400 = 1600$ Kg

$B = 10{,}000$

$y_o = \frac{1200}{1600} = 0.75$

$N_o = \frac{10{,}000}{1600} = 6.25$

LN

$N = 0.5 = \frac{B}{A+C} = \frac{10{,}000}{60 + C}$

A = 60 Kg

$\downarrow$ C = 19,940

$y_N = \frac{60}{20{,}000} = 3 \times 10^{-3}$,

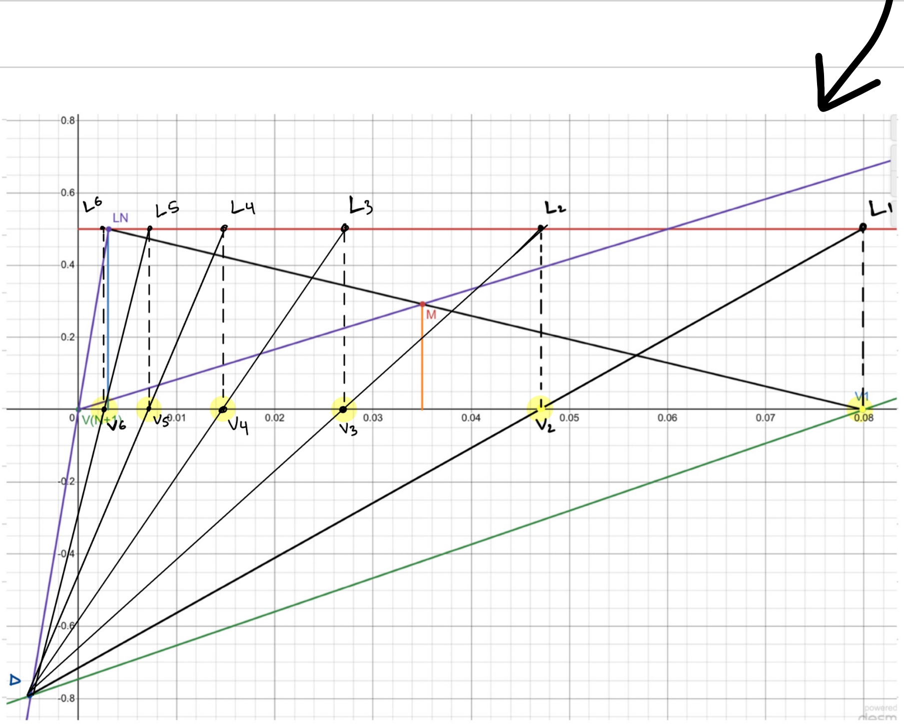
$L_N = \overset{C}{19{,}940} + \overset{A}{60} = 20{,}000$ kg/h

$M = V_1 + L_N = 14250 + 20{,}000$

$M = 34250$

$x_M = \frac{14250(8\%) + 20{,}000(3\times10^{-3})}{34250}$

$= 0.035$



≈ 5.8 stages

31.3-4. Countercurrent Multistage Leaching of Halibut Livers.

Fresh halibut livers containing 25.7 wt % oil are to be extracted with pure ethyl ether to remove 95% of the oil in a countercurrent multistage leaching process. The feed rate is 1000 kg of fresh livers per hour. The final exit overflow solution is to contain 70 wt % oil. The retention of solution by the inert solids (oil-free liver) of the liver varies as follows (C1), where *N* is kg inert solid/kg solution retained and y_A is kg oil/kg solution:

N	y_A
4.88	0
3.50	0.2
2.47	0.4
1.67	0.6
1.39	0.81

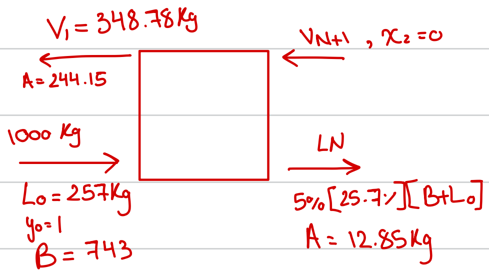
Calculate the amounts and compositions of the exit streams and the total number of theoretical stages.

$N_0 = \frac{743}{257} = 2.9$ $\quad V_1 = 348.78$

$y_0 = 1$

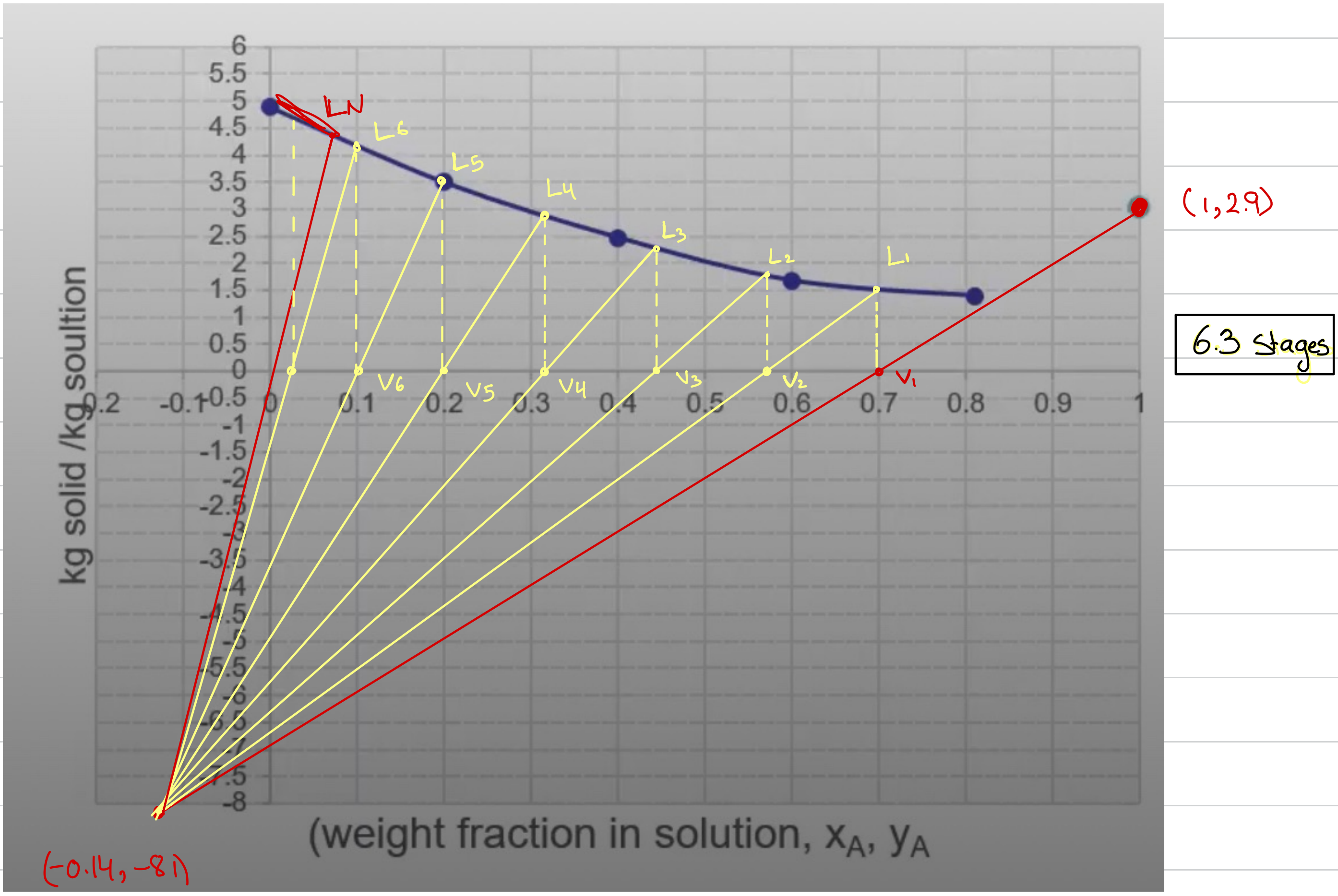
$\Delta = L_0 - V_1 = -91.78$, $N_\Delta = \frac{743}{\Delta} = \frac{743}{-91.78} = -8.1$

$x_\Delta = \frac{L_0 \cdot (1) - V_1 (70\%)}{-91.78} = -0.14$,



Remove 95% , $N_N = 4.25 = \frac{743}{L_N}$, $L_N = 174.8$, $y_N = 0.073$

$V_{N+1} = 174.8 + 348.78 - 257 = 266.58$

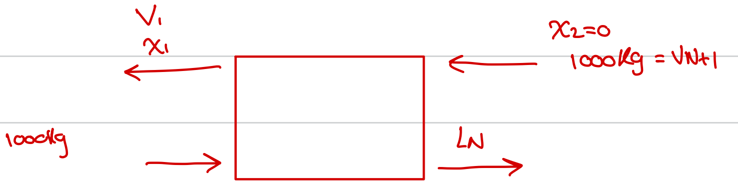


$\boxed{6.3 \text{ Stages}}$

31.3-5. Countercurrent Leaching of Flaked Soybeans. Soybean flakes containing 22 wt % oil are to be leached in a countercurrent multistage process to contain 0.8 kg oil/100 kg inert solid using fresh and pure hexane solvent. For every 1000 kg soybeans, 1000 kg hexane is used. Experiments (S1) give the following retention of solution with the solids in the underflow, where *N* is kg inert solid/kg solution retained and y_A is wt fraction of oil in solution:

V_1, L_N

Calculate the exit flows and compositions and the number of theoretical stages needed.



$L_0 = 220$
$B = 780$
$N_0 = 3.54$
$y_0 = 1$

$A = 6.24$ Kg
$B = 780$ Kg

$$\frac{N}{y} = \frac{B}{A} = 124.8$$

$M = 220 + 1000 = 1220$ Kg

$$X_M = \frac{220(1) + 1000}{1220} = 0.18$$

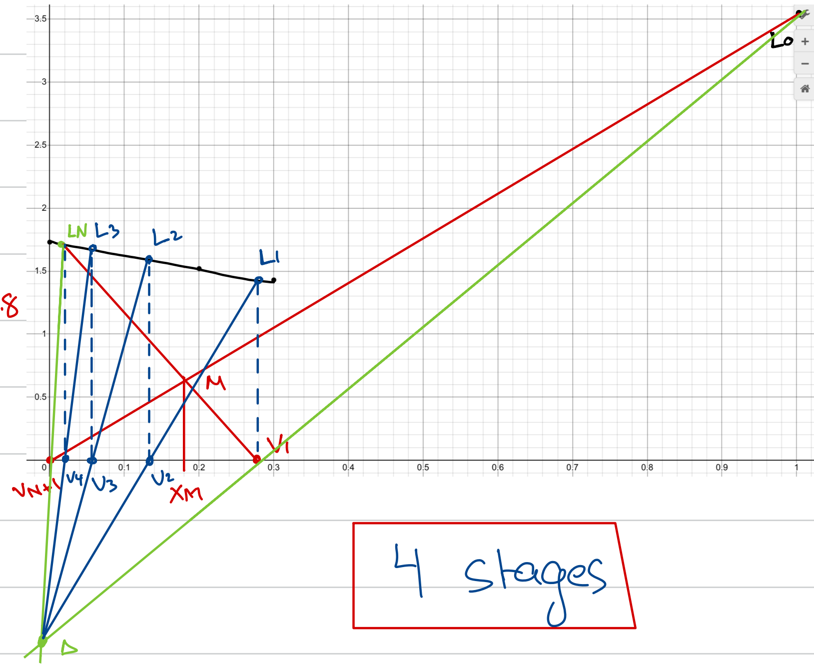
$N = 124.8y$

$$N_N = 1.7 = \frac{B}{L_N} \rightarrow L_N = 458.82$$

$y_N = 0.2$

$V_1 = 1000 + 220 - 458.82 = 761.18$

$x_1 = 0.28$



4 stages

2- Humidification

23.1-1. *Humidity from Vapor Pressure.* The air in a room is at 37.8°C and a total pressure of 101.3 kPa abs containing water vapor with a partial pressure $p_A = 3.59$ kPa. Calculate:

a. Humidity
b. Saturation humidity and percentage humidity
c. Percentage relative humidity

T = 37.8°C

p_A = 3.59 kPa

H ?

% H ? @ saturation ?

relative humidity ?

from Table : $P_{AS} = 6.61$

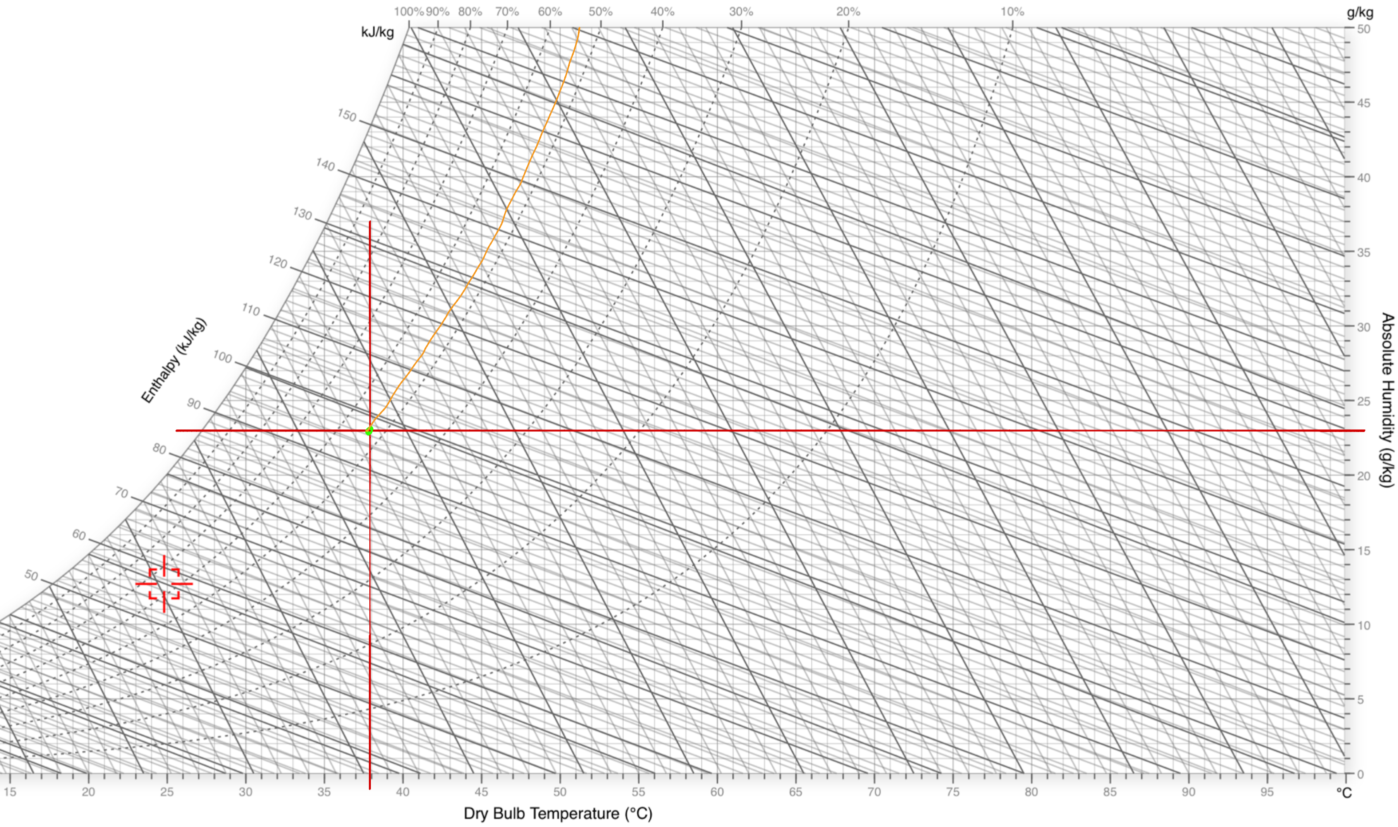
a- $H = 0.622 \cdot \frac{P_A}{P - P_A} = 0.622 \cdot \frac{3.59}{101.3 - 3.59} = 0.023$

b- Saturation Humidity $= .622 \times \frac{P_{AS}}{P - P_{AS}}$

$= .622 \times \frac{6.612}{101.3 - 6.612} = 0.043$

percentage humidity : from chart 53%

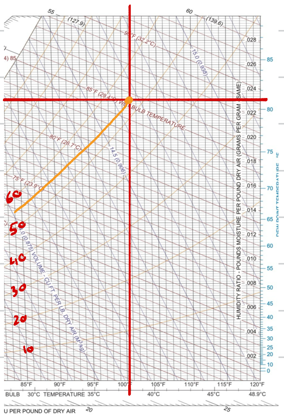
or $(H/H_S) \times 100 = \frac{0.023}{0.043} \times 100 = 53.5\%$



c- HR : $\frac{P_A}{P_{As}} \times 100 = \frac{3.59}{6.61} \times 100 = 54.3\%$

or chart :-

≈ % 54



23.1-2. *Percentage and Relative Humidity.* The air in a room has a humidity *H* of 0.021 kg H_2O/kg dry air at 32.2°C and 101.3 kPa abs pressure. Calculate:

a. Percentage humidity H_P

b. Percentage relative humidity H_R

Ans. (a) $H_P = 67.5\%$; (b) $H_R = 68.6\%$

$H = 0.021$ KgH2O/Kg Dry Air

@ 32.2°C

$P_s = 4.824$

from Tables:-

$$H_p = \frac{H}{H_s}$$

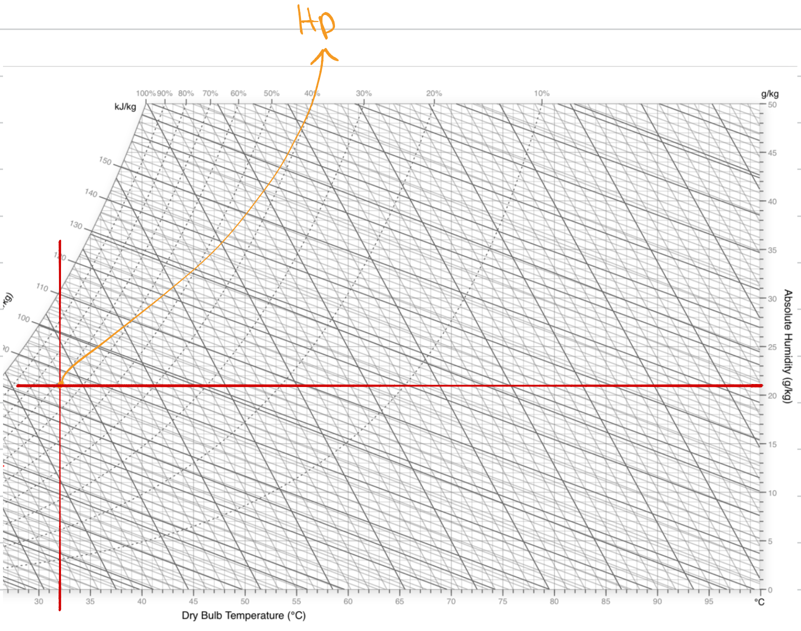
$$\hookrightarrow \frac{P_s}{P - P_s} \times .622 = 0.0311$$

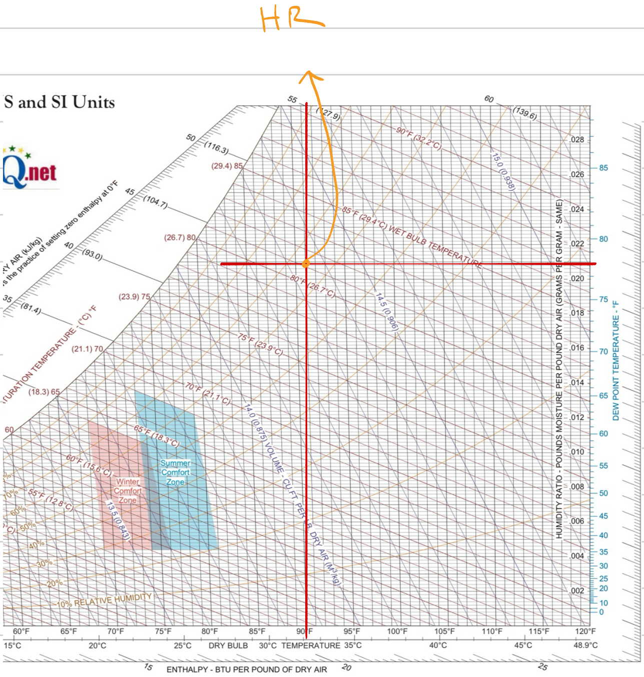
$$H_p : \frac{0.021}{0.0311} \times 100 = 67.5\%$$

$$HR = \frac{P_A}{P_s} = \frac{3.308}{4.824} \times 100 = 68.6\%$$

P_A ?

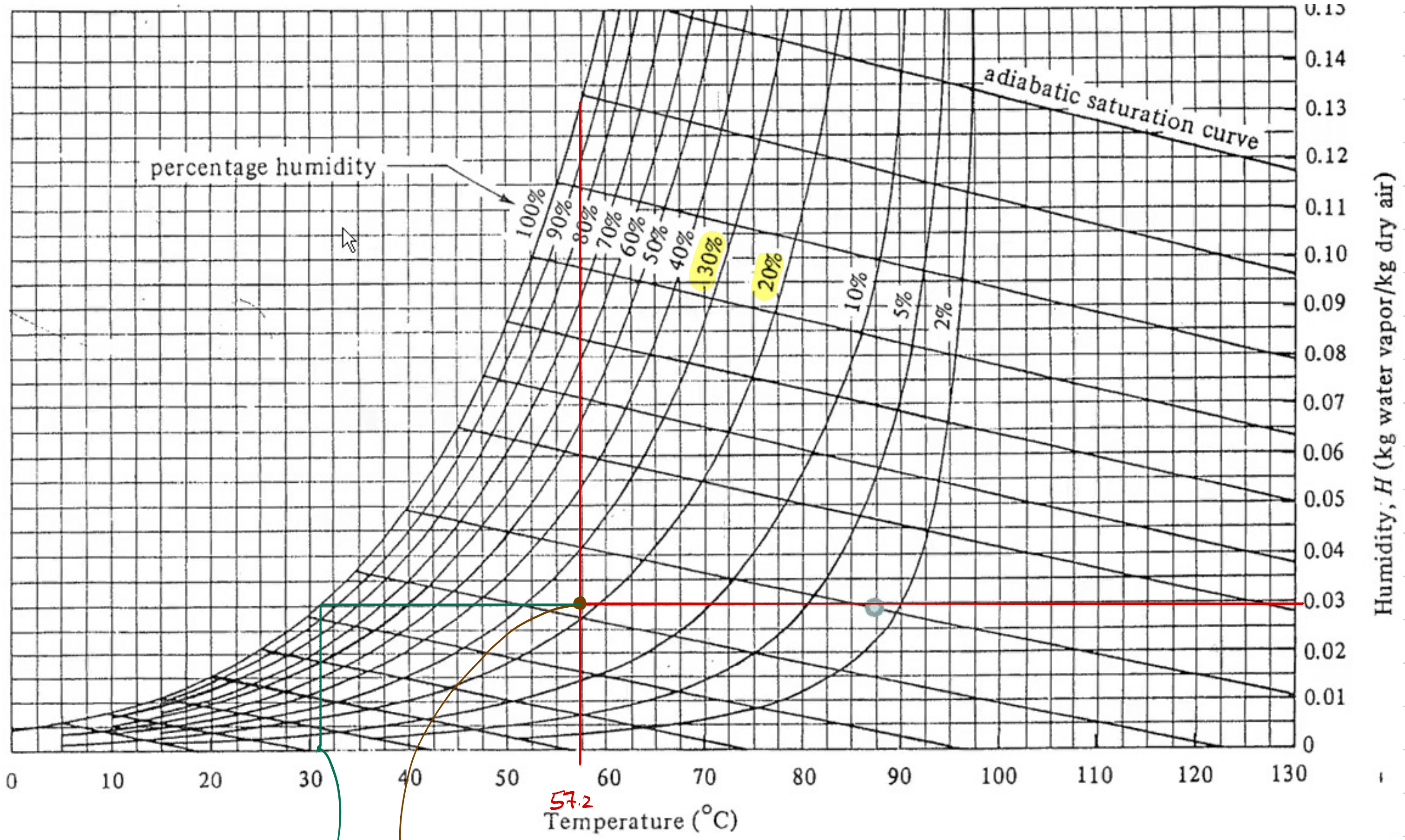
$$H = 0.622 \cdot \frac{P_A}{P - P_A} \rightarrow 3.308$$





23.1-4. ***Properties of Air to a Dryer.*** An air–water vapor mixture going to a drying process has a dry bulb temperature of 57.2°C and a humidity of 0.030 kg H_2O/kg dry air. Using the humidity chart and appropriate equations, determine the percentage humidity, saturation humidity at 57.2°C, dew point, humid heat, and humid volume.

$T = 57.2°C$
$H = 0.03$
$H_p = ?$
$H_s = ?$
Dew point ?
humid heat ?
humid volume ?



$H_p \approx 23\%$

$\hookrightarrow \frac{H}{H_s}$

$$H_s = \frac{0.03}{0.23} = \underline{0.13} \frac{kg\ H_2O}{kg\ Air}$$

Dew point = 31.7°C

humid heat $C_s = 1.005 + 1.88H$

$= 1.0614$

$$v_H = (2.83\times10^{-3} + 4.56\times10^{-3} H)\times \overset{(57.2+273.15)K}{T}$$

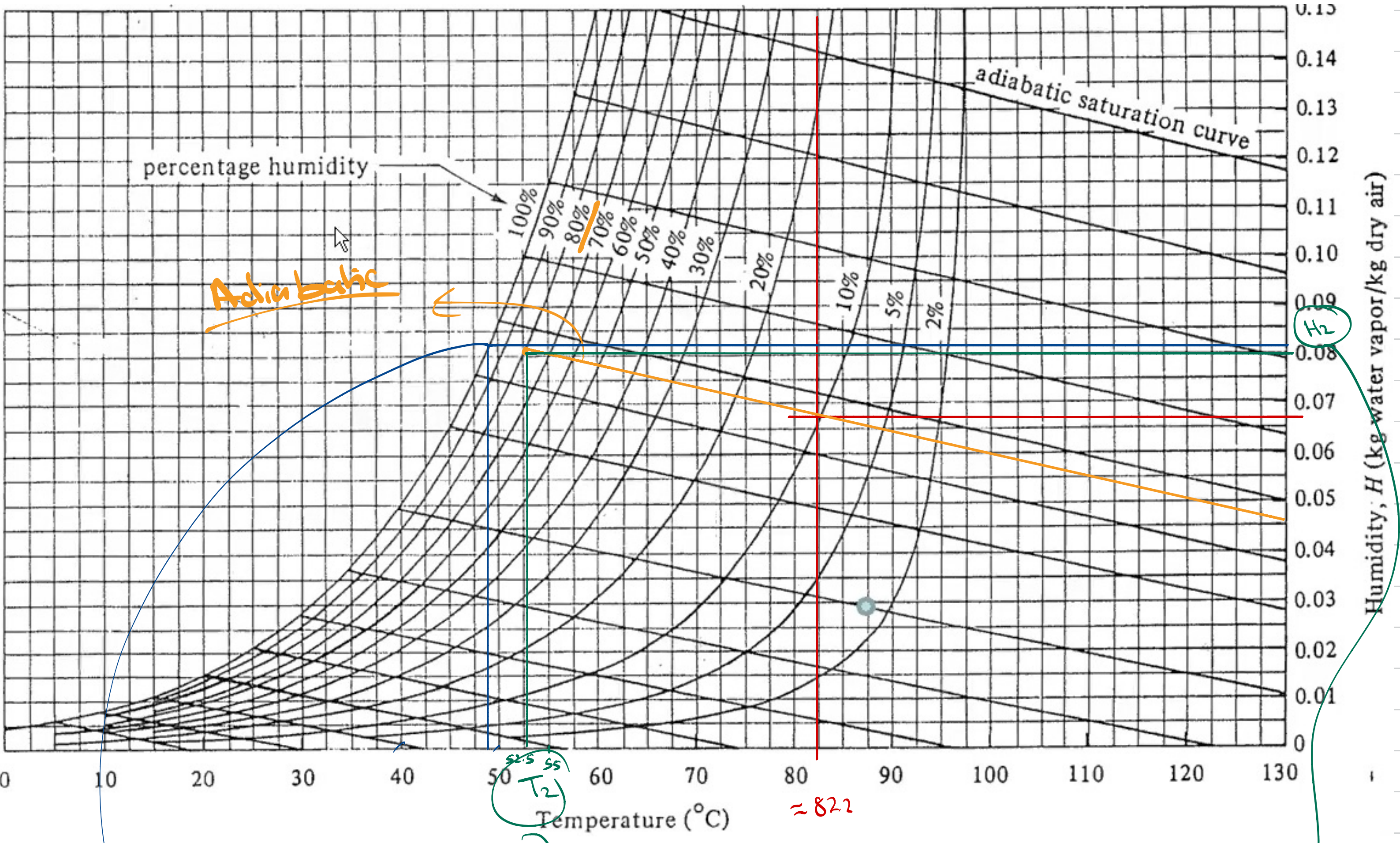
$= 0.98\ m^3/kg$ Dry Air

23.1-5. ***Adiabatic Saturation Temperature.*** Air at 82.2°C having a humidity $H = 0.0655$ kg H_2O/kg dry air is contacted with water in an adiabatic saturator. It exits at 80% saturation.

a. What are the final values of H and T°C?

b. For 100% saturation, what would be the values of H and T?

Ans. (a) $H = 0.079$ kg H_2O/kg dry air, $T = 52.8$°C



a-

$T_2 \approx 52.6$°C

$H_2 \approx 0.08$

@ 100 sat

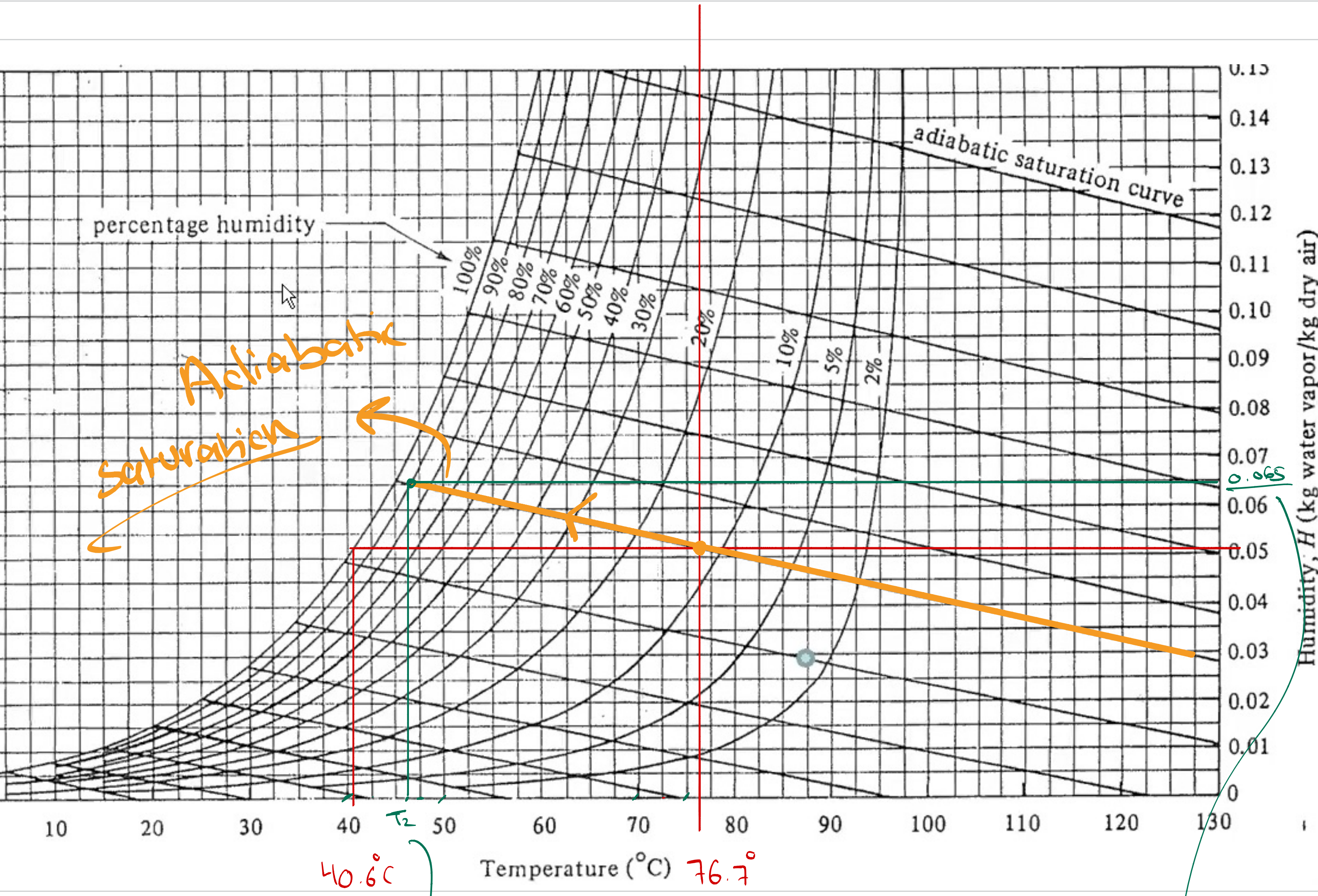
$T_3 \approx 48.8$°C

$H_1 = 0.081$ kgH_2O/kg Dry Air.

23.1-6. *Adiabatic Saturation of Air.* Air having a temperature of 76.7°C and a dew-point temperature of 40.6°C enters an adiabatic saturator. It exits the saturator 90% saturated. What are the final values of *H* and *T*°C?

$T = 76.7°C$

$T_{Dp} = 40.6°C$

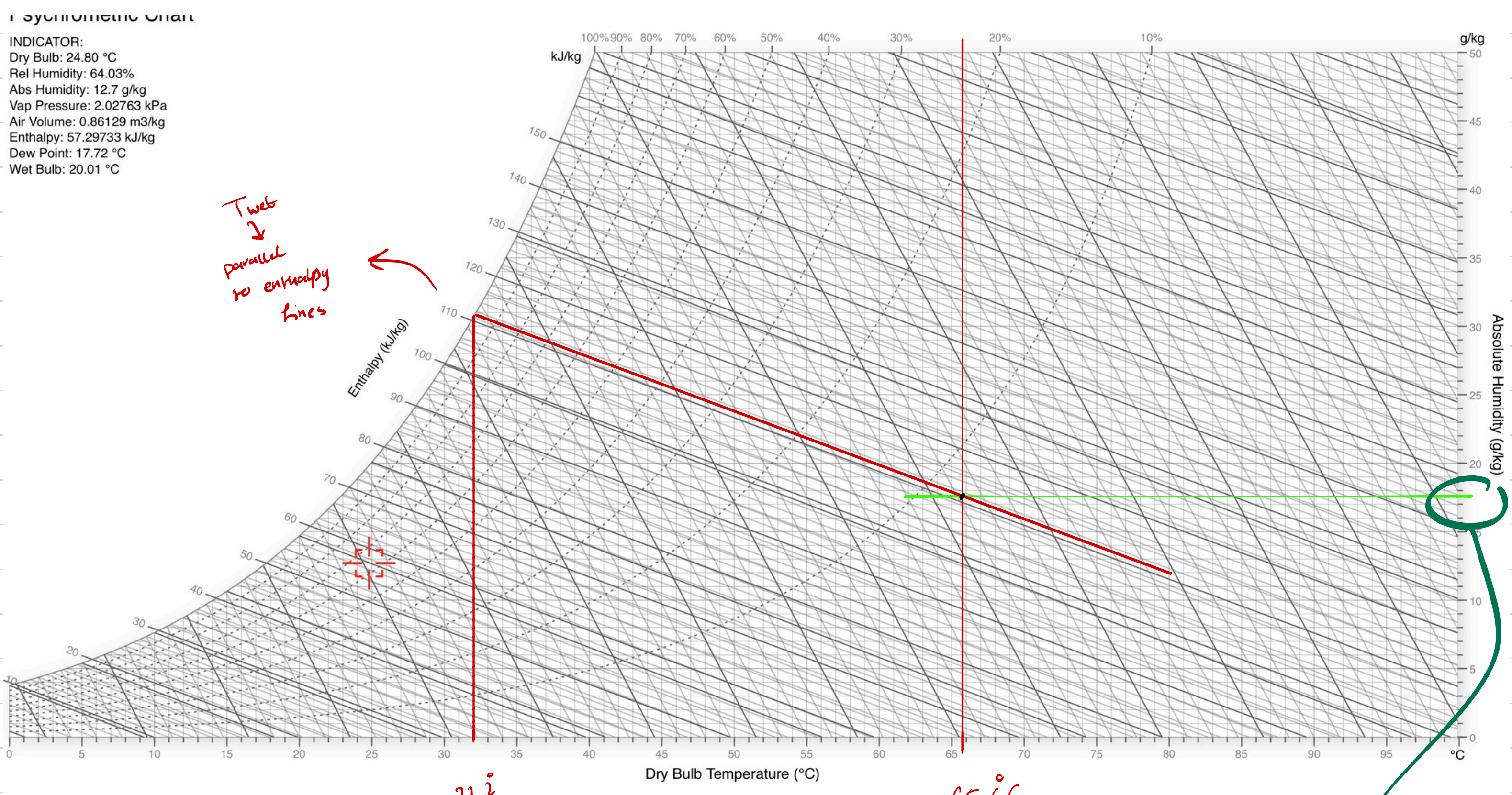


$T_2 \approx 46.3°C$

$H_2 = 0.065$

23.1-7. ***Humidity from Wet and Dry Bulb Temperatures.*** An air–water vapor mixture has a dry bulb temperature of 65.6°C and a wet bulb temperature of 32.2°C. What is the humidity of the mixture?

Ans. $H = 0.0175$ kg H_2O/kg dry air



INDICATOR:
Dry Bulb: 24.80 °C
Rel Humidity: 64.03%
Abs Humidity: 12.7 g/kg
Vap Pressure: 2.02763 kPa
Air Volume: 0.86129 m3/kg
Enthalpy: 57.29733 kJ/kg
Dew Point: 17.72 °C
Wet Bulb: 20.01 °C

T wet → parallel to enthalpy lines

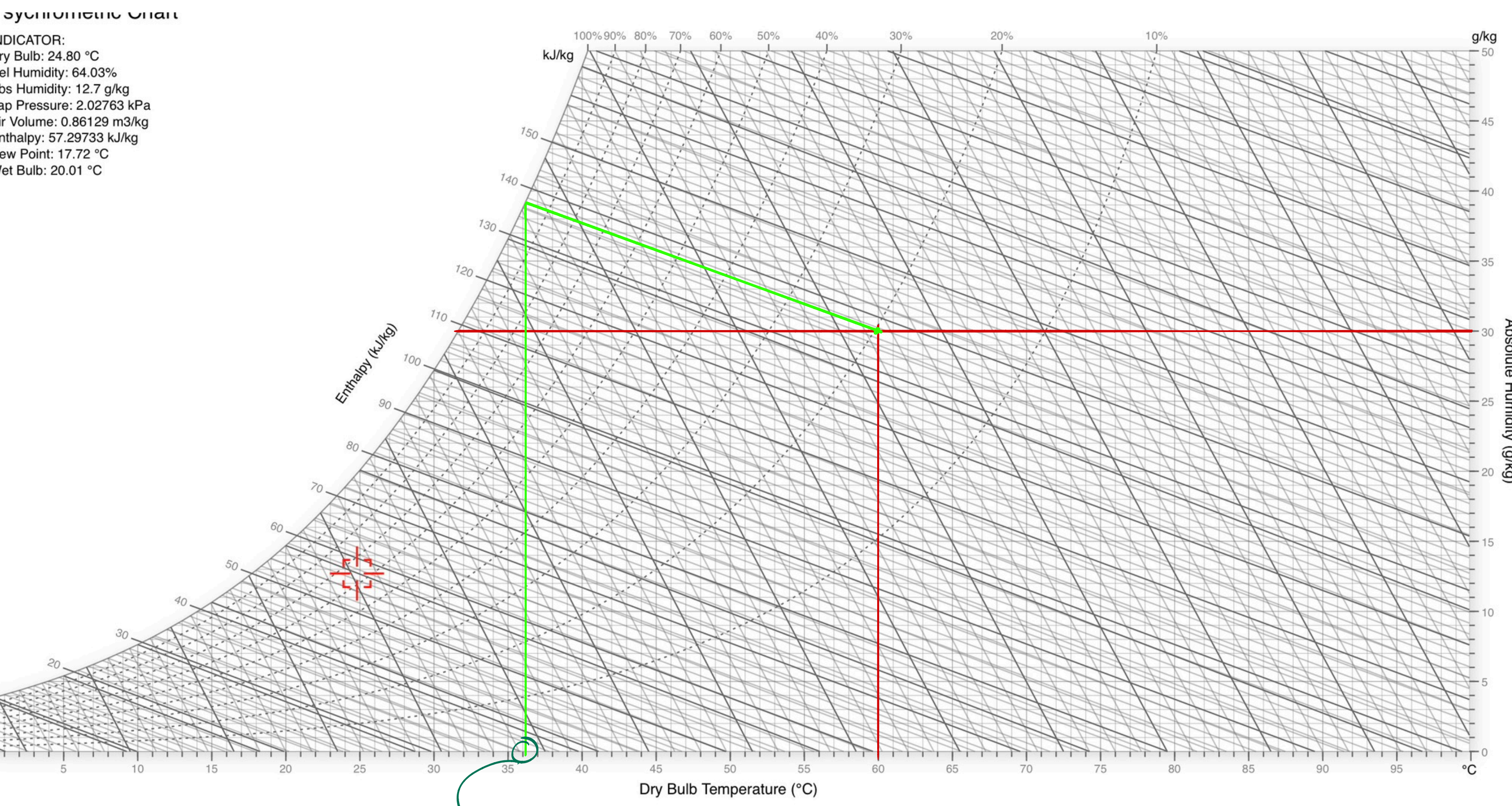
32.2

65.6C Dry

≈

$H = 0.017 \frac{Kg\ H_2O}{Kg\ Dry\ Air}$

23.1-8. *Humidity and Wet Bulb Temperature.* The humidity of an air–water vapor mixture is $H = 0.030$ kg H_2O/kg dry air. The dry bulb temperature of the mixture is 60°C. What is the wet bulb temperature?


sychrometric Chart

DICATOR:
ry Bulb: 24.80 °C
el Humidity: 64.03%
bs Humidity: 12.7 g/kg
ap Pressure: 2.02763 kPa
ir Volume: 0.86129 m3/kg
nthalpy: 57.29733 kJ/kg
ew Point: 17.72 °C
Vet Bulb: 20.01 °C

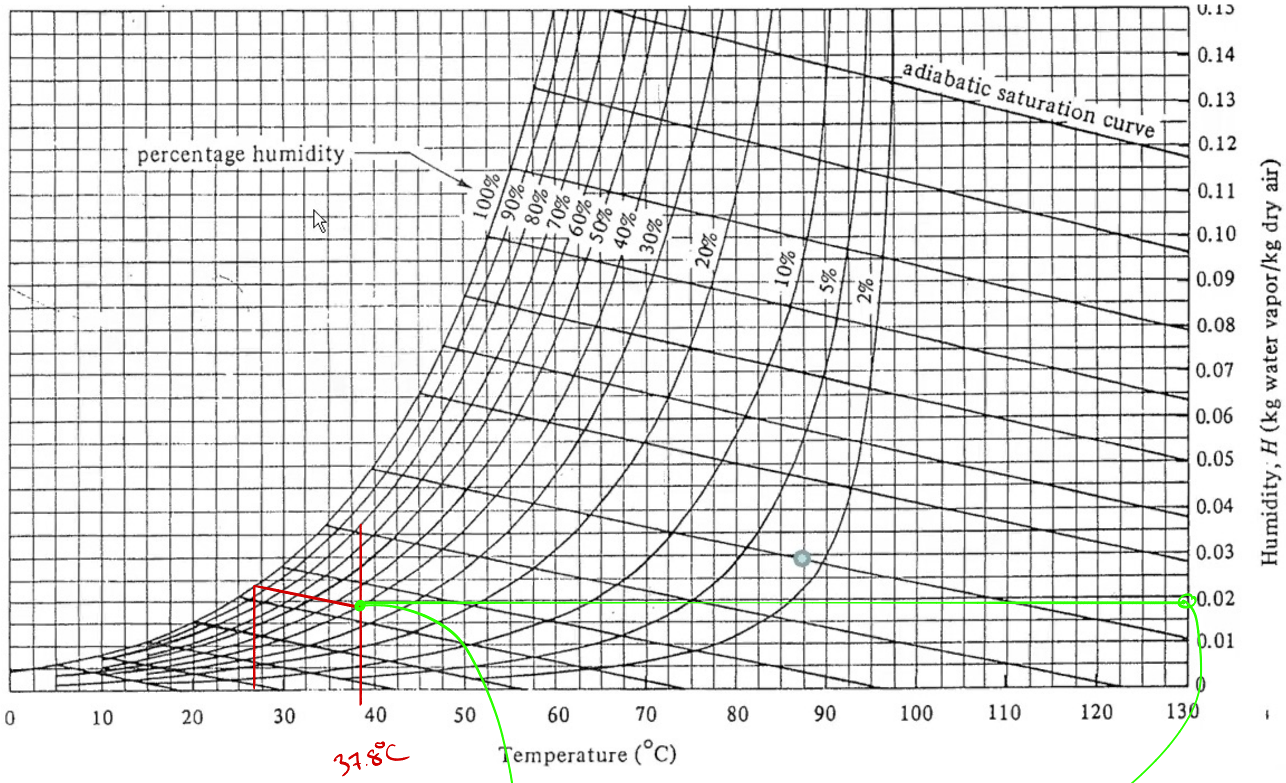
Twet ≈ 36.2°C

23.1-9. *Dehumidification of Air.* Air having a dry bulb temperature of 37.8°C and a wet bulb temperature of 26.7°C is to be dried by first cooling to 15.6°C to condense water vapor and then heating to 23.9°C.

a. Calculate the initial humidity and percentage humidity.

b. Calculate the final humidity and percentage humidity. [*Hint:* Locate the initial point on the humidity chart. Then, go horizontally (cooling) to the 100% saturation line. Follow this line to 15.6°C. Then, go horizontally to the right to 23.9°C.]

Ans. (b) $H = 0.0115$ kg H_2O/kg dry air, $H_P = 60\%$

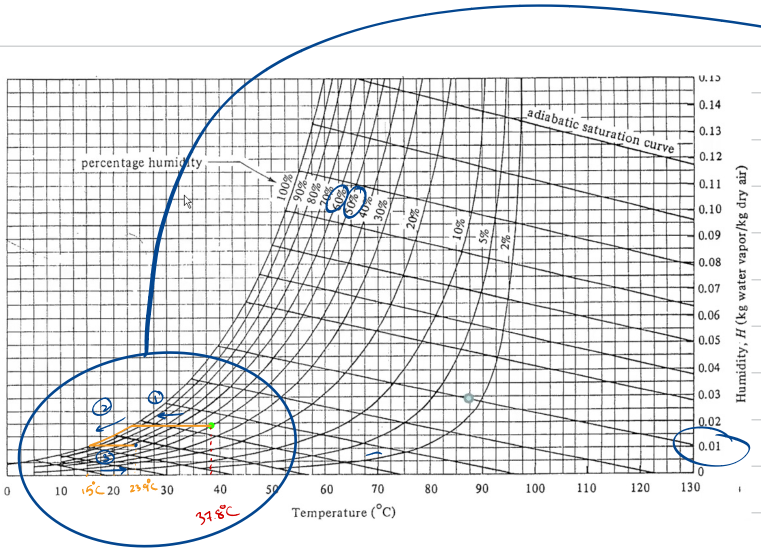


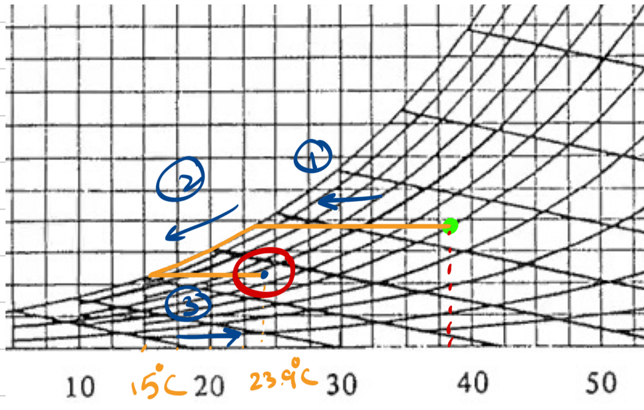
a-

$H_{P_1} \approx 40\%$

$H = 0.019$ Kg H_2O/ Kg Dry Air

b-





Hp= 59 %

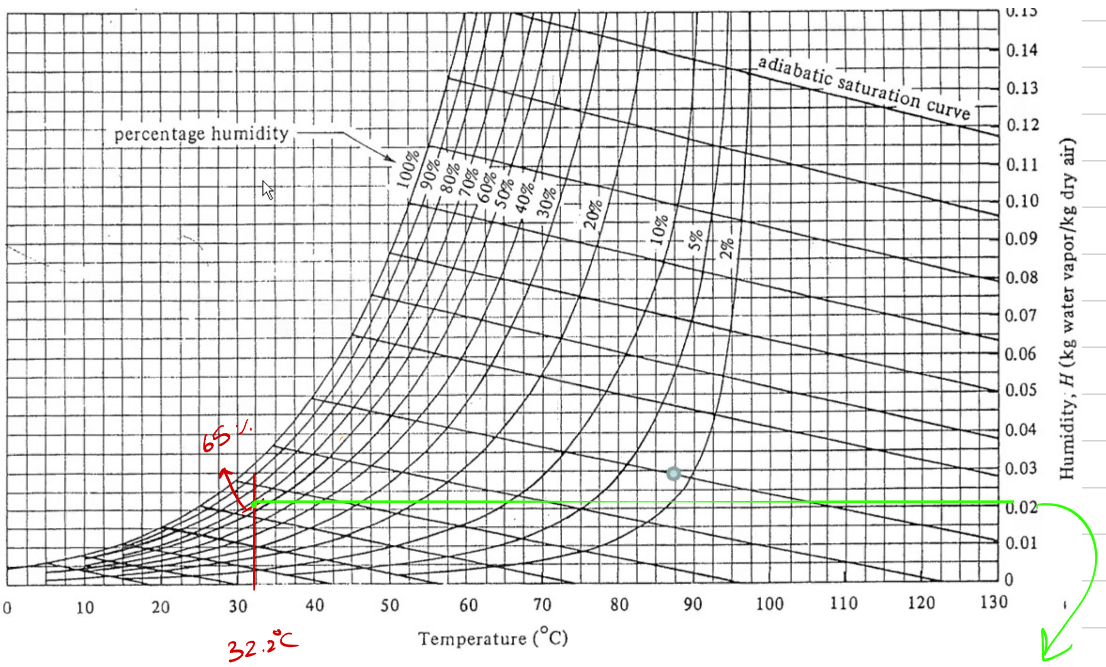
H= 0.011 Kg H_2O/Kg Dry Air

23.1-10. Cooling and Dehumidifying Air. Air entering an adiabatic cooling chamber has a temperature of 32.2°C and a percentage humidity of 65%. It is cooled by a cold water spray and saturated with water vapor in the chamber. After leaving, it is heated to 23.9°C. The final air has a percentage humidity of 40%.

a. What is the initial humidity of the air?

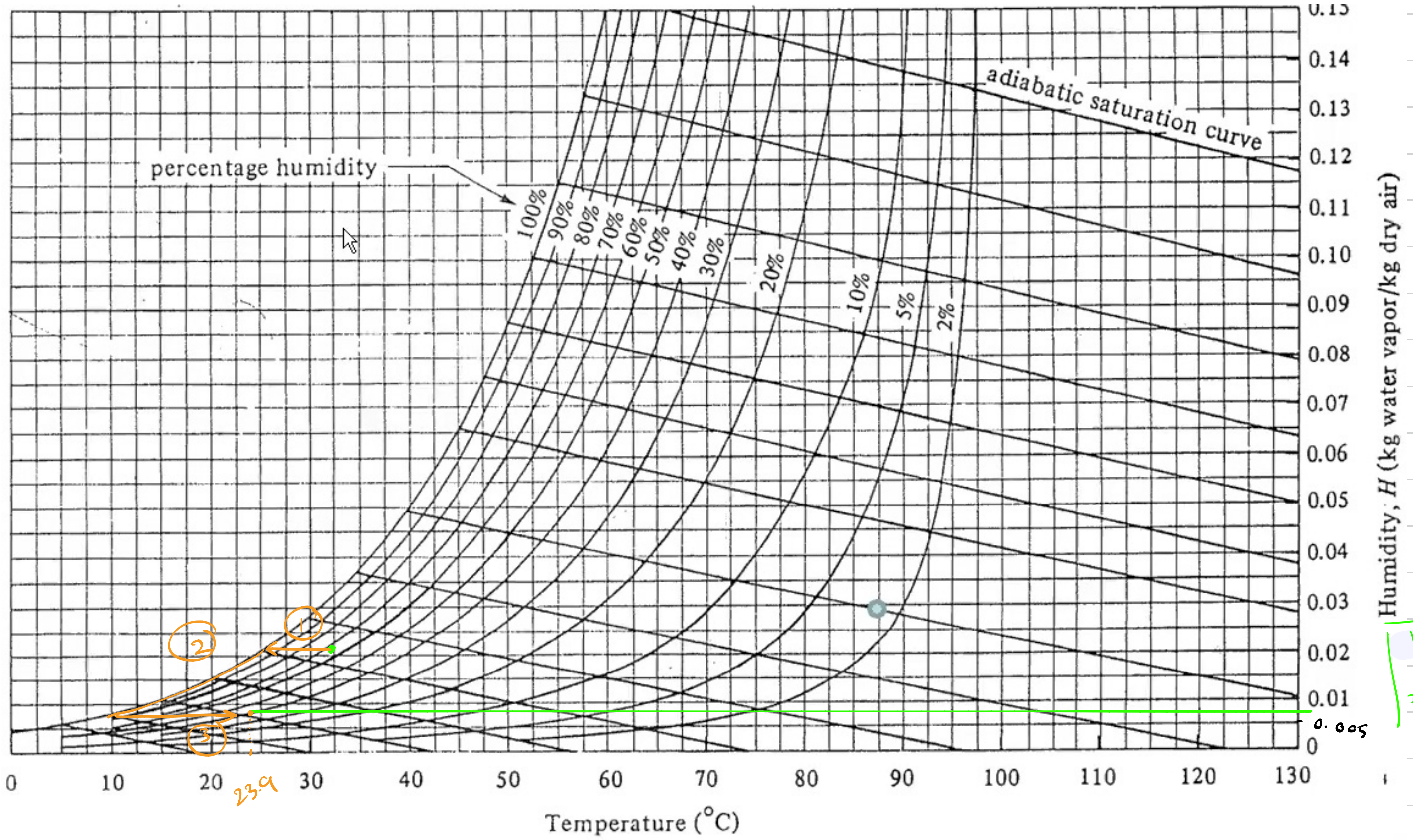
b. What is the final humidity after heating?

a -



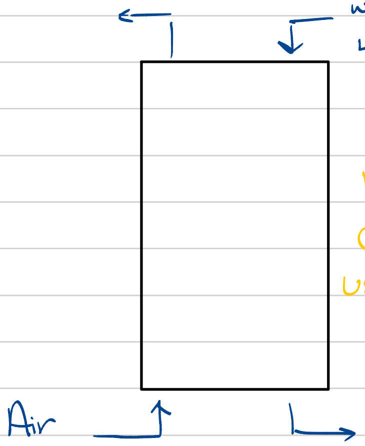
≈ H = 0.022 KgH₂O / Kg Dry Air

b



H = 0.007

23.3-1. *Countercurrent Water-Cooling Tower.* A forced-draft countercurrent water-cooling tower is to cool water from 43.3 to 26.7°C. The air enters the bottom of the tower at 23.9°C with a wet bulb temperature of 21.1°C. The value of H_G for the flow conditions is $H_G = 0.533$ m. The heat-transfer resistance in the liquid phase will be neglected; that is, h_L is very large. Hence, values of H^*_y should be used. Calculate the tower height needed if 1.5 times the minimum air rate is used.



water

$43.3°C = T_{L_2}$

$H_G = 0.533\,m$

$G = 1.5\,G_{min}$

use H_y^*

Air

$T_{G_1} = 23.9°C$

$26.7°C = T_{L_1}$

$T_{WB_1} = 21.1°C$

$H_1 \rightarrow$ chart

$H_{y_1} \rightarrow$ chart

or by calculation :-

$C_s = 1.005 + 1.88(0.0145)$

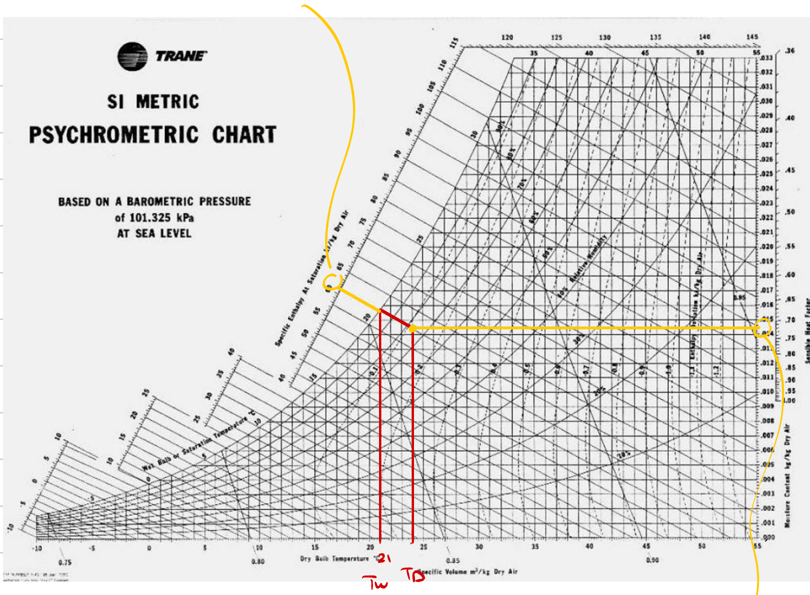
$= 1.03$

$H_{y_1} = C_s(T_{G_1} - T_0) + H_1\lambda$

23.9 0.0145 2502.3

$H_{y_1} = 60.95 \approx 61$ ✓

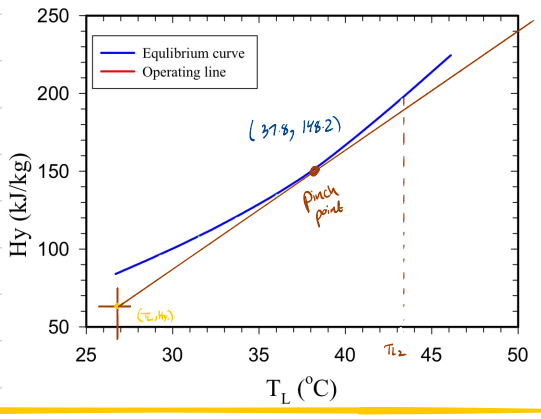
$H_{y_1} = 61$



$H = 0.0145$

$\underline{G_{min}}$: (T_{L_1}, H_{y_1}) $(26.7, 61)$, slope $= \frac{L c_L}{G_{min}} = 7.85/c_L$

$L/G_{min} = 1.876$



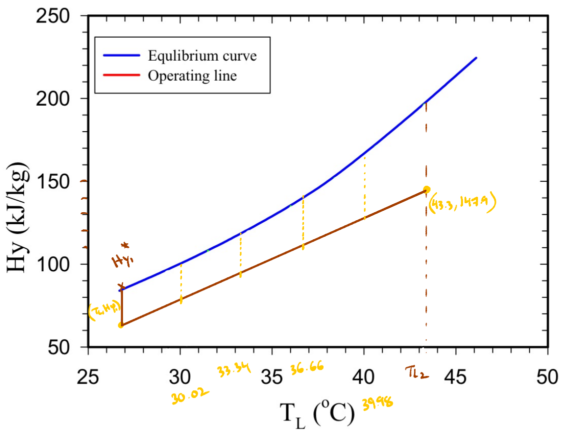
$G(H_{y_2} - H_{y_1}) = L c_L (T_{L_2} - T_{L_1})$

$1.5\,G_{min}$

$$\left[\frac{H_{y_2} - H_{y_1}}{T_{L_2} - T_{L_1}}\right] = \boxed{\frac{L}{G_{min}}} \times \frac{c_L}{1.5}$$

1.876

$H_{y_2} = 147.9$ KJ/kg



(KJ/kg)

Hy	Hy*	Hy* - Hy	1/Hy* - Hy
61	83	22	4.5×10^{-2}
79	100	21	4.7×10^{-2}
95	118	23	4.34×10^{-2}
111	140	29	3.44×10^{-2}
127	165	38	2.63×10^{-2}
147.9	198	50.1	2×10^{-2}

$$\frac{\left[\frac{147.9 - 61}{5}\right]}{2} \times \left[f(x_0) + 2\left[f(x_1) + f(x_2) + f(x_3) + f(x_4)\right] + f(x_5)\right]$$

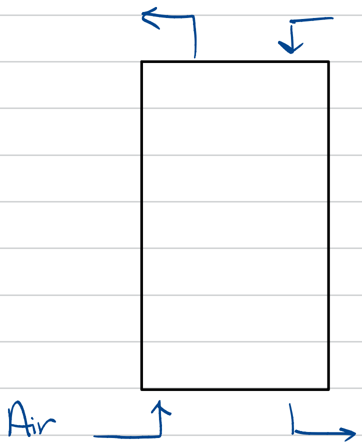
$= 3.19$

$Z = H_G \times NTU$

$0.533 \times 3.19 = 1.7\,m$

23.3-2. ***Minimum Gas Rate and Height of a Water-Cooling Tower.*** It is planned to cool water from 110°F to 85°F in a packed countercurrent water-cooling tower using entering air at 85°F with a wet bulb temperature of 75°F. The water flow is 2000 $lb_m/h \cdot ft^2$ and the air flow is 1400 lb_m air/h · ft^2. The overall mass-transfer coefficient is $K_G a = 6.90$ lb mol/h · ft^3 · atm.

a. Calculate the minimum air rate that can be used.
b. Calculate the tower height needed if the air flow of 1400 lb_m air/h · ft^2 is used.



$110°F = T_{L_2}$

$L = 2000$ lbm/h·ft²

$T_{G_1} = 85°F$

$85°F = T_{L_1}$

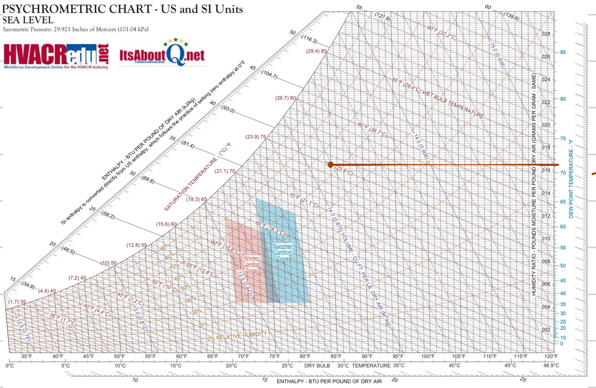
$T_{WB1} = 75°F$

$K_G a = 6.9$

$Z = HTU \times NTU$

$$HTU = \frac{G}{M \times P \times K_G \times a}$$

H_{y_1} ?



0.0165

$H_{y_1} = (0.24 + 0.45H)T$

$[0.24 + 0.45(0.0165)](85-32) + 1075.8(0.0165) = \boxed{30.8}$

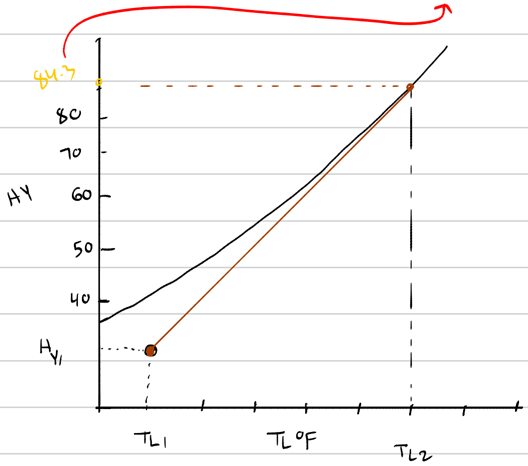
$H_{y_1} = 30.8$

a- G_{min}?

$G_{min}(H_{y_2} - H_{y_1}) = L c_L \times (T_{L_2} - T_{L_1})$

$G_{min} \times (84.3 - 30.8) = 2000 \times (1)(110 - 85)$

$G_{min} = 935.7 \frac{lbm}{h \cdot ft^2}$



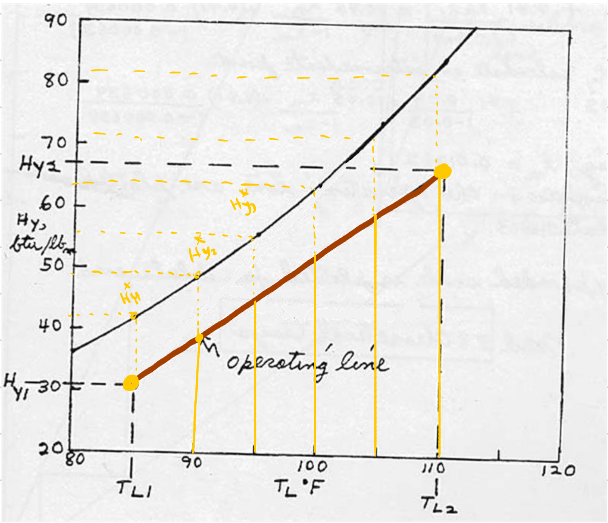
if $G = 1400 \rightarrow Z$?

① H_{y_2}

$1400(H_{y_2} - H_{y_1}) = 2000 \times 1 \times (110 - 85)$

$H_{y_2} = 66.5$

Hy	Hy^*	$Hy^* - Hy_1$	$1/Hy^* - Hy_1$
30.8	41.8	11	0.091
38	48	10	0.1
45.2	55.3	10.1	0.099
52.4	63.7	11.3	0.0884
59.5	73.6	14.1	0.071
66.7	84.5	19.8	0.056



$$\frac{[66.7 - 30.8]}{5 \times 2}\left[0.0908 + 0.05262 + 2[0.1 + 0.099 + 0.0885 + 0.07]\right]$$

$= \underline{3.08}$

$$Z = \frac{1400}{29 \times 1 \times (6.9)} \times 3.08$$

$\downarrow$ M $\quad \downarrow$ P $\quad \downarrow$ $K_G \cdot a$

$Z = 21.6m$

23.1-3. ***Use of the Humidity Chart.*** The air entering a dryer has a temperature of 65.6°C (150°F) and a dew point of 15.6°C (60°F). Using the humidity chart, determine the actual humidity and percentage humidity. Calculate the humid volume of this mixture and also calculate c_S using SI and English units.

Ans. $H = 0.0113$ kg H_2O/kg dry air, $H_P = 5.3\%$, $c_S = 1.026$ kJ/kg · K (0.245 btu/lb$_m$ °F), $\upsilon H = 0.976$ m^3 air + water vapor/kg dry air

$T = 65.6°C$

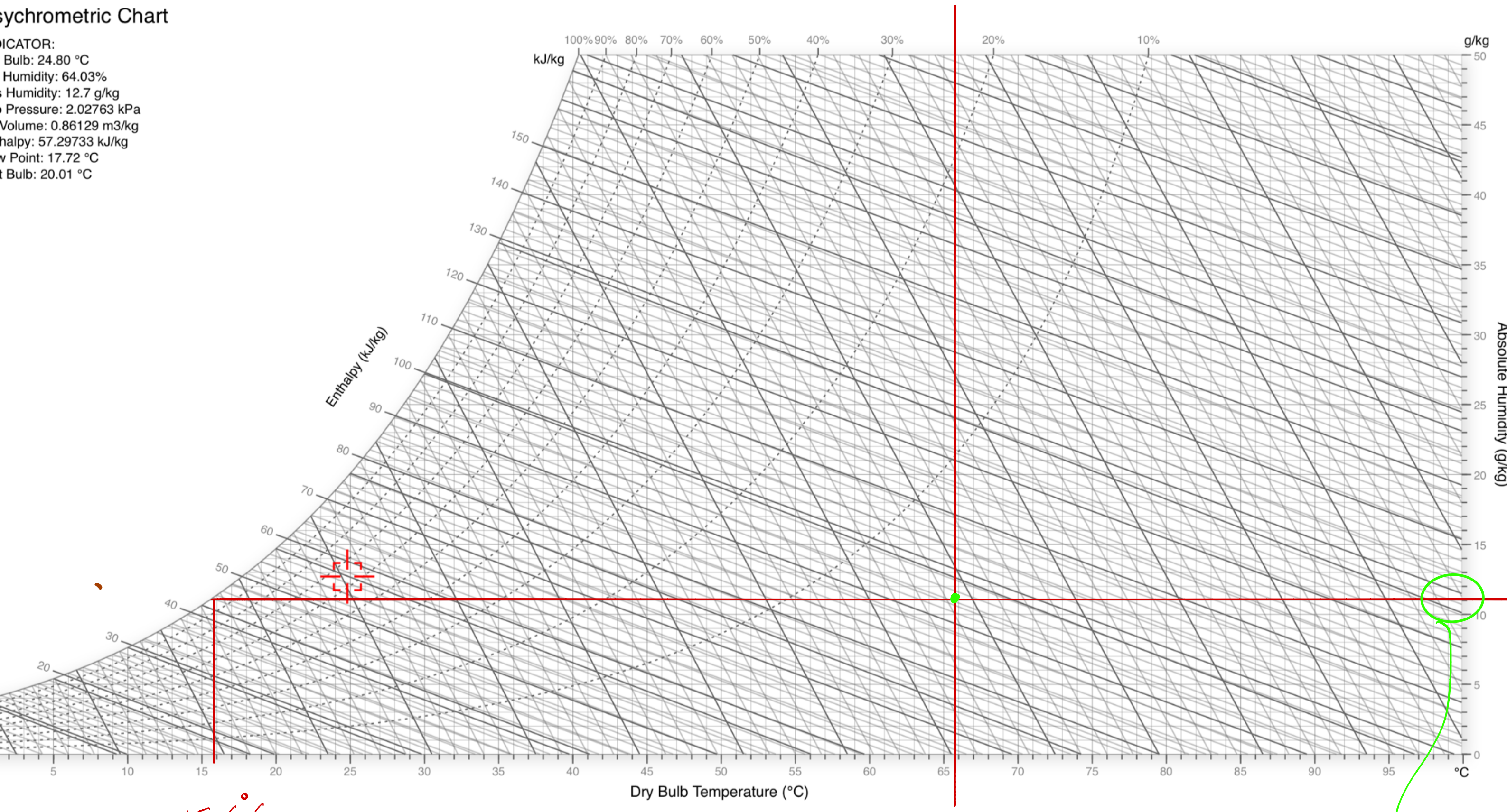
$T_{DP} = 15.6°C$

$H = ?$ ✓

$H_p = ?$ ✓

$\nu_H = ?$ ✓

$c_s = ?$



15.6°C

Dew point.

H_p : less than 10%

so by calculation :- $H/H_s \rightarrow ?$ ✓

$$H_s = \frac{P_s}{P - P_s} \cdot 622$$

$$P_s = 25.78 \rightarrow \frac{25.78}{101.3 - 25.78} \cdot 622 \times 100$$

$$= 0.212$$

$$H_p = \frac{0.011}{0.212} \times 100 = 5.2\ \%$$

$H = 0.011 \,\text{kg}_{H_2O}/\text{kg}_{\text{Dry Air}}$

$$H_r = \frac{P_A}{P_{AS}} = \frac{1.76}{25.78}$$

no V_H on chart so by calculation :-

$$v_H = (2.83 \times 10^{-3} + 4.56 \times 10^{-3} \times H)\, T$$

$$= (2.83 \times 10^{-3} + 4.56 \times 10^{-3} \times 0.011)(656 + 273.15)$$

$$v_H = 0.9756$$

$$C_s = 1.005 + 1.88 H$$

$$1.005 + 1.88 \times 0.011$$

$$= 1.026$$

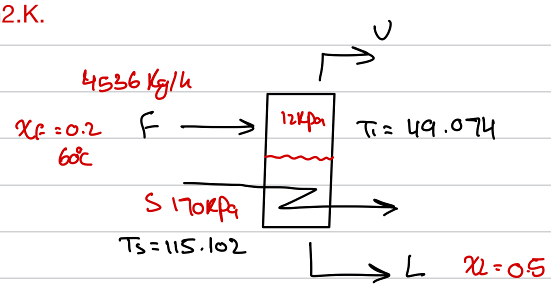
3-Evaporation

Exercise

Repeat Example 8.4.3 assuming that the thermal properties of the liquid in the evaporator can be approximated by those of water.

An evaporator is used to concentrate 4536 kg/h of a 20% NaOH solution entering at 60°C to a product of 50% solids.

The pressure of the saturated steam used is 170 kPa and the vapor space pressure of the evaporator is at 12 kPa. The overall coefficient U is 1560 W/m2.K.



$U = 1560$

$F = 4536$

$L = 1814\,4$

$V = 2721.6$

$S = 2834.51$

$h_F = 251.42$

$h_L = 205.462$

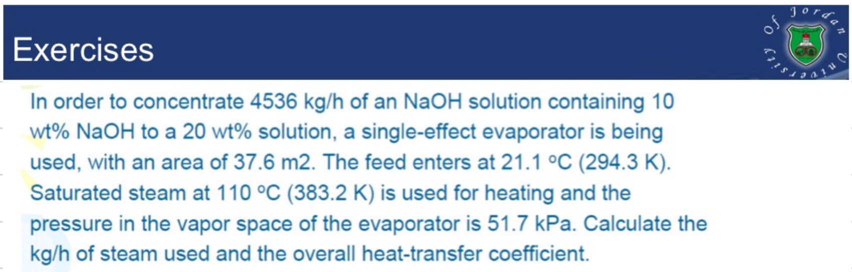
$H_v = 2589.66$

$\lambda_s = 2\,215.68$

$\lambda . S = 1744.55$ KW

$$A = \frac{\lambda . S}{U(T_s - T_i)} = \frac{1744.55}{\frac{1560}{1000} \cdot 66} = 16.9 m^2$$

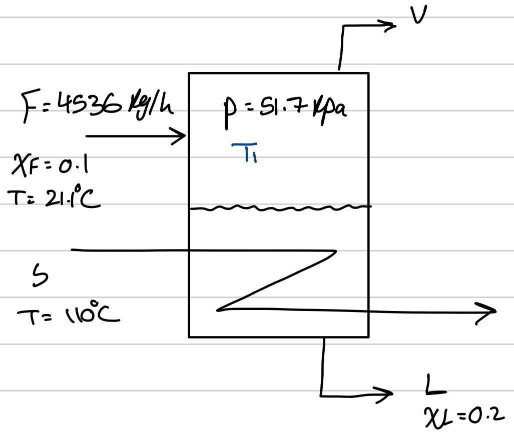
$$\text{Economy} = V/S = \frac{2721.6}{2834.51} = 0.96$$



Exercises

In order to concentrate 4536 kg/h of an NaOH solution containing 10 wt% NaOH to a 20 wt% solution, a single-effect evaporator is being used, with an area of 37.6 m2. The feed enters at 21.1 °C (294.3 K). Saturated steam at 110 °C (383.2 K) is used for heating and the pressure in the vapor space of the evaporator is 51.7 kPa. Calculate the kg/h of steam used and the overall heat-transfer coefficient.

Geankoplis 32.4-8



$A = 37.6\ m^2$

S? U?

$F\,x_F = L\,x_L$

$L = 2268$

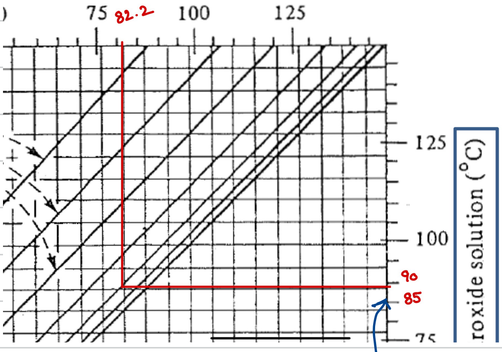
$F = V + L$

$V = 2268$ kg/h

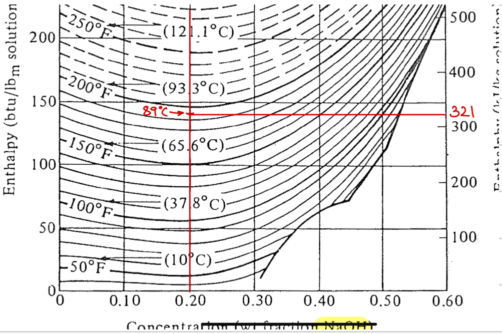
$$S\lambda_s = L\overset{1}{h_L} + V\overset{2}{H_V} - F\overset{3}{h_F}$$

① at 51.7 kPa

$P = 51.7 \rightarrow T = 82.2°C$



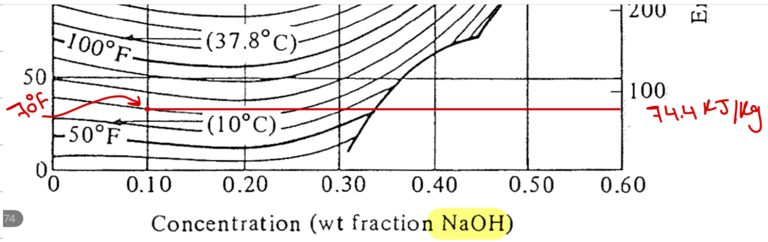
$T_1 \rightarrow$ Boiling point of solution $= 88.9°C$



$h_L = 321$ kJ/kg ✓

② $H_V \rightarrow$ Sat-table @ 88.9°C $\rightarrow$ 2657.68 kJ/kg ✓

③ $h_F \rightarrow$



$h_F = 74.4$ kJ/kg ✓

λ_s : from Steam Tables @ 110°C

$\lambda_s = 2230$ kJ/kg

$S\lambda_s = 2268(321) + 2268(2657.68) - 4536(74.4)$

$= \frac{6418167.84}{3600}$ kJ/h

$\boxed{= 1782.82\ kW}$

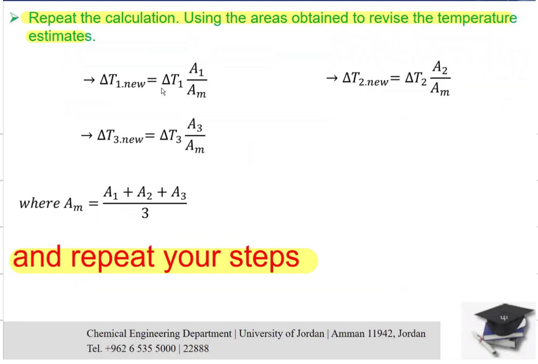
$S = \frac{6418167.84}{2230} = 2878.1$

$U = \frac{\lambda S}{A \times (T_s - T_1)}$

$U = \frac{1782.82}{37.6 \times (110 - 88.9)}$

$= 2.2471\ \frac{kW}{m^2.K} = 2247.1\ \frac{W}{m^2.K}$

HW


- Repeat the calculation. Using the areas obtained to revise the temperature estimates.

$\rightarrow \Delta T_{1.new} = \Delta T_1 \frac{A_1}{A_m}$ $\rightarrow \Delta T_{2.new} = \Delta T_2 \frac{A_2}{A_m}$

$\rightarrow \Delta T_{3.new} = \Delta T_3 \frac{A_3}{A_m}$

$where\ A_m = \frac{A_1 + A_2 + A_3}{3}$

and repeat your steps

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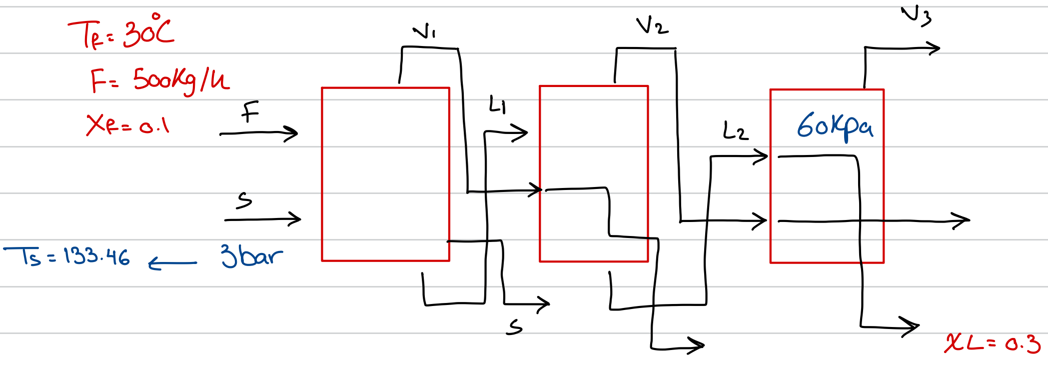
Tel. +962 6 535 5000 | 22888



$U_1 = 2270$
$U_2 = 2000$
$U_3 = 1420$

$F x_F = L x_L$

$L = 166.67$ Kg/h , $\Sigma V = 500 - 166.67 = 333.33$ Kg/h

60Kpa → $T_3 = 85.86°C$

$T_3 = 102$, $\Sigma T = T_s - T_3 = 30.46$

$T_s = 133.46$

$\Delta T_1 = \frac{\Sigma T}{1 + \frac{U_1}{U_2} + \frac{U_1}{U_3}} = 8.15$

$T_1 = 125.3$

$\Delta T_2 = \frac{U_1}{U_2} \Delta T_1 = T_1 - T_2$

$T_2 = 116.05$

$T_3 = 103$
Temp of Solution

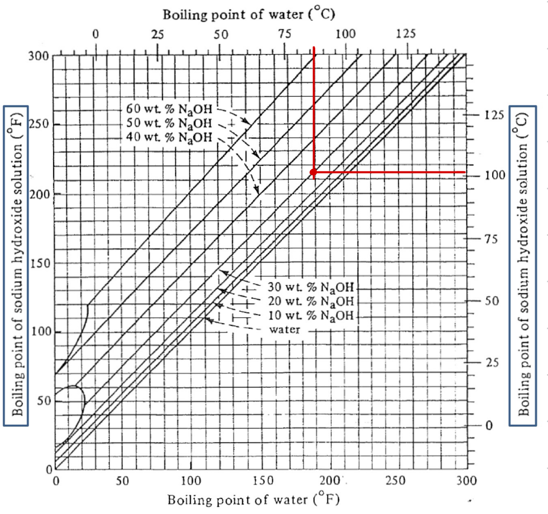


FIGURE 8.4-2. *Dühring lines for aqueous solutions of sodium hydroxide.*

① $S \times \lambda_s + F h_F = L_1 h_L + V_1 H_{V_1}$

⑤ $L_1 = 500 - V_1$

⑥ $L_2 = 500 - V_1 - V_2$

② $L_1 h_L + V_1 \lambda_{H_1} = V_2 H_2 + L_2 h_{L_2}$

③ $L_2 h_{L_2} + V_2 \lambda_{H_2} = V_3 H_3 + L_3 h_{L_3}$

L_3 ✓

④ $V_1 + V_2 + V_3 = 333.33$ Kg/h

Assume $V_1 = V_2 = V_3 = 111.11$

$X_1 = 0.13$ $X_2 = 0.18$

$X_3 = 0.3$

$S_o = 192.47$ Kg/h
$V_1 = 110.21$ Kg/h
$V_2 = 112.92$ Kg/h
$V_3 = 110.2$ Kg/h
$L_1 = 389.79$ Kg/h
$L_2 = 276.87$ Kg/h

$X_1 = 0.128$ $X_2 = 0.18$
$X_3 = 0.3$

$A_1 = 6.198\ m^2$ $A_2 = 3.62\ m^2$ $A_3 = 3.74\ m^2$

From steam Tables

$\lambda_s = 2163.59$

$\lambda_{H_1} = 2187.236$, $\lambda_{H_2} = 2213.08$

$H_{V_1} = 2713.52$ $H_{V_3} = 2680.28$

$H_{V_2} = 2700.154$

From chart :-

h_F : 120 KJ/Kg
h_{L_1} : 455 KJ/Kg
h_{L_2} : 410 KJ/Kg
h_{L_3} : 400 KJ/Kg

2nd iteration

$$A_m = \frac{A_1 + A_2 + A_3}{3} \longrightarrow \frac{6.198 m^2 + 3.62 m^2 + 3.74 m^2}{3}$$

$$= 4.519 m^2$$

$$\Delta T_{1new} = \Delta T_1 \frac{A_1}{A_m} \qquad \Delta T_{2new} = \Delta T_2 \frac{A_2}{A_m} \qquad \Delta T_{3new} = \Delta T_3 \frac{A_3}{A_m}$$

$$= 8.15 \times \frac{6.198}{4.519} \qquad = 9.25 \times \frac{3.62}{4.519} \qquad = 13.05 \times \frac{3.74}{4.519}$$

$$= 11.178 \qquad = 7.41 \qquad = 10.8 \quad = T_2 - T_3$$

$$= T_1 - T_2 \qquad T_2 = 113.8°$$

$$T_1 = 121.21°$$

$$h_{L1} (\overset{x}{0.128}, \overset{T}{121.21}) = 445 \qquad \lambda_s = 2163.59 \qquad \lambda_{HV1} : 2198.74$$

$$h_F = 120 \qquad \lambda_{HV2} : 2219.28$$

$$h_{L2} (\overset{x}{0.18}, \overset{T}{113.8}) = 410$$

$$H_{V1} = 2707.72 \qquad H_{V3} = 2680.28$$

$$h_{L3} (\overset{x}{0.3}, \overset{T}{103}) = 400 \qquad H_{V2} = 2696.8$$

① $S \times \lambda_s + F h_F = L_1 h_L + V_1 H_{V1}$

② $L_1 h_L + V_1 \lambda_{H1} = V_2 H_2 + L_2 h_{L2}$

③ $L_2 h_{L2} + V_2 \lambda_{H2} = V_3 H_3 + L_3 h_{L3}$

L_3 ✓

④ $V_1 + V_2 + V_3 = 333.33$ kg/h

⑤ $L_1 = 500 - V_1$

⑥ $L_2 = 500 - V_1 - V_2$

$S = 191.318$ $V_1 = 109.39$ $V_2 = 112.868$ $V_3 = 111.067$ $L_1 = 390.61$ $L_2 = 277.742$

$$x_1 = \frac{x_F . F}{F - V_1} \qquad x_2 = \frac{x_F . F}{F - V_1 - V_2} \qquad x_3 = \frac{x_F . F}{F - V_1 - V_2 - V_3}$$

$$x_1 = 0.128 \qquad x_2 = 0.18 \qquad x_3 = 0.3$$

$$A_1 = \frac{S \lambda_s}{U_1 \Delta T_1} \qquad A_2 = \frac{V_1 \lambda H_1}{U_2 \Delta T_2} \qquad A_3 = \frac{V_2 \lambda H_2}{U_3 \Delta T_3}$$

$$= 4\,52 m^2 \qquad = 4.5 m^2 \qquad = 4.53 m^2$$

2.4-5. ***Boiling-Point Rise of NaOH Solutions.*** Determine the boiling temperature of the solution and the boiling-point rise for the following cases:

a. A 30% NaOH solution boiling in an evaporator at a pressure of 172.4 kPa (25 psia)

b. A 60% NaOH solution boiling in an evaporator at a pressure of 3.45 kPa (0.50 psia)

Ans. (a) Boiling point = 130.6°C, boiling-point rise = 15°C

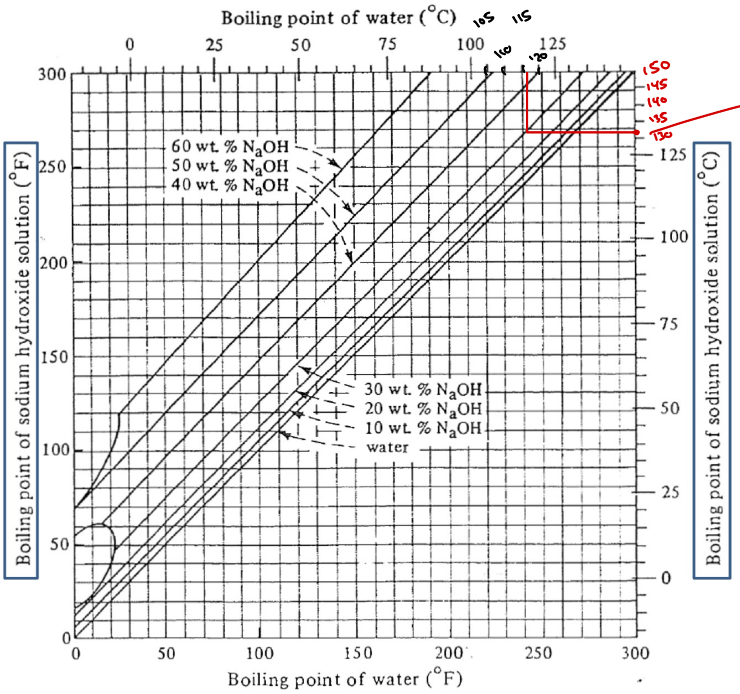


FIGURE 8.4-2. *Dühring lines for aqueous solutions of sodium hydroxide.*

a- 172.4 Kpa → from Steam Tables

T= 115.55°C

T= 131°C

Bp rise = 131 − 115.55

= 15.4°C ✓

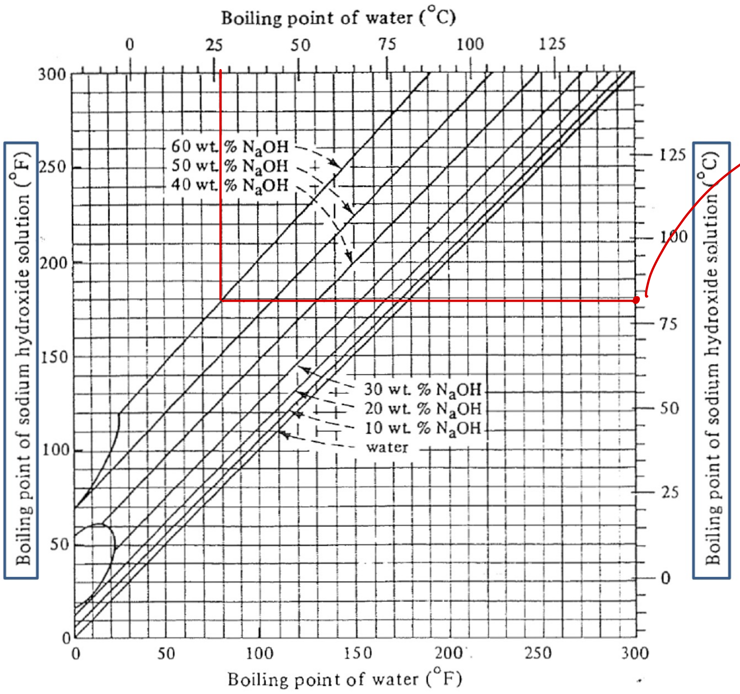


FIGURE 8.4-2. *Dühring lines for aqueous solutions of sodium hydroxide.*

b- 3.45 Kpa → from Steam Tables

T= 26.276°C

T= 82°C

Bp rise = 82−26.276

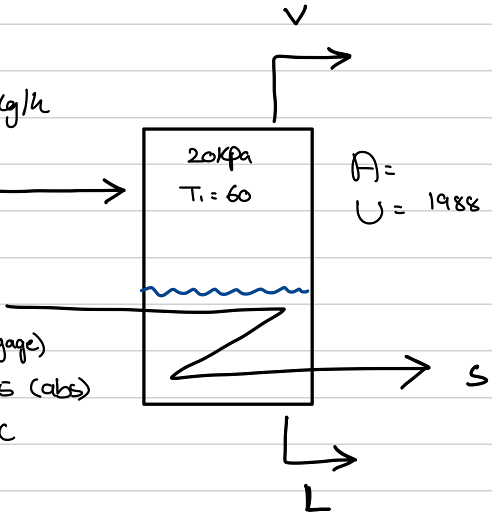
= 55.724°C ✓

2.4-7. ***Effect of Feed Temperature on Evaporating an NaOH Solution.*** A single-effect evaporator is concentrating a feed of 9072 kg/h of a 10 wt % solution of NaOH in water to a product of 50% solids. The pressure of the saturated steam used is 42 kPa (gage) and the pressure in the vapor space of the evaporator is 20 kPa (abs). The overall heat-transfer coefficient is 1988 W/m^2 · K. Calculate the steam used, the steam economy in kg vaporized/kg steam, and the area for the following feed conditions:

a. Feed temperature of 288.8 K (15.6°C)
b. Feed temperature of 322.1 K (48.9°C)

Ans. (a) S = 8959 kg/h of steam, A = 296.9 m^2

$S = ?$ $A = ?$



$F = 9072$ kg/h

$x_F = 10\%$

a- $T = 15.6°C$

S

$p = 42$ kPa (gage)

$p = 42 + 101.325$ (abs)

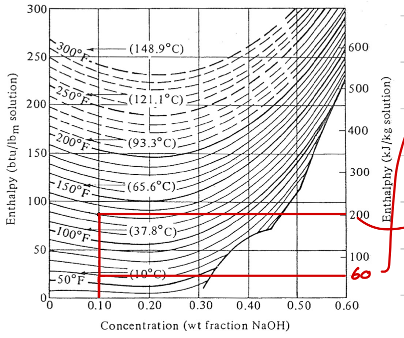
$T_s = 109\ 91°C$

$A =$

$U = 1988$

$X_L = 50\%$

①



$h_f : 60$ @ 15.6 - a

$h_f : 200$ @ 48.9 - b

@ 50% $T = 60.06°C$

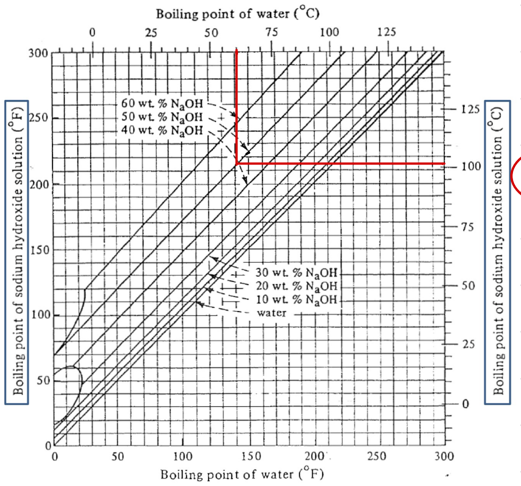
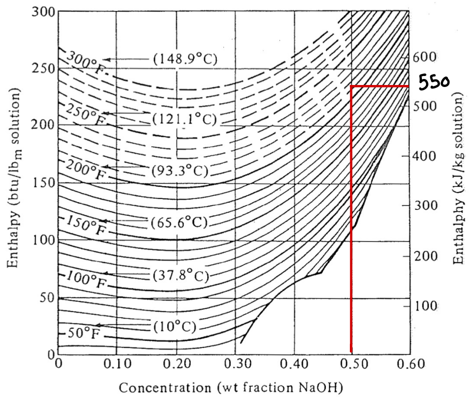


FIGURE 8.4-2. *Dühring lines for aqueous solutions of sodium hydroxide.*

Solution Temp

100.5°



Hv

@ 100.5°C

+ 20 kPa

= 2690.068

---

a-

$F x_F = L x_L$

$L = 1814\ 4$

$V = 7257.6$

$\lambda_s = 2229.9$

$S\lambda_s = Lh_L + VH_V - Fh_F$

$S(22299) = 1814.4(550) + 7257.6(2690.1) - 9072(60)$

$S = 8958.71$ ✓

$$A = \frac{8958 \times 2229.9}{1988 \times (109.91 - 100.5)} \times \frac{1000}{3600} = 296.6\,m^2$$ ✓

---

b -

$S\lambda_s = Lh_L + VH_V - Fh_F$

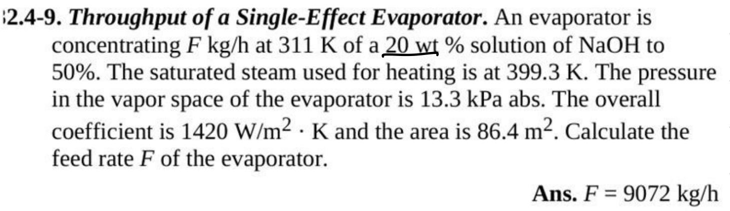
$S(22299) = 1814.4(550) + 7257.6(2690.1) - 9072(200)$

$S = 8389.25$ ✓

$A = 277.78\ m^2$ ✓

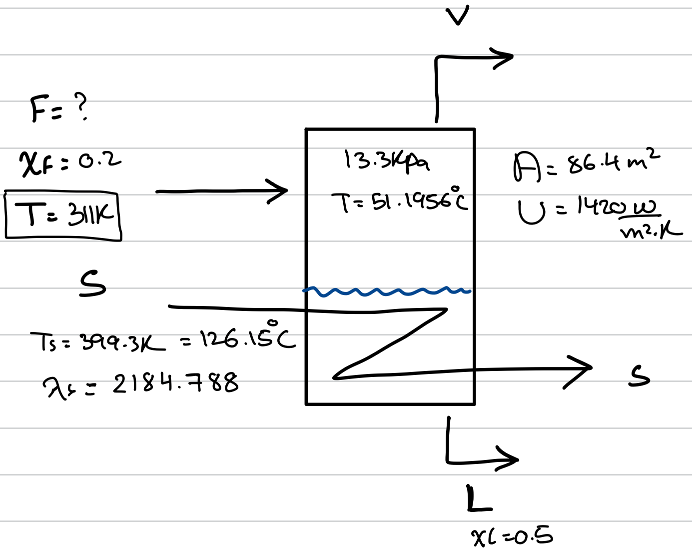
Feed Temp ↑

We need Less Area



2.4-9. ***Throughput of a Single-Effect Evaporator.*** An evaporator is concentrating F kg/h at 311 K of a 20 wt % solution of NaOH to 50%. The saturated steam used for heating is at 399.3 K. The pressure in the vapor space of the evaporator is 13.3 kPa abs. The overall coefficient is 1420 W/m^2 · K and the area is 86.4 m^2. Calculate the feed rate F of the evaporator.

Ans. F = 9072 kg/h



$$F(0.2) = L(0.5)$$

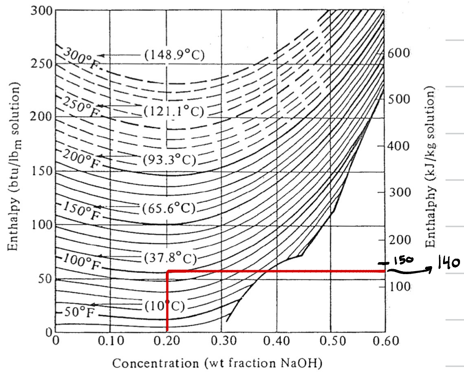
$$L = \frac{0.2}{0.5} \cdot F \quad \#$$

$$\lambda S = U \times A \times \Delta T$$

$$\underset{(T_S - T_i)}{UA\Delta T} = -Fh_f + Lh_L + VH_V$$

$$UA\Delta T = F(H_V - h_f) + L(h_L - H_V)$$

① $h_f = 130$



② Bp rise @ 51.2°C , 0.5

h_L = 520 kJ/kg

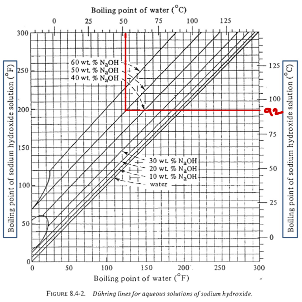
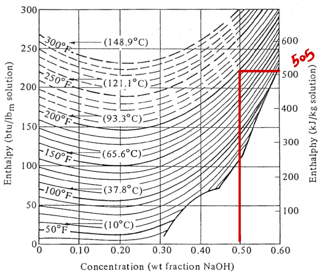


FIGURE 8.4-2. *Dühring lines for aqueous solutions of sodium hydroxide.*



H_V @ 92°C + 13.3kPa

Superheated table = 2672

UAΔT

$$1420 \times 86.4 \times (126.15 - 92) \times \frac{3600}{1000} =$$

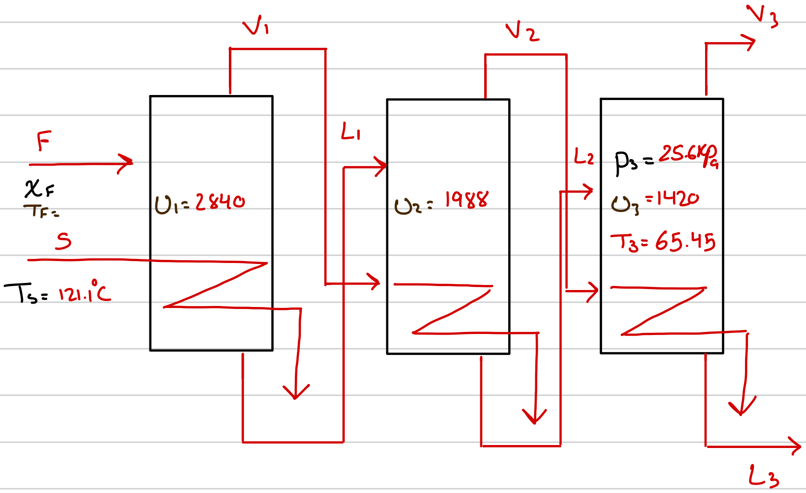
$$= x[\,2662.8 - 140\,] + \frac{0.2}{0.5} \cdot x[505 - 2662.8]$$

$$= 9058 \text{ Kg/h}$$

$$\frac{9072 - 9058}{9072} \times 100 = \text{error } 0.15\%$$

2.5-1. *Boiling Points in a Triple-Effect Evaporator.* A solution with a negligible boiling-point rise is being evaporated in a triple-effect evaporator using saturated steam at 121.1°C (394.3 K). The pressure in the vapor of the last effect is 25.6 kPa abs. The heat-transfer coefficients are $U_1 = 2840$, $U_2 = 1988$, and $U_3 = 1420$ W/m$^2 \cdot$ K, the areas are equal. Estimate the boiling point in each of the evaporators.

Ans. $T_1 = 108.6$°C (381.8 K)



T_1? T_2? T_3?

① $\sum \Delta T = T_S - T_3 = 121.1°C - 65.45$

$= 55.64°C$

$$\Delta T_1 = \frac{\sum \Delta T}{1+\frac{U_1}{U_2}+\frac{U_1}{U_3}} = \frac{55.64}{1+\frac{2840}{1988}+\frac{2840}{1420}}$$

$= 12.56 = T_S - T_1$

$T_1 = 108.53$ ✓

② $\Delta T_2 = \frac{2840}{1988} \times 12.56 = 18$

$T_1 - T_2 = 18$

$T_2 = 90.6$ ✓

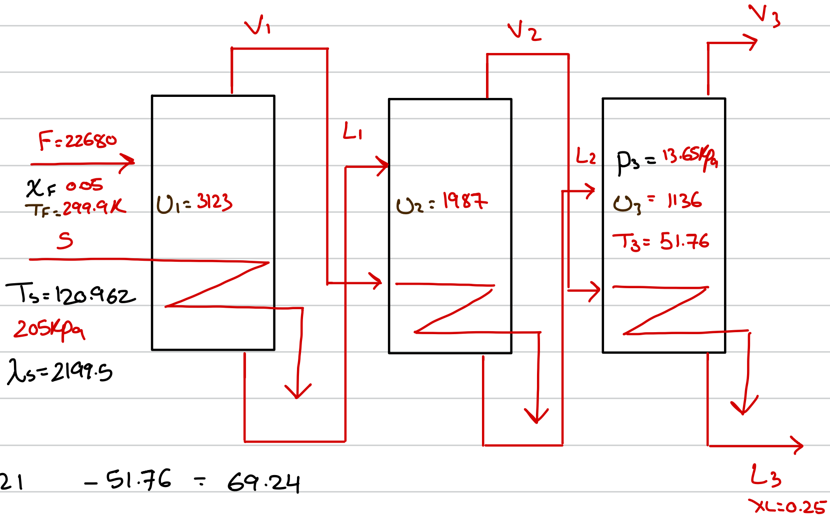
③ $\Delta T_3 = \frac{2840}{1420} \times 12.56 = 25.12$

$T_2 - T_3 = 25.12$

$T_3 = 65.48$ ✓

2.5-2. ***Evaporation of a Sugar Solution in a Multiple-Effect Evaporator.*** A triple-effect evaporator with forward feed is evaporating a sugar solution with negligible boiling-point rise (less than 1.0 K, which will be neglected) and containing 5 wt % solids to 25% solids. Saturated steam at 205 kPa abs is being used. The pressure in the vapor space of the third effect is 13.65 kPa. The feed rate is 22 680 kg/h and the temperature 299.9 K. The liquid heat capacity is $c_p = 4.19 - 2.35x$, where c_p is in kJ/kg · K and x in wt fraction (K1). The heat-transfer coefficients are $U_1 = 3123$, $U_2 = 1987$, and $U_3 = 1136$ W/m^2 · K.

Calculate the surface area of each effect if each effect has the same area, and the steam rate.



$cp = 4.19 - 2.35x$

A? S?

$\Sigma\Delta T = T_s - T_3 = 121 - 51.76 = 69.24$

$F x_F = L x_L$

$22680(0.05) = L(0.25)$

$L = 4536$

$\Delta T_1 = \dfrac{\Sigma \Delta T}{1+\frac{U_1}{U_2}+\frac{U_1}{U_3}} = 13.01 = T_s - T_1$

$T_1 = 107.98$

$\Delta T_2 = \Delta T_1 \times \frac{U_1}{U_2} = 20.44 = T_1 - T_2 \rightsquigarrow T_2 = 87.53$

$\lambda_{T_1} = 2236.145$

$\lambda_{T_2} = 2288.8$

$\lambda_{T_3} = 2377.65$

$V_1 + V_2 + V_3 = 18144$

Assume $V_1 = V_2 = V_3$

6048

$\hookrightarrow x_1 = 0.068$ $cpF = 4.07$

$\hookrightarrow x_2 = 0.107$ $cp = 4.0302$

$\hookrightarrow x_3 = 0.25$ $cp = 3.94$

① $\overset{?}{S}\lambda_s = F cpF(T_1 - T_F) + \overset{?}{V_1}\lambda_{V_1}$

② $\overset{?}{V_1}\lambda_1 = L_1 cp_1(T_2 - T_1) + \overset{?}{V_2}\lambda_{V_2}$

③ $\overset{?}{V_2}\lambda_2 = \overset{?}{L_2} cp_2(T_3 - T_2) + V_3 \lambda_{V_3}$

④ $V_1 + V_2 + V_3 = 18144$

S? V_1? V_2? V_3?

$L_3 = 4536$

$\boxed{V_3 = L_2 - L_3}$

$L_2 = V_3 - L_3$

$V_2 = L_1 - L_2$

$V_1 = F - L_1$

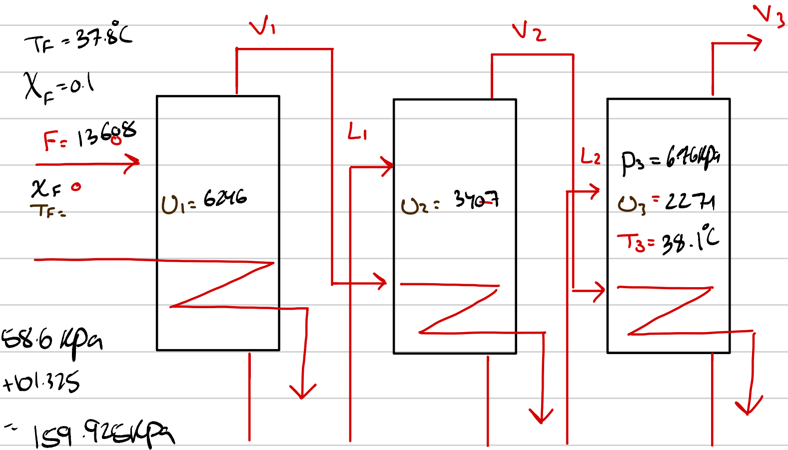
$L_1 = F - V_1$

6 Equations 6 unknowns ✓

might need 2nd? iteration

12.5-4. *Concentration of NaOH Solution in a Triple-Effect Evaporator.* A forced-circulation triple-effect evaporator using forward feed is to be used to concentrate a 10 wt % NaOH solution entering at 37.8°C to 50%. The steam used enters at 58.6 kPa gage. The absolute pressure in the vapor space of the third effect is 6.76 kPa. The feed rate is 13 608 kg/h. The heat-transfer coefficients are $U_1 = 6246$, $U_2 = 3407$, and $U_3 = 2271$ W/m$^2 \cdot$ K. All effects have the same area. Calculate the surface area and steam consumption.

Ans. $A = 97.3$ m^2, $S = 5284$ kg steam/h



① No BPRise

S

p: 58.6 kPa

+101.325

= 159.925kPa

T_S= 113.2°C

$X_L = 0.5$

$\Sigma \Delta T = T_S - T_3$

$= 75.11$

$$\Delta T_1 = \frac{75.11}{1 + \frac{U_1}{U_2} + \frac{U_1}{U_3}}$$

$\Delta T_1 = 13.45$

$= T_S - T_1$

$T_1 = 99.7°C$

$F x_F = L x_L$

$L_3 = 2721.6$

$V_1 + V_2 + V_3 = 10886.4$ ✳

$\Delta T_2 = \Delta T_1 \times \frac{U_1}{U_2}$

$\Delta T_2 = 24.657$

$T_2 = 75.04$

$\Delta T_3 = 36.94$

$T_3 = 38.1°C$

$S\lambda_S = V\lambda_1$ ×

$V\lambda_1 = V_2\lambda_2$ ×

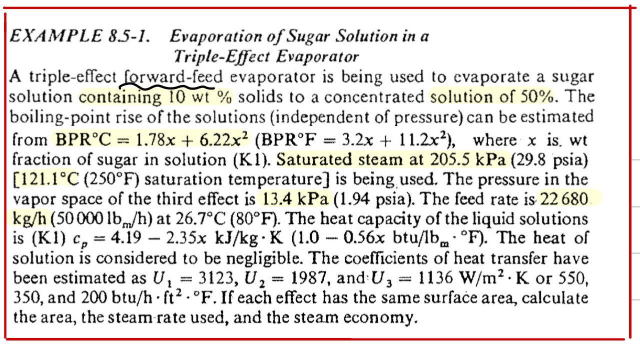
$V_2\lambda_2 = V_3\lambda_3$ ×

$\lambda_S = 2220.9$

$\lambda_1 = 2257.25$

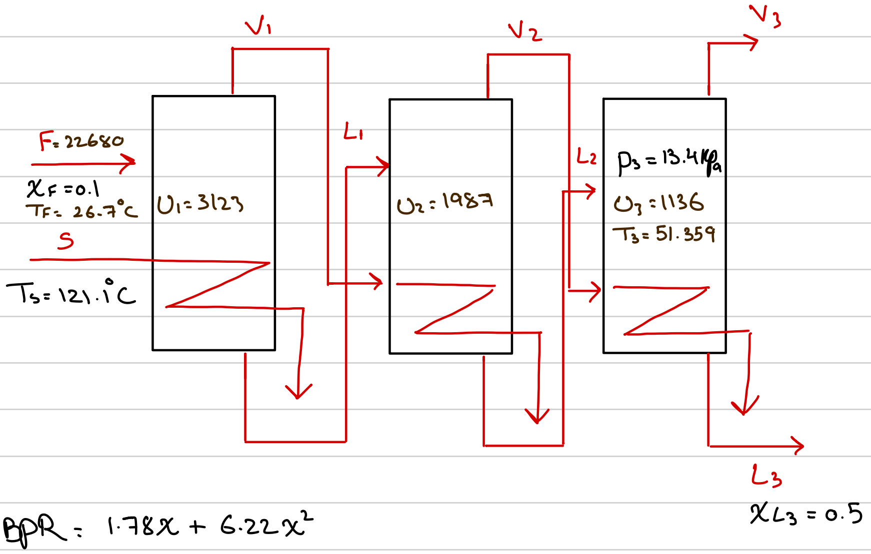
$\lambda_2 = 2320.44$

$\lambda_3 = 2410.52$



EXAMPLE 8.5-1. Evaporation of Sugar Solution in a Triple-Effect Evaporator

A triple-effect forward-feed evaporator is being used to evaporate a sugar solution containing 10 wt % solids to a concentrated solution of 50%. The boiling-point rise of the solutions (independent of pressure) can be estimated from BPR°C = $1.78x + 6.22x^2$ (BPR°F = $3.2x + 11.2x^2$), where x is wt fraction of sugar in solution (K1). Saturated steam at 205.5 kPa (29.8 psia) [121.1°C (250°F) saturation temperature] is being used. The pressure in the vapor space of the third effect is 13.4 kPa (1.94 psia). The feed rate is 22 680 kg/h (50 000 lb_m/h) at 26.7°C (80°F). The heat capacity of the liquid solutions is (K1) $c_p = 4.19 - 2.35x$ kJ/kg · K (1.0 − 0.56x btu/lb_m · °F). The heat of solution is considered to be negligible. The coefficients of heat transfer have been estimated as $U_1 = 3123$, $U_2 = 1987$, and $U_3 = 1136$ W/m² · K or 550, 350, and 200 btu/h · ft² · °F. If each effect has the same surface area, calculate the area, the steam rate used, and the steam economy.



$$BPR = 1.78(0.5) + 6.22(0.5)^2 = 2.445$$

$$T_3 = 2.45 + 51.67$$
$$= 54.12°C$$

* $T_S - T_3 = \sum \Delta T = 121.1 - 54.12 = 66.98$

$$\Delta T_1 = \frac{\sum \Delta T}{1 + \frac{U_1}{U_2} + \frac{U_1}{U_3}} = \frac{66.98}{1 + \frac{3123}{1987} + \frac{3123}{1136}} = 12.6$$

$$= T_S - T_1$$

$$T_1 = 108.5$$

$$\Delta T_2 = \frac{U_1}{U_2} \Delta T_1 = \frac{3123}{1987} (12.6 \quad) = 19.8$$

$$T_1 - T_2 = 19.8$$

$$T_2 = 88.7$$

- $BPR = 1.78x + 6.22x^2$
- $cp = 4.19 - 2.35x$
- $A_1 = A_2 = A_3 = ?$
- $S?$ Economy?

$cp = 4.19 - 2.35x$

$F x_F = L x_L$

$L_3 = 4536$

$V_1 + V_2 + V_3 = 18144$ ①

Assume $V_1 = V_2 = V_3$

$V = 6048$
$\to x_1 = 0.136$
$\to x_2 = 0.214$
$\to x_3 = 0.5$

$cp_F = 3.955$
$cp = 3.87$
$cp = 3.68$

$$S\lambda = F cp_F (T_1 - T_F) + V_1 \lambda_1$$
$$V_1 \lambda_1 = L_1 cp_1 (T_2 - T_1) + V_2 \lambda_2$$
$$V_2 \lambda_2 = L_2 Cp_2 (T_3 - T_2) + V_3 \lambda_3$$

$L_1 = F - V_1$ ⑤
$L_2 = F - V_1 - V_2$ ⑥

* 6 unknowns 6 equations ✓

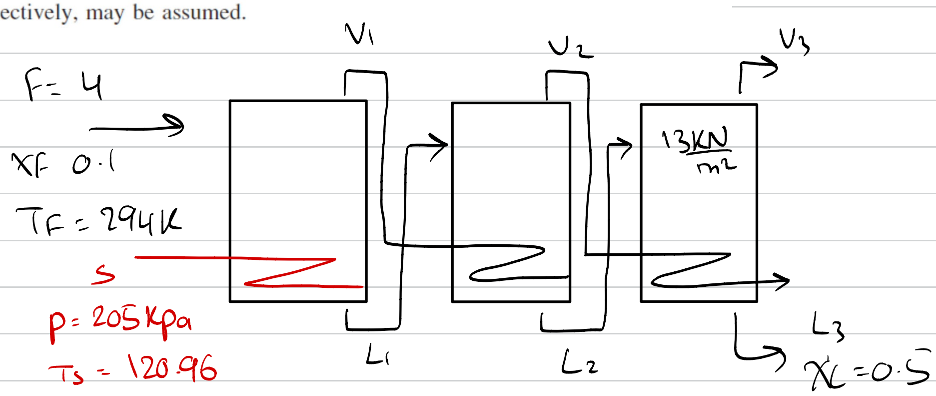
$\to$ V_1 ✓ V_2 ✓ V_3 ✓
L_1 ✓ L_2 ✓ S ✓

$$\text{Economy} = \frac{V}{S}$$

Exercise

4 kg/s (14.4 tonne/hour) of a liquor containing 10 per cent solids is fed at 294 K to the first effect of a triple-effect unit. Liquor with 50 per cent solids is to be withdrawn from the third effect, which is at a pressure of 13 kN/m^2 (~0.13 bar). The liquor may be assumed to have a specific heat of 4.18 kJ/kg K and to have no boiling point rise. Saturated dry steam at 205 kN/m^2 is fed to the heating element of the first effect, and the condensate is removed at the steam temperature in each effect as shown

If the three units are to have equal areas, estimate the area, the temperature differences and the steam consumption. Heat transfer coefficients of 3.1, 2.0 and 1.1 kW/m^2 K for the first, second, and third effects respectively, may be assumed.



$p = 205$ Kpa

$T_s = 120.96$

$\lambda_s = 2199.48$

$c_p = 4.18$

$U_1 = 3100$ W/m^2.K

$U_2 = 2000$ W/m^2.K

$U_3 = 1100$ W/m^2.K

$\Sigma \Delta T = 70K$

① $T_3 = 50.706$

$\Delta T_1 = 13.08$ $T_1 = 107.88$

$\Delta T_2 = 20.274$ $T_2 = 87.606$

$\Delta T_3 = 36.86$ $T_3 = 50.746$

$\lambda_s ? = 2199.48$

$\lambda_1 ? = 2380.3$

$\lambda_2 ? = 2288.6$

$\lambda_3 ? = 2235.38$

$$\lambda_s S = F c_p (T_1 - T_F) + V_1 \lambda_1$$

$$V_1 \lambda_1 = \overset{(F-V_1)}{L_1} c_p (T_2 - T_1) + V_2 \lambda_2$$

$$V_2 \lambda_2 = \overset{(F-V_1-V_2)}{L_2} c_p (T_3 - T_2) + V_3 \lambda_3$$

$L_3 = 0.8$

$V_1 + V_2 + V_3 = \boxed{3.2}$

$V_1 = 0.9$ ✓

$V_2 = 1.06$ ✓

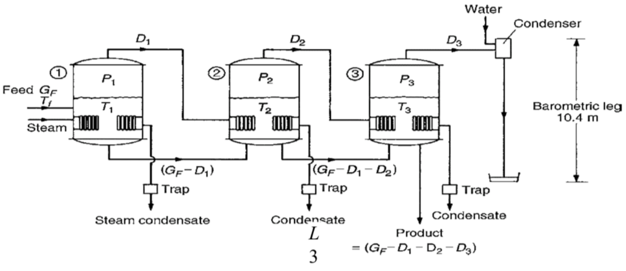
$V_3 = 1.22$ ✓

$S = 1.64$ ✓

$A_1 = 89$ m^2

$A_2 = 52.8$ m^2

$A_3 = 59.83$ m^2



Solution:

$Q1 = Q2 = Q3 \rightarrow U1\ A1\ \Delta T1 = U2\ A2\ \Delta T2 = U3\ A3\ \Delta T3$ ....(1)

But the areas are equal i.e. $U1\ \Delta T1 = U2\ \Delta T2 = U3\ \Delta T3$ ....(2)

From steam table at 205 kN/m2 the temp. To = 394 K and at 13 kN/m2 the temp. $T3$ = 325 K

So the total temp. difference $\sum \Delta T = \Delta T1 + \Delta T2 + \Delta T3 = 394 - 325 = 69$ K

$$\therefore \frac{U_2}{U_1}\Delta T_2 + \Delta T_2 + \frac{U_2}{U_3}\Delta T_2 = 69 \rightarrow \Delta T_2 = 20 \text{ K},$$

From Eq. 2 → $\Delta T1$ = 13 K & $\Delta T3$ = 36 K

Since the feed is cold, it will be necessary to have a greater value of $\Delta T1$ than given by this analysis.

It will be assumed that $\Delta T1$ = 18 K, $\Delta T2$ = 17 K, $\Delta T3$ = 34 K.

If the latent heats are given by λo, $\lambda 1$, $\lambda 2$ and $\lambda 3$, then from the Steam Tables in the Appendix:

For steam to 1: To = 394 K and λo = 2200 kJ/kg
For steam to 2: $T1$ = 376 K and $\lambda 1$ = 2249 kJ/kg
For steam to 3: $T2$ = 359 K and $\lambda 2$ = 2293 kJ/kg
$T3$ = 325 K and $\lambda 3$ = 2377 kJ/kg

Assuming that the condensate leaves at the steam temperature, then heat balances across each effect may be made as follows:

Effect 1: $Do\lambda o = GFCp(T1 - Tf) + D1\lambda 1$,

OR 2200 Do = 4×4.18(376 − 294) + 2249 $D1$

$$\lambda_s S = Fcp\,(T_1 - T_f) + V_1\lambda_1$$

Effect 2: $D1\lambda 1 = (GF - D1)Cp(T2 - T1) + D2\lambda 2$, or

2249 $D1$ = (4 − $D1$)4.18(359 - 376) + 2293 $D2$

$$V_1\lambda_1 = L_1 cp(T_2 - T_1) + V_2\lambda_2$$

Effect 3: $D2\lambda 2 = (GF - D1 - D2)Cp(T3 - T2) + D3\lambda 3$,

OR 2293 $D2$ = (4 − D1 − D2)4.18(325 − 359) + 2377 $D3$

$$V_2\lambda_2 = L_2\, cp\,(T_3 - T_2) + V_3\lambda_3$$

Where GF is the mass flow rate of liquor fed to the system, and Cp is the specific heat capacity of the liquid, which is assumed to be constant.

A material balance over the evaporator is: $GF = (D1 + D2 + D3) + L3$

Solid material balance $0.1 \times GF = 0.5\ L3$

→ $L3$ = 0.8 kg/s & $(D1 + D2 + D3)$ = 3.2 kg/s

Then from the above eqns $D1$= 0.991kg/s ,

$D2$ = 1.065 ,

$D3$ = 1.144kg/s

& Do = 1.635 kg/s

The area of the surface of each effect necessary to transmit the necessary heat under the given temperature difference may then be obtained as: $Q_1 = U_1 A_1 \Delta T_1 = D_o\lambda_o$

$$\rightarrow A_1 = \frac{D_o\lambda_o}{U_1\Delta T_1} = \frac{1.635 \times 2200}{3.1 \times 18} = 64.5\ m^2$$

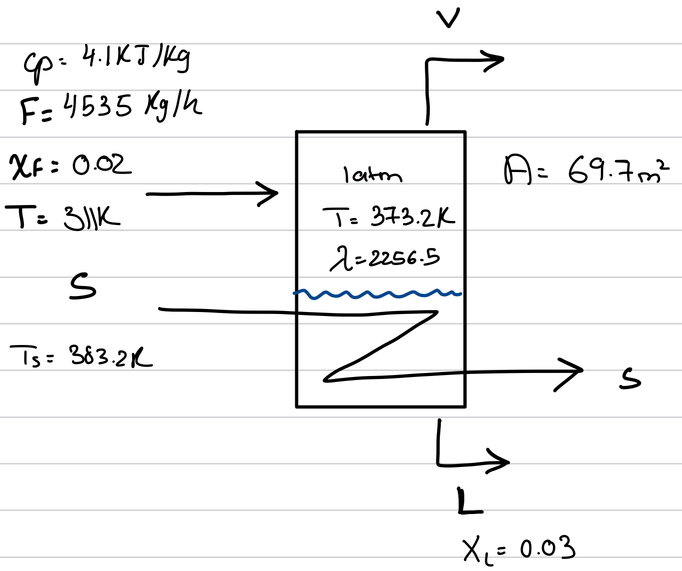
$$A_2 = \frac{D_1\lambda_1}{U_2\Delta T_2} = \frac{0.992 \times 2249}{2 \times 17} = 65.6\ m^2$$

$$A_3 = \frac{D_2\lambda_2}{U_3\Delta T_3} = \frac{1.065 \times 2293}{1.1 \times 34} = 65.3\ m^2$$

Economy = e = $(D_1 + D_2 + D_3)/D_o$ = 3.2/1.635 = 2

2.4-1. *Heat-Transfer Coefficient in a Single-Effect Evaporator*. A feed of 4535 kg/h of a 2.0 wt % salt solution at 311 K enters continuously a single-effect evaporator and is being concentrated to 3.0%. The evaporation is at atmospheric pressure and the area of the evaporator is 69.7 m^2. Saturated steam at 383.2 K is supplied for heating. Since the solution is dilute, it can be assumed to have the same boiling point as water. The heat capacity of the feed can be taken as $c_p = 4.10$ kJ/kg · K. Calculate the amounts of vapor and liquid product, and the overall heat-transfer coefficient U.

Ans. $U = 1823\ W/m^2 \cdot K$



* no Bp Elevation

$$A = \frac{S\lambda_s}{U \times T} \longrightarrow U = \frac{S\lambda_s}{A \times T}$$

①

$F x_F = L x_L$

$4535(0.02) = L(0.03)$

$L = 3023.33$ ✓

$V = 4535 - 3023.33$

$= 1511.66$ kg/h ✓

②

$S\lambda_s + F h_F = L h_L + V H_V$

$S\lambda_s = F c_{pF}(T_1 - T_F) + V\lambda$ kg/h · KJ/kg

$S\lambda_s = 4535 \times 4.1(373.15 - 311) + 1511.66(2256.5)$

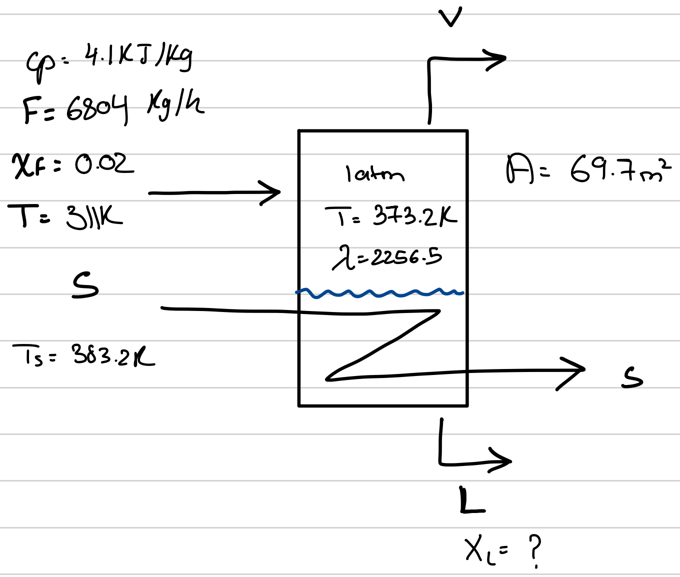
$= 4566089.01$ KJ/h

③

$$U = \frac{4566089.01\ KJ/h}{69.7m^2 \times (383.2 - 373.15)K} = \frac{6518\ KJ}{h \cdot m^2 \cdot K} \times \frac{1000}{3600} = 1810.55\ \frac{W}{m^2 \cdot K}$$ ✓

2.4-2. *Effects of Increased Feed Rate in an Evaporator*. Using the same area, value of U, steam pressure, evaporator pressure, and feed temperature as in Problem 32.4-1, calculate the amounts of liquid and vapor leaving, and the liquid outlet concentration if the feed rate is increased to 6804 kg/h.

Ans. $V = 1256$ kg/h, $L = 5548$ kg/h, $x_L = 2.45\%$



$A = 69.7$

$U = 1810.55$

$L?$

$V?$

$x_L?$

$$\lambda S_{T_s} = F c_p (T_1 - T_F) + V \lambda_{T_1}$$

$$4566089.01 = 6804 \times 4.1 \times (373.15 - 311) + V \cdot 2256.5$$

$$V = 1255.2 \checkmark$$

$$L = 6804 - 1255.2 = 5548.8 \text{ Kg/h} \checkmark$$

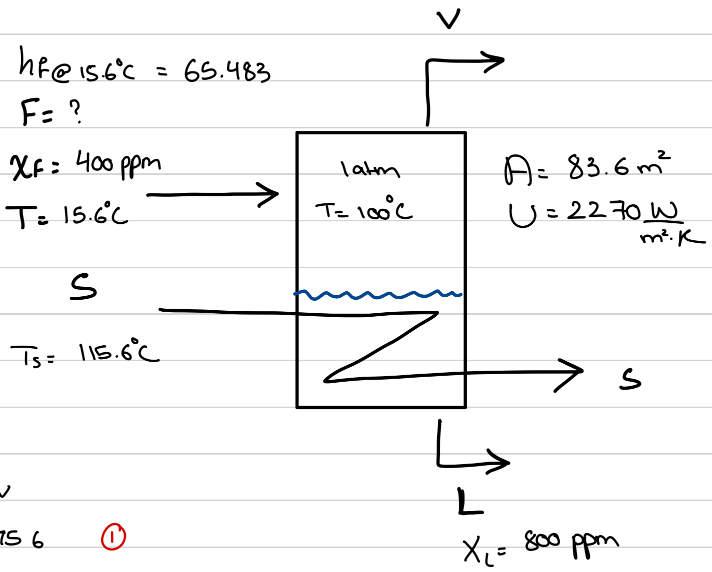
$$F x_F = L x_L$$

$$6804(0.02) = 5548.8\, x_L$$

$$x_L = 0.0245$$

$$= 2.45\% \checkmark$$

2.4-4. *Production of Distilled Water.* An evaporator having an area of 83.6 m^2 and $U = 2270$ W/$m^2 \cdot$ K is used to produce distilled water for a boiler feed. Tap water having 400 ppm dissolved solids at 15.6°C is fed to the evaporator operating at 1 atm pressure abs. Saturated steam at 115.6°C is available for use. Calculate the amount of distilled water produced per hour if the outlet liquid contains 800 ppm solids.



$$\overset{(T_S - T_1)}{\uparrow}$$

$$\lambda . S = U \Delta T . A$$

$$\lambda . S = 2270 \frac{W}{m^2 . K} \times (115.6 - 100) \times 83.6 \times \frac{3600}{1000}$$

$$\lambda . S = 10862549.28 \quad KJ/h = F . h_F + L h_L + V H_V$$

$$10862549.28 = F(65.483) + L(419.06) + (F - L)\ 2675\ 6 \quad ①$$

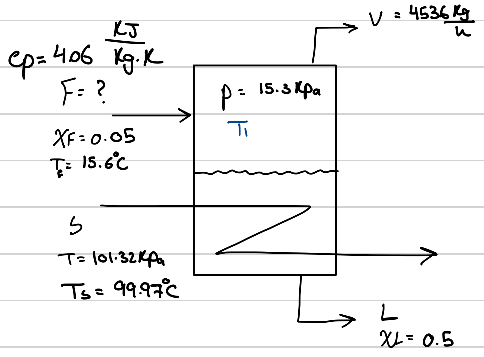
$$F x_F = L x_L$$

$$F(400) - L(800) = 0 \quad ②$$

$$\boxed{\begin{matrix} F = 6735.157 \\ L = 3367.57 \end{matrix}}$$

A single-effect evaporator is concentrating a feed solution of organic colloids from 5 to 50 wt %. The solution has a negligible boiling-point elevation. The heat capacity of the feed is c_p=4.06 kJ/kg.K and the feed enters at 15.6 °C. Saturated steam at 101.32 kPa is available for heating, and the pressure in the vapor space of the evaporator is 15.3 kPa. A total of 4536 kg/h of water is to be evaporated. The overall heat transfer coefficient is 1988 W/m².K. What is the required surface area in m² and the steam consumption?

Geankoplis 32.4-10



$U = 1988 \ W/m^2.K$

A? S?

$$S\Delta_s = F\overset{\checkmark}{c_p}(T_1 - \overset{\checkmark}{T_F}) + \overset{\checkmark}{V}(\underbrace{H_v - h_L})$$

T_1 ↓ sat table @ 15.3 KPa = 54.3°C

λ from table: @ 15.3 KPa = 2371 $\frac{KJ}{Kg}$

$F.x_F = L.x_L$

$L \rightarrow (F-V)$

F - 4536

F × 0.05 = (F - 4536) × 0.5

F = 5040 Kg/h

Table @ 101.32 KPa → ΔS = 2256.5 KJ/Kg

$$S\Delta_s = 5040 \times 4.06 \times (54.3 - 156) + 4536\ (2371)$$

$$= \frac{1154 6750.88}{3600}\ KJ/h = 3207.4\ KW$$

① $S = \frac{11546750.88}{2256.5} = 5117.1\ Kg/h$

② $A = \frac{\Delta.S}{U \times (T_s - T_1)} = \frac{3207.4}{\frac{1988}{1000} \times (99.97 - 54.3)} = 35.34\ m^2$

4-Drying

In the previous example, suppose that the metal bottom of the tray has a thickness of 0.610 mm and its thermal conductivity is 43.3 W/(m.K). The thermal conductivity of the wet solid can be assumed as 0.865 W/(m.K). The top drying surface, also receives direct radiation from upper steam heated pipe whose surface temperature is 93.3 ºC. The emissivity of solid is 0.92. **Estimate the rate of drying for constant-rate period**.

$A = 0.457^2\ m^2$

$H = 0.01\ Kg\ H_2O / Kg\ Dry\ Air$

$T_D = 65.6\ ^\circ C$

$V = 6.1\ m/s$

$Z_s = 25.4 \times 10^{-3}\ m$

$Z_m = 0.61 \times 10^{-3}\ m$

$T_{rad} = 93.3^\circ C = 366.45 K$

$\varepsilon = 0.92$

$K_s = 0.865$

$K_m = 43.3$

$$\left(1 + \frac{U_K}{h_c}\right)(T - T_s) + \frac{h_R}{h_c}(T_R - T_s) = \frac{\lambda_s}{C_s}(H_s - H)$$

① $h_c = 0.0204\ G^{0.8}$

$G = \rho \times V$

$\rho = 1/v$

$v = (2.83 \times 10^{-3} + 4.56 \times 10^{-3}\ \underset{\downarrow}{H})\ T$

$(\ \ '' \ \ + \ \ '' \ \ 0.01) \times (65.6 + 273.15)$

$v = 0.974\ m^3/Kg\ Dry\ Air$

$H = \dfrac{0.01\ Kg\ H_2O}{Kg\ Dry\ Air} \rightarrow 1\ Kg\ Dry\ Air \rightarrow Kg\ mixture = 1.01\ Kg$

$\rho = \dfrac{Kg\ mixture}{m^3\ mixture} = \dfrac{1.01\ Kg\ mixture}{Kg\ Dry\ Air} \times \dfrac{Kg\ Dry\ Air}{0.974\ m^3} = 1.036\ \dfrac{Kg}{m^3}$

$G = 1.036 \times \dfrac{6.1\ m}{s} \times \dfrac{3600 s}{1 h} = 22771.66$

$h_c = 0.0204 \times G^{0.8} = 62.45\ W/m^2.K$

② $U_K = \dfrac{1}{1/h_c + Z_m/K_m + Z_s/K_s}$

$U_K = \dfrac{1}{1/62.45 + \dfrac{0.61 \times 10^{-3}}{43.3} + \dfrac{25.4 \times 10^{-3}}{0.865}}$

$U_K = 22.03\ \dfrac{W}{m^2.K}$

③ $c_s = (1.005 + 1.88 H) \times 10^3$

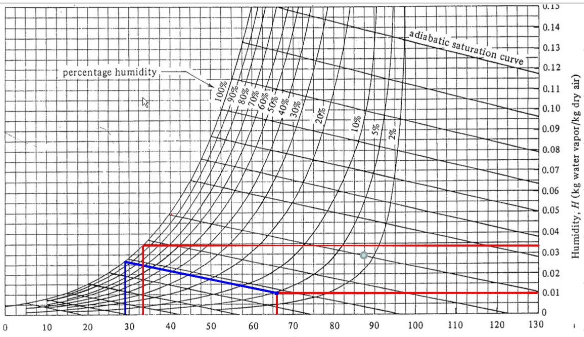
$(1.005 + 1.88 \times 0.01) \times 10^3$

$= 1023.8\ J/Kg\ Dry\ Air.K$

④ $h_R = \varepsilon \times 5.676 \times 10^{-8}\ \dfrac{T_R^4 - T_s^4}{T_R - T_s}$

$= 5.22 \times 10^{-8} \times \dfrac{1.8 \times 10^{10} - T_s^4}{366.45 - T_s}$

⑤ T_w ?



$T_w = 28.9^\circ C$

★ By Trial and Error guess an initial value for T_s

$T_s \geq T_w$

initial guess $\rightarrow T_s = 30^\circ C$ $\lambda_s = 2406$

1- $\lambda_s = ?$ Steam Tables $\rightarrow$ 2429.8 $H_s = 0.05$

2- $H_s = ?$ psychrometric chart $\rightarrow$ 0.0275

$$\left(1 + \frac{U_K}{h_c}\right)(T - T_s) + \frac{h_R}{h_c}(T_R - T_s) = \frac{\lambda_s}{C_s}(H_s - H)$$

$$\left(1 + \frac{22.03}{62.45}\right)(338.75 - T_s) + \frac{5.22 \times 10^{-8}}{62.45} \cdot \frac{1.8 \times 10^{10} - T_s^4}{366.45 - T_s}(366.45 - T_s) = \frac{2429.8 \times 1000}{1023.8} \times (0.0275 - 0.01)$$

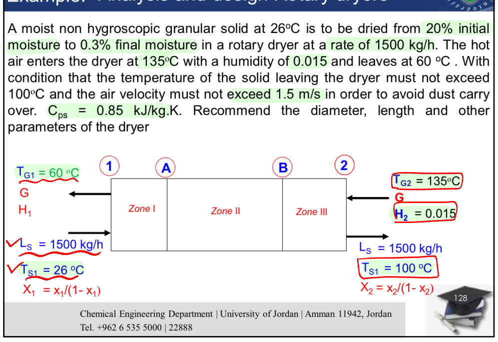
$T_s = 313.22 = 40^\circ C \neq 30^\circ C$

2nd Trial $\rightarrow$ $T_s = 32.5^\circ C \rightarrow \lambda_s = 2423.85 \rightarrow H_s = 0.0315 \rightarrow T_s = 305.95 = 32.8^\circ C \approx 32.5^\circ C$

3rd Trial $\rightarrow$ $T_s = 32.8^\circ C \rightarrow \lambda_s = 2423.136 \rightarrow H_s = 0.032 \rightarrow T_s = 305.96 = 32.8 = 32.8$ ✓

$$R_c = \frac{(h_c + U_K)(T - T_s) + h_R(T_R - T_s)}{\lambda_s}$$

$= 1.34 \times 10^{-3}\ Kg/m^2.s = 4.83\ \dfrac{Kg}{m^2.h}$



A moist non hygroscopic granular solid at 26ºC is to be dried from 20% initial moisture to 0.3% final moisture in a rotary dryer at a rate of 1500 kg/h. The hot air enters the dryer at 135ºC with a humidity of 0.015 and leaves at 60 ºC . With condition that the temperature of the solid leaving the dryer must not exceed 100ºC and the air velocity must not exceed 1.5 m/s in order to avoid dust carry over. C_{ps} = 0.85 kJ/kg.K. Recommend the diameter, length and other parameters of the dryer

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① mass of Dry solid $L_s = 1500\,(80\%) = 1200$

$X_1 = \frac{.2}{1-.2} = 0.25$

$X_2 = \frac{.003}{1-0.003} = 3.01\times10^{-3}$

②

$\overset{in\;-\;out}{L_s\times(X_1 - X_2)} = G(\overset{out}{H_1} - \overset{in}{H_2})$

$1200\times(.25 - 3.01\times10^{-3}) = G(H_1 - 0.015)$ #1

$L_s(H_{s1} - H_{s2}) = G(H_{y1} - H_{y2})$

$H_{s1} = c_{ps}\,T_{s1} + X_{T1}\times C_L\times T_{s1}$

$H_{s2} = c_{ps}\,T_{s2} + X_{T2}\times C_L\times T_{s2}$

$\rightarrow H_{s1} - H_{s2} = -36.94$

$H_{y2} = (1.005 + 1.88 H_2)(T_{G2}) + 2500 H_2$

$= 176.982$

$1200(-36.94) = G[(1.005 + 1.88H_1)\times60 + 2500H_1) - 177]$

$-44328 = \left[\frac{296.388}{H_1 - 0.015}\right][2612.8H_1 - 116.682]$

$H_1 = 0.04305$ $G = 10{,}560\ \frac{\text{Kg Dry Air}}{h}$

③ must choose maximum between inlet and exit Humid volume

$\nu_{H_2} = (2.83\times10^{-3} + 4.56\times10^{-3}H)T = 1.183$ >

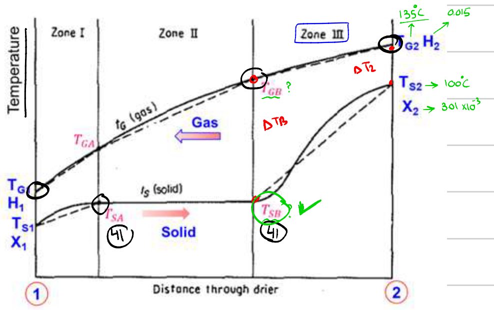
$\nu_{H_1} = (2.83\times10^{-3} + 4.56\times10^{-3}H)T = 1.008$

$\nu_{H_2}\times G = 1.183\times10{,}560 = 12492\ \frac{m^3}{h} = 3.47\ \frac{m^3}{s}$

max Allowed velocity → $1.5\ m/s - 1.5\times0.2 = 1.2$

$m^2\ (\pi/4\ d^2)\times1.2\frac{m}{s} = 3.47\ \frac{m^3}{s} \longrightarrow d = 2m$

④ Find N_{TG} for Zone 1, 2 and 3.



For Zone 3

T_{GB} + T_{SB} unknown

① Assume value for T_{SB} = wet Bulb Temp of Air at inlet Humidity (0.015) + Assumed Temp → (115°C) will be corrected

at 115°C + 0.015 $T_{wb} = 41°C$

$L_s(\overset{@\,41°C,\,X_2}{H_{s2}} - H_{sB}) = G\times C_{sB}(T_{G2} - T_{GB})$

$1200(86.2 - 35.37) = 10{,}560\times1.033(135 - T_{GB})$

$T_{GB} = 129.4°C \neq 115°C$

calculate real T_{SB}

① H @ 129°C + 0.015 = 41.3°C

Since 41.3°C ≈ 41°C Keep current values calculated

$\Delta T_B = T_{GB} - T_{SB} = 129 - 41 = 88°C$

$\Delta T_2 = 135 - 100 = 35°C$

$\Delta T_m = \frac{88 - 35}{\ln\frac{88}{35}} = 57.5°C$

$N_{TG_{III}} = \frac{T_2 - T_{GB}}{\Delta T_m} = \frac{135 - 129}{57.5} = 0.104$

For Zone 2

$\Delta T_A = ?$ $\Delta T_m = \frac{\Delta T_G - \Delta T_A}{\ln\frac{\Delta T_G}{\Delta T_A}}$

Enthalpy Balance on Zone II

$G\,T_{GB} + L_s\,T_{SA} = L_s\,T_{SB} + G\,T_{GA}$

$L_s(\overset{35.37}{H_{SB}} - H_{SA}) = G(H_{yB} - \underset{?}{H_{yA}})$

① $H_{SA} = c_{ps}\times T_{SA} + X_1 C_L T_{S1} = 0.85\times41 + 0.25\times4.187\times41 = 77.77$

② $H_{yB} = (1.005 + 1.008\times0.015)\,129 + 2500\times0.015 = 170.8$

$1200(35.37 - 77.77) = 10560(170.8 - H_{yA}) \rightarrow H_{yA} = 175.6 \rightarrow H = 0.04306$

$T_{GA} = 63°C$, $\Delta T_A = 63 - 41 = 22° \longrightarrow \Delta T_{lm} = \frac{88 - 22}{\ln(88/22)} = 47.6$

$(N_{tG})_{II} = \frac{T_{GB} - T_{GA}}{\Delta T_{lm}} = \frac{129 - 63}{47.6} = 1.386$

For Zone 1

ΔT_1 ? ΔT_A ↑ = 22°C

$\Delta T_1 = 60°C - 26°C = 34°C$

$\Delta T_{lm} = \frac{34 - 22}{\ln(34/22)} = 27.56$

$N_{tG_I} = \frac{T_{GA} - T_{G1}}{27.56}$

$= \frac{63 - 60}{27.56} = 0.109$

⑤ NTG Total = for zone 1 + zone 2 + zone 3

$= 0.109 + 1.386 + 0.104 = 1.59$

⑥ $H_{toG} = \frac{G\times C_s}{U_a}$, $G' = \frac{G(1+H_1) + G(1+H_2)}{2}$ Average gas mass flowrate

$G' = \frac{10{,}560(1+0.015) + 10{,}560(1+0.043)}{2}$

$G' = \frac{10{,}867}{\pi/4\,d^2\times3600} = 0.961\ \frac{kg}{m^2.s}$

⑦ $U_{xa} = \frac{237\,G'^{\,0.67}}{d} = 115\ W/m^3.K$ ($G' \rightarrow 0.961$, $d \rightarrow 2$)

⑧ Humid heat at the ends

→ $C_{S1} = 1.005 + 1.88\overset{0.043}{H_1} = 1.08$

→ $C_{S2} = 1.005 + 1.88\overset{0.015}{H_2} = 1.0332$

C_s Average $= \frac{1.08 + 1.0332}{2} = 1.056\times1000 = 1056.6\ \frac{J}{\text{Kg DryAir}.K}$

⑨ $H_{toG} = \frac{G\,C}{U_{xa}} = \frac{0.96\times1056.6}{115} = 8.82\ m$

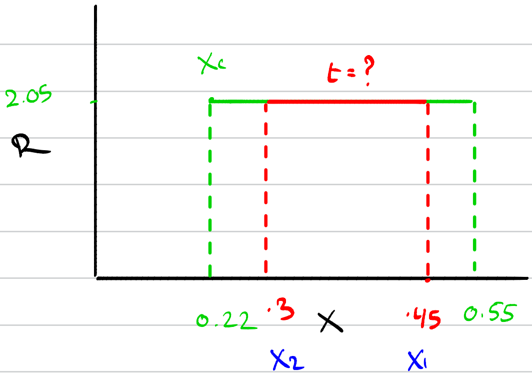
⑩ Length of Dryer = $8.82\times\overset{N_{TG}}{1.59}$ = 14 m → 15m Long Dryer.

3.6-1. ***Time for Drying in the Constant-Rate Period.*** A batch of wet solid was dried on a tray dryer using constant-drying conditions and a thickness of material on the tray of 25.4 mm. Only the top surface was exposed. The drying rate during the constant-rate period was $R = 2.05$ kg $H_2O/h \cdot m^2$ (0.42 lb_m $H_2O/h \cdot ft^2$). The ratio L_S/A used was 24.4 kg dry solid/m^2 exposed surface (5.0 lb_m dry solid/ft^2). The initial free moisture was $X_1 = 0.55$ and the critical moisture content $X_C = 0.22$ kg free moisture/kg dry solid.

Calculate the time to dry a batch of this material from $X_1 = 0.45$ to $X_2 = 0.30$ using the same drying conditions but a thickness of 50.8 mm, with drying from the top and bottom surfaces. (*Hint:* First calculate L_S/A for this new case.)

same as 24.4

Ans. $t = 1.785$ h



$$R = -\frac{L_s}{A} \int_{x_1}^{x_2} \frac{\partial X}{\partial t}$$

$$R_c = \frac{L_s}{A} \times \frac{(X_1 - X_2)}{t}$$

$$t = \frac{L_s (X_1 - X_2)}{R_c \times A}$$

$R_c = 2.05$

$L_s/A = 24.4$

$t = 1.785h$

3.6-2. ***Prediction of the Effect of Process Variables on the Drying Rate.*** Using the conditions in Example 33.6-3 for the constant-rate drying period, do as follows:

a. Predict the effect on R_C if the air velocity is only 3.05 m/s.

b. Predict the effect if the gas temperature is raised to 76.7°C and H remains the same.

c. Predict the effect on the time t for drying between moisture contents X_1 to X_2 if the thickness of material dried is 38.1 mm instead of 25.4 mm and the drying is still in the constant-rate period.

Ans. (a) RC = 1.947 kg H_2O/h · m^2 (0.399 lb_m H_2O/h · ft^2); (b) R_C = 4.21 kg H_2O/h · m^2

$A = .457^2\ m^2$

$V = 6.1\ m/s$

$T_{Air} = 65.6°C$

$H = 0.01$

$h_c =$

a- $R_c = ?$ → $V = 3.05$

① $v = (2.83\times10^{-3} + 4.56\times10^{-3} H)\cdot T$

$= (2.83\times10^{-3} + 4.56\times10^{-3} \times 0.01)\times(65.6+273.15)$

$v_H = 0.974\ \frac{m^3\ mixture}{Kg\ Dry\ Air}$ → 1Kg Dry Air → 0.01 Kg H_2O

$\frac{1.01\ Kg\ mixture}{Kg\ Dry\ Air}$

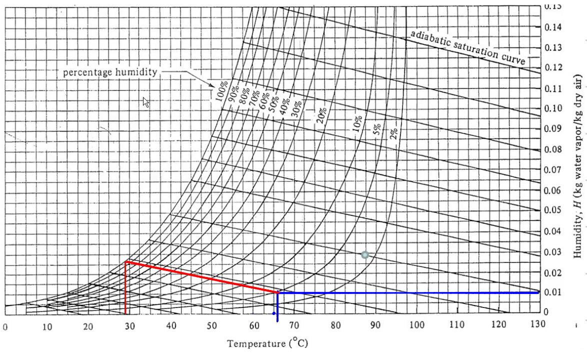
$\rho = \frac{1.01\ Kg\ mixture}{Kg\ \cancel{Dry\ Air}} \times \frac{1Kg\ \cancel{Dry\ Air}}{0.974\ m^3\ mixture}$

$\rho = 1.036 \times 3.05\ m/s = \frac{3.162\ Kg}{m^2 \cdot s} \times 3600 = 11384.55\ \frac{Kg}{m^2 \cdot h} = G$

$h_c = .0204\ G^{0.8} = 35.865$

$R_c = \frac{h_c \times (T_D - T_W)}{\lambda_W}$

T_W psychometric chart at $H = 0.01$ + $T_D = 65.6$ = 28.9°C → $\lambda_W = 2432.418$



$R_c = \frac{35.865 \times (65.6 - 28.9)}{2432.418} = 5.4\times10^{-4}\ \frac{Kg}{m^2 \cdot s} = 1.948\ \frac{Kg}{m^2 \cdot h}$

Shortcut method For a Example 33.6-3 $R_c = 3.39 \to V = 6.1$

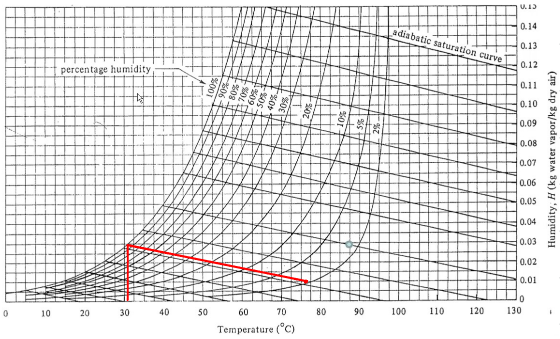
$R_c = ? \to V = 3.05$

$R_c \propto h_c \to G^{0.8} \to \rho V^{0.8} \to R_c \propto V^{0.8}$

$\frac{3.39}{R_{c2}} = \frac{6.1^{0.8}}{3.05^{0.8}} \to R_{c2} = 1.947$ ✓

b- T_{Air} → 76.7

T_W + λ_W → will change



$T_{W2} = 31.1°C$

$\lambda_{W2} = 2427.182$

h_c won't change → 62.45

$R_c = \frac{62.45 \times (76.7 - 31.1)}{2427.182 \times 1000} \times 3600 = 4.22$

c- $z_1 = 25.4 \to z_2 = 38.1$

$L_{S1} = \rho \times z_1 A_1 \to L_{S2} = \rho \times z_2 A_2$

How time will change ?

will change based on thickness

$t = \frac{L_S}{A\checkmark} \times \frac{(X_1 - X_2)\checkmark}{R\checkmark}$ constants

$\frac{t_2}{t_1} = \frac{38.1}{25.4} \to t_2 = 1.5\,t_1$

Summary :

- ✱ Decreasing velocity → Decreases $R_c \propto V^{0.8}$
- ✱ Increasing T_D → Increases R_c
- ✱ Increasing L_s → Increases time needed

3.6-4. ***Drying a Filter Cake in the Constant-Rate Region.*** A wet filter cake in a pan 1 ft × 1 ft square and 1 in. thick is dried on the top surface with air at a wet bulb temperature of 80°F and a dry bulb temperature of 120°F flowing parallel to the surface at a velocity of 2.5 ft/s. The dry density of the cake is 120 lb_m/ft^3 and the critical free moisture content is 0.09 lb H_2O/lb dry solid. How long will it take to dry the material from a free moisture content of 0.20 lb H_2O/lb dry material to the critical moisture content?

Ans. t = 13.3 h

$T_W = 80°F$

$T_D = 120°F$

$V = 2.5\ ft/s$

$X_c = 0.09\ lb\,H_2O / lb$ Dry solid

$t = ?$

$$t = \frac{L_S}{A} \times \frac{(X_1 - X_2)}{R_c}$$

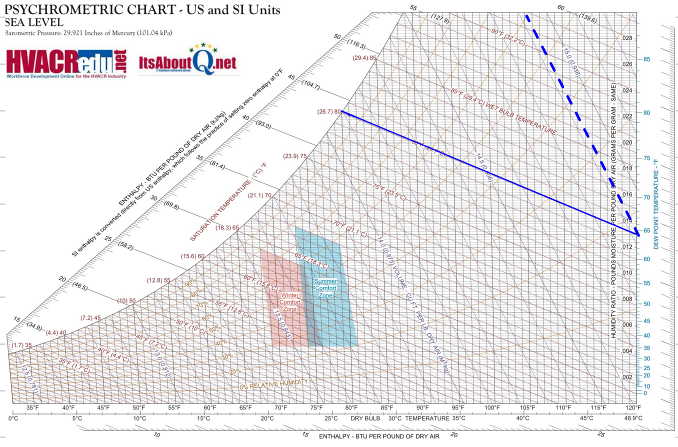
① $L_S \longrightarrow \rho \times z \times A = 120 \frac{lb\,Dry}{ft^3} \times 1 \times 1 \times (0.0833) = 10$ lb Dry solid

② $A = 1\ ft^2$

③ $X_1 = 0.2$ ④ $X_2 = 0.09$

⑤ $R_c = ?$

①



$v = 14.9\ ft^3 / lb$ Dry Air

$$H = 0.0135 \frac{lb\ H_2O}{lb\ Dry\ Air} \rightarrow \frac{1.0135\ lb\ mixture}{lb\ Dry\ Air} \times \frac{lb\ Dry\ Air}{14.9\ ft^3}$$

$= 0.068$

$$G = 0.068 \times 2.5 \times 3600 = \frac{612.18\ lbm}{h \cdot ft^2}$$

$h_c = 0.0128\ G^{0.8} \rightarrow h_c = 2.171$

$$R_c = \frac{h_c\,(T_D - T_W)}{\lambda_w}$$

↳ steam table at 80°F = 1048.3 btu/lbm

$$R_c = \frac{2.171 \times (120 - 80)}{1048.3} = 0.0828$$

$$t = \frac{10}{1} \times \frac{(0.2 - 0.09)}{0.0828} = 13.27\ h$$

3.8-1. ***Drying Biological Material in Tray Dryer.*** A granular biological material wet with water is being dried in a pan 0.305 × 0.305 m and 38.1 mm deep. The material is 38.1 mm deep in the pan, which is insulated on the sides and bottom. Heat transfer is by convection from an air stream flowing parallel to the top surface at a velocity of 3.05 m/s, having a temperature of 65.6°C and humidity $H = 0.010$ kg H_2O/kg dry air. The top surface receives radiation from steam-heated pipes whose surface temperature $T_R = 93.3$°C. The emissivity of the solid is $\varepsilon = 0.95$. It is desired to keep the surface temperature of the solid below 32.2°C so that decomposition will be kept low. Calculate the surface temperature and the rate of drying for the constant-rate period.

Ans. $T_S = 31.3°C$, $R_C = 2.583$ kg $H_2O/h \cdot m^2$

$U_K = 0$ (no conduction)

$A = 0.305^2\ m^2$

$z = 38.1 \times 10^{-3}\ m$

$v = 3.05\ m/s$

$T_R = 93.3°C$

$T_D = 65.6°C$

$\varepsilon = 0.95$

$H = 0.01$

$T_S < 32.2°C$

$R_c = ?$

$T_s ? \rightarrow$ Trial and error

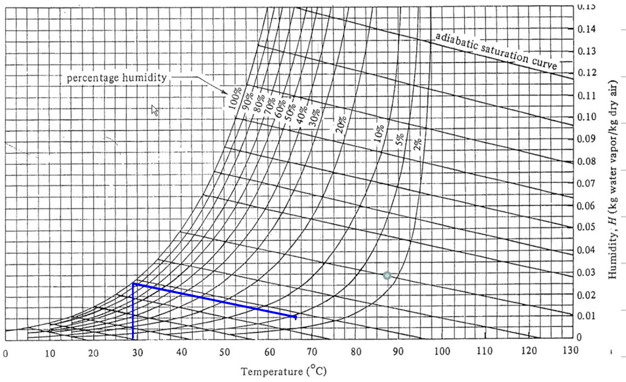
① h_c ?

$$R_c = \frac{h_c \times (T_D - T_W)}{\lambda_W}$$

$$h_c = 0.0204\, G^{0.8}$$

$$G = \rho \times v$$

$\rho ? \rightarrow$ From $H = 0.01$ + $T_D = 65.6°C$



$T_W = 28.9°C$

$\lambda_W = 2432.418$

$$V_H = (2.83 \times 10^{-3} + 4.56 \times 10^{-3} \times 0.01)(65.6 + 273.15)$$

$$V_H = 0.974\ \frac{m^3}{kg\ Dry\ Air}$$

$$\rho = \frac{1.01}{0.974} = 1.0369$$

$$G = 1.0369 \times 3.05 \times 3600 = 11385.83$$

$h_c = 35.869$

②

$$R_c = \frac{(h_c + \cancel{U_K})(T - T_s) + h_R(T_R - T_s)}{\lambda_s}$$

$$\left(1 + \cancel{\frac{\overset{0}{U_K}}{h_c}}\right)(T - T_s) + \frac{h_R}{h_c}(T_R - T_s) = \frac{\lambda_s}{c_s}(H_s - H)$$

$$(T - T_s) + \frac{h_R}{h_c}(T_R - T_s) = \frac{\lambda_s}{c_s}(H_s - H)$$

$$c_s = (1.005 + 1.88H) \times 10^3 \quad , \quad h_R = \varepsilon(5.676 \times 10^{-8})\frac{T_R^4 - T_s^4}{T_R - T_s}$$

$$= 1024$$

Assume Value For $T_s \rightarrow$ $T_s = 30°C$

$\lambda_s = 2429.8$

$H_s = 0.028$

$$(338.75 - T_s) + \frac{5.39 \times 10^{-8}}{35.869} \cdot \frac{366.45^4 - T_s^4}{366.45 - T_s}(366.45 - T_s) = \frac{2429.8}{1024} \times 1000\,(0.028 - 0.01)$$

$T_{s\,New} = 31.08°C$

Trial 2 $\rightarrow$ Assume $T_s = 31.7°C$ $\lambda_s = 2426.5 \times 10^3$

$H_s = 0.0305$

$$(338.75 - T_s) + \frac{5.39 \times 10^{-8}}{35.869} \times \frac{366.45^4 - T_s^4}{366.45 - T_s}(366.45 - T_s) = \frac{2426.5 \times 1000}{1024}(0.0305 - 0.01)$$

$T_{s\,New} = \boxed{31.3°C} \approx 31.7°$ ✓

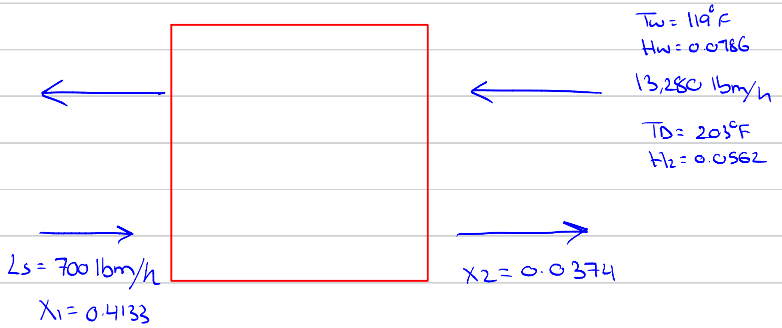
$$R_c = \frac{h_c \times (T - T_s) + h_R(T_R - T_s)}{\lambda_s} = 2.583$$

3.10-5. *Drying in a Continuous Tunnel Dryer.* A rate of feed of 700 lb_m dry solid/h containing a free moisture content of $X_1 = 0.4133$ lb H_2O/lb dry solid is to be dried to $X_2 = 0.0374$ lb H_2O/lb dry solid in a continuous-counterflow tunnel dryer. A flow of 13 280 lb_m dry air/h enters at 203°F with an $H_2 = 0.0562$ lb H_2O/lb dry air. The stock enters at the wet bulb temperature of 119°F and remains essentially constant in temperature in the dryer. The saturation humidity at 119°F from the humidity chart is $H_W = 0.0786$ lb H_2O/lb dry air. The surface area available for drying is $(A/L_S) = 0.30$ ft^2/lb_m dry solid.

A small-batch experiment was performed using approximately the same constant-drying conditions, air velocity, and temperature of the solid as in the continuous dryer. The equilibrium critical moisture content was found to be $X_C = 0.0959$ lb H_2O/lb dry solid, and the experimental value of k_yM_B was found as 30.15 lb_m air/h · ft^2. In the falling-rate period, the drying rate was directly proportional to X.

For the continuous dryer, calculate the time in the dryer in the constant-rate zone and the falling-rate zone.

Ans. $H_C = 0.0593$ lb H_2O/lb dry air, $H_1 = 0.0760$ lb H_2O/lb dry air, t = 4.20 h in the constant-rate zone; t = 0.47 h in the falling-rate zone



$A/L_s = 0.3$

$X_c = 0.0959$

$K_yM_B = 30.15$

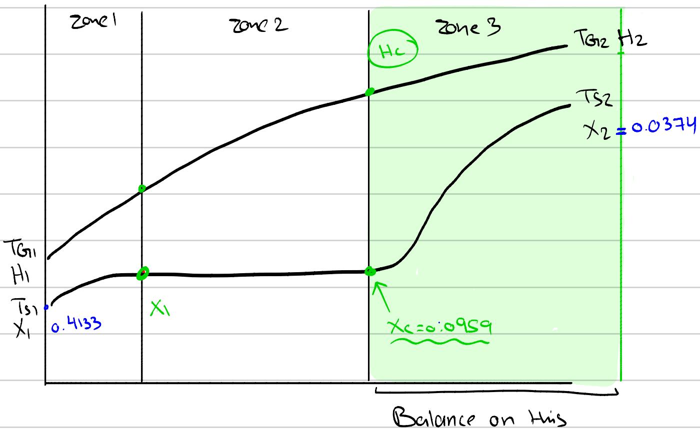
① H_1 ?

$L_sX_1 + GH_2 = L_sX_2 + GH_1$

$700(0.4133) + 13{,}280(0.0562) = 700(0.0374) + 13280(H_1)$

$H_1 = 0.076$

$\dfrac{1.0593 \text{ lbm Air}}{\text{lbm Dry Air}}$



$\breve{L}\breve{X}_c + \breve{H}_2\breve{G} = \breve{L}\breve{X}_2 + \breve{G}\underline{H_c}$
?

$H_c = 0.059$

① constant rate period

$R = K_yM_B(H_w - H)$

$t = \dfrac{L_s}{A}\displaystyle\int_{X_c}^{X_1}\dfrac{dX}{R}$

$\ast\, dX = \dfrac{G}{L_s}\,dH$

$t = \dfrac{L_s}{A}\cdot\displaystyle\int_{X_c}^{X_1}\dfrac{dX}{K_yM_B(H_w - H)}$

$t = \dfrac{L_s}{A}\displaystyle\int_{H_c}^{H_1}\dfrac{G\,dH}{L_sK_yM_B(H_w - H)}$

$t = \dfrac{L_s}{A}\times\dfrac{G}{L_s}\times\dfrac{1}{K_yM_B}\displaystyle\int_{H_c}^{H_1}\dfrac{dH}{H_w - H} \rightarrow t = \dfrac{L_s}{A}\times\dfrac{G}{L_s}\times\dfrac{1}{K_yM_B}\cdot\ln\dfrac{H_w - H_c}{H_w - H_1}$

$t = \dfrac{1}{0.3}\times\dfrac{13280}{700}\times\dfrac{1}{30.15}\times\ln\left(\dfrac{0.0786 - 0.059}{0.0786 - 0.076}\right)$

$t = 4.2\text{ h}$

② falling rate period

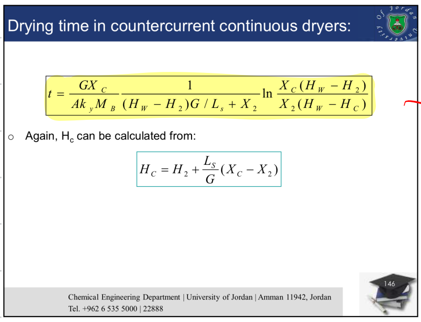
$R = R_c \times \dfrac{X}{X_c} = K_yM_B(H_w - H)\cdot\dfrac{X}{X_c}$

$t = \dfrac{L_s}{A}\times\displaystyle\int\dfrac{dX}{R} = \dfrac{L_s}{A}\times\displaystyle\int\dfrac{G}{L_s}\times\dfrac{dH}{R}$

$t = \dfrac{L_s}{A}\times\dfrac{G}{L_s}\times\displaystyle\int\dfrac{X_c}{K_yM_B(H_w - H)\cdot X}\,dH$

$t = \dfrac{G}{L_s}\times\dfrac{L_s}{A}\cdot\dfrac{X_c}{K_yM_B}\cdot\dfrac{1}{(H_w - H_2)\frac{G}{L_s} + X_2}\cdot\ln\dfrac{X_c(H_w - H_2)}{X_2(H_w - H_c)}$

$t = 0.467$



Drying time in countercurrent continuous dryers:

$$t = \frac{GX_C}{Ak_yM_B}\,\frac{1}{(H_W - H_2)G/L_s + X_2}\ln\frac{X_C(H_W - H_2)}{X_2(H_W - H_C)}$$

- Again, H_c can be calculated from:

$$H_C = H_2 + \frac{L_S}{G}(X_C - X_2)$$

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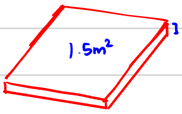
Seader || Chapter 18

18.27. Batch drying of raw cotton.

Raw cotton having an initial total moisture content of 95% (dry basis) and a dry density of 43.7 lb/ft^3 is to be dried batchwise to a final moisture content of 10% (dry basis) in a cross-circulation tray dryer. The trays, which are insulated on the bottom, are each 3 cm high, with an area of 1.5 m^2, and are completely filled. The heating medium, which is air at 160°F and 1 atm with a relative humidity of 30%, flows across the top surface of the tray at a mass velocity of 500 lb/h-ft^2. Equilibrium-moisture content isotherms for the cotton are given in Figure 18.25. Experiments have shown that under the given conditions, critical moisture content will be 0.4 lb water/lb bone-dry cotton, and the falling-rate drying period will be like that of Figure 18.31a, based on free-moisture content. Determine: (a) amount of raw cotton in pounds (wet basis) that can be dried in one batch if the dryer contains 16 trays; (b) drying time for the constant-rate period; (c) drying time for the falling-rate period; (d) total drying time if the preheat period is 1 h.

a- amount of cotton Dried? → 16 trays



$V = 3\times10^{-2} \times 1.5 = 0.045\ m^3$ Volume of tray

$\frac{43.7 lb}{\cancel{ft^3}} \times 0.045 \cancel{m^3} \times \frac{\cancel{ft^3}}{0.0283 \cancel{m^3}} = 69.4 lb$ ← Dry cotton per tray

H₂O amount in cotton

$\frac{.95\ H_2O}{lb\ Dry\ cotton} \times 69.4\ lb\ Dry\ cotton = \underline{66.01\ lb H_2O} + \underline{69.4\ lb}$

Wet cotton = 135.4 wet cotton

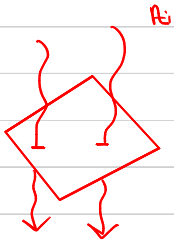
For 16 trays ⤴ ×16 = 2166.6 lb wet cotton

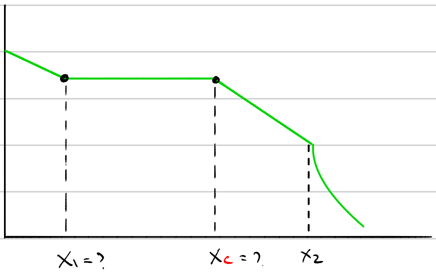
$X_c = 0.4$

Air @ 160°F

$H_R = 30\%$

$G = \frac{500\ lb}{h \cdot ft^2}$





b- constant rate period?

$$t = \overset{69.4\ lb}{\frac{L_s}{\underset{1.5m^2 \to 16.23 ft^2}{A}}} \times \int_{X_c}^{X_1} \frac{X}{R}$$

$R \to \frac{h_c \times (T_D - T_w)}{\lambda_w}$

$R_c = 0.073$

$G = \frac{500 lb}{h \cdot ft^2} \times \frac{453.6 g}{lb} \times \frac{ft^2}{.304 m^2}$

$= \frac{2441.24\ kg}{h \cdot m^2}$

$h_c = 0.0204\ G^{.8}$

$h_c = 10.46 \frac{W}{h \cdot m^2 \cdot K}$

$= 1.85\ BTU/h \cdot ft^2 \cdot °F$

From psychrometric chart

at $T_D = 160°F$

$T_w = 118.7°F$, $\lambda_w = 1026.5$ ← Steam Table

$t = 31.6\ h$ → neglecting sensible heat

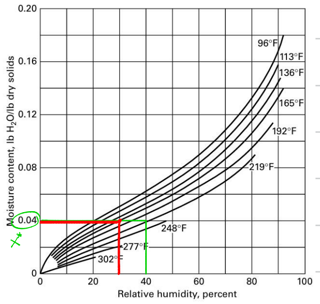
if we want to include sensible heat

$R = \frac{h \times (T_D - T_w)}{(\lambda_w + c_p(T_D - T_w))}$

$\boxed{t = 32.2\ h}$

A way to get X₁ and X₂ from EMC curve

equilibrium moisture content



$\frac{Kg\ Total\ H_2O}{Kg\ Solid}$

$X_1 = X_T - X^*$

$= 0.95 - 0.04 = \boxed{.91}$

$X_c = 0.4 - 0.04 = \boxed{0.36}$

$X_2 = 0.1 - 0.04 = 0.06$

c-

$$t = \frac{L_s}{A} \int_{X_2}^{X_c} \frac{dX}{R}$$

$$t = -\frac{L_s}{A} \cdot \frac{X_c}{R_c} \ln \frac{X_2}{X_c}$$

$$t = -\frac{69.4}{16.2} \times \frac{0.36}{0.0732} \ln \frac{0.06}{0.36}$$

$t = 37.75\ h$

d-

$t_{Total} = 1h + 32.2h + 37.7h$

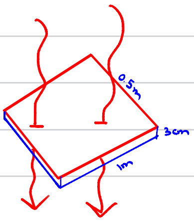
$= 70.9\ h$

18.28. Batchwise drying of filter cake.

Slabs of filter cake with a bone-dry density of 1,600 kg/m^3 are to be dried from an initial free-moisture content of 110% (dry basis) to a final free-moisture content of 5% (dry basis) batchwise in trays that are 1 m long by 0.5 m wide, with a depth of 3 cm. Drying will take place from the top surface only. The drying air conditions are 1 atm, 160°C, and a 60°C wet-bulb temperature. The air velocity across the trays is 3.5 m/s. Experiments under these drying conditions show a critical free-moisture content of 70% (dry basis), with a falling-rate period like that of Figure 18.31a, based on free-moisture content. Determine: (a) drying time for the constant-rate period; (b) drying time for the falling-rate period.

$X_c = 0.4$

Air @ 160°C



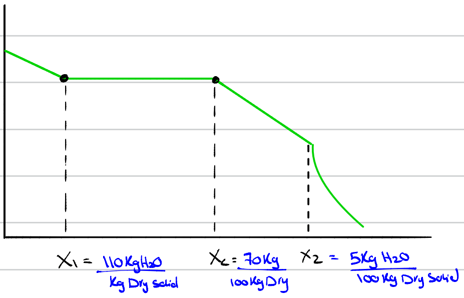
$T_W = 60°C$

$v = 3.5\,m/s$

$\rho_{Dry} = \frac{1600 \text{ Kg Dry Solid}}{m3}$

$L_s = \rho_{Dry} \times V$

$1600 \times 1 \times 0.5 \times 3 \times 10^{-2} = 24$



Constant Rate period

① $t = \frac{L_s}{A} \cdot \frac{(X_1 - X_c)}{R} = \frac{24}{0.5} \cdot \frac{(1.1 - 0.7)}{4.53} = 4.24h$ ⑧

② $R = \frac{h\,(T_D - T_W)}{\lambda_w}$ ⑦ $R = \frac{29.7 \times (160 - 60)}{2357.7 \times 1000} = 1.26 \times 10^{-3} = \underline{4.53}$

③ $h = 0.0204\ G^{0.8}$ $h = 0.0204(8996.4)^{.8} = 29.7$ ⑥

④ $G = \rho \times V$

⑤ $G = 0.714 \times 3.5 \times 3600$

$= 8996.4$

From psychrometric chart $T_D = 160°C + T_W = 60°C$

$v = 1.4\ m^3/\text{Kg Dry Air}$

$H = \frac{0.1 \text{ Kg H}_2\text{O}}{\text{Kg Dry Air}}$

$\rho = \frac{H}{v} = \frac{0.1}{1.4} = 0.714$

Steam Tables at 60°C $\lambda_w \rightarrow 2357.7$

Falling Rate period

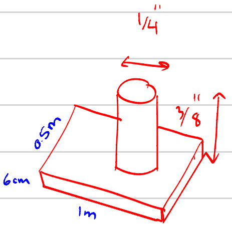
$$t = -\frac{L_s}{A} \cdot \frac{X_c}{R_c} \times \ln\left(\frac{X_2}{X_c}\right)$$

$$= -\frac{24}{0.5} \times \frac{0.7}{4.53} \times \ln\left(\frac{0.05}{0.7}\right) = 19.57h$$

18.29. Batchwise drying of extrusions.

The filter cake of Exercise 18.28 is extruded into cylindrical-shaped pieces measuring 1/4 inch in diameter by 3/8 inch long that are placed in trays that are 6 cm high × 1 m long × 0.5 m wide and through which the air passes. The external porosity is 50%. If the superficial air velocity, at the same conditions as in Exercise 18.28, is 1.75 m/s, determine: (a) drying time for the constant-rate period; (b) time for the falling-rate period.

✱ cylindrical shaped



$T_D = 160°c$

$T_w = 60°c$

$\lambda_w = 2357.7$ KJ/Kg

Constant Rate period

$\varepsilon = 0.5$

$V = 1.75$ m/s

① $t = \frac{L_s}{A} \cdot \frac{(X_1 - X_c)}{R}$

② $R = \frac{h(T_D - T_w)}{\lambda_w}$

How to find h?

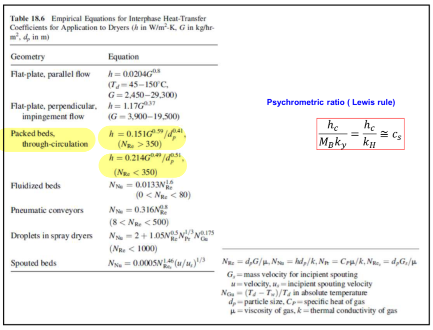


Table 18.6 Empirical Equations for Interphase Heat-Transfer Coefficients for Application to Dryers (h in W/m²-K, G in kg/hr-m², d_p in m)

Geometry	Equation
Flat-plate, parallel flow	$h = 0.0204G^{0.8}$ $(T_d = 45–150°C,$ $G = 2{,}450–29{,}300)$
Flat-plate, perpendicular, impingement flow	$h = 1.17G^{0.37}$ $(G = 3{,}900–19{,}500)$
Packed beds, through-circulation	$h = 0.151G^{0.59}/d_p^{0.41}$, $(N_{Re} > 350)$ $h = 0.214G^{0.49}/d_p^{0.51}$, $(N_{Re} < 350)$
Fluidized beds	$N_{Nu} = 0.0133N_{Re}^{1.6}$ $(0 < N_{Re} < 80)$
Pneumatic conveyors	$N_{Nu} = 0.316N_{Re}^{0.8}$ $(8 < N_{Re} < 500)$
Droplets in spray dryers	$N_{Nu} = 2 + 1.05N_{Re}^{0.5}N_{Pr}^{1/3}N_{Gu}^{0.175}$ $(N_{Re} < 1000)$
Spouted beds	$N_{Nu} = 0.0005N_{Re_s}^{1.46}(u/u_s)^{1/3}$

$N_{Re} = d_pG/\mu$, $N_{Nu} = hd_p/k$, $N_{Pr} = C_P\mu/k$, $N_{Re_s} = d_pG_s/\mu$
G_s = mass velocity for incipient spouting
u = velocity, u_s = incipient spouting velocity
$N_{Gu} = (T_d - T_w)/T_d$ in absolute temperature
d_p = particle size, C_P = specific heat of gas
μ = viscosity of gas, k = thermal conductivity of gas

Psychrometric ratio (Lewis rule)

$$\boxed{\frac{h_c}{M_B k_y} = \frac{h_c}{k_H} \cong c_s}$$

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$N_{Re} > < 350$?

$Re = \frac{d \times G}{\mu}$ $\quad$ $0.714 \times 1.75 \times 3600 = 4498.2$

Given: $d_p = 0.00897$m

$\mu = 0.072$

$Re = \frac{0.00897 \times 4500}{0.072}$

$= 560 > 350$

$h = 0.151 \frac{G^{0.59}}{d_p^{0.41}} = 149 \frac{W}{m^2 \cdot K}$

$R = 6.319 \times 10^{-3} = 22.75$

$L_s = 1600 \times (0.5 \times 1 \times 6 \times 10^{-2}) \times \varepsilon \rightarrow 0.5$

$= 24$ Kg

$A = ?$ $= \frac{\pi}{4} D^2 \cdot L = \frac{\pi}{4} \times (1/4")^2 \times 3/8" = 0.0184$ inch^3 $= 3.02 \times 10^{-7}$ m^3

tray volume $= (0.5 \times 1 \times 6 \times 10^{-2}) \times \varepsilon \rightarrow 0.5 = 0.015$ m^3

number of packing (cylinders) $= \frac{0.015}{3.02 \times 10^{-7}} = 49{,}700$

Surface area of cylinders $= \pi D L + 2\frac{\pi D^2}{4} = 2.53 \times 10^{-4}$ m^2

$A = 49750 \times 2.53 \times 10^{-4} = 12.6$ m^2

$t = 0.0334$h $= 2$min

b- falling rate period

$t = \frac{L_s}{A} \frac{X_c}{R_c} \times \ln\left(\frac{X_2}{X_c}\right) = 0.154$ h $= 9.2$min

18.32. Drying time for wood.

A piece of hemlock wood measuring 15.15 × 14.8 × 0.75 cm is to be dried from the two large faces from an initial total moisture content of 90% to a final average total moisture content of 10% (both dry basis), for drying taking place in the falling-rate period with liquid-diffusion controlling. The moisture diffusivity has been experimentally determined as 1.7×10^{-6} cm²/s. Estimate the drying time if bone-dry air is used.

$V = 15.15 \times 14.8 \times 0.75 = 1.68 \times 10^{-4}\ m^3$

$X_1 \rightarrow X_2$

$D_L = 1.7 \times 10^{-6}\ cm^2/s$

Assume HR = 17.5%

from EMC curve

$X^* = 0.04$

$X_{1T} = .9$

$X_{2T} = .1$

$z = 0.75$ cm

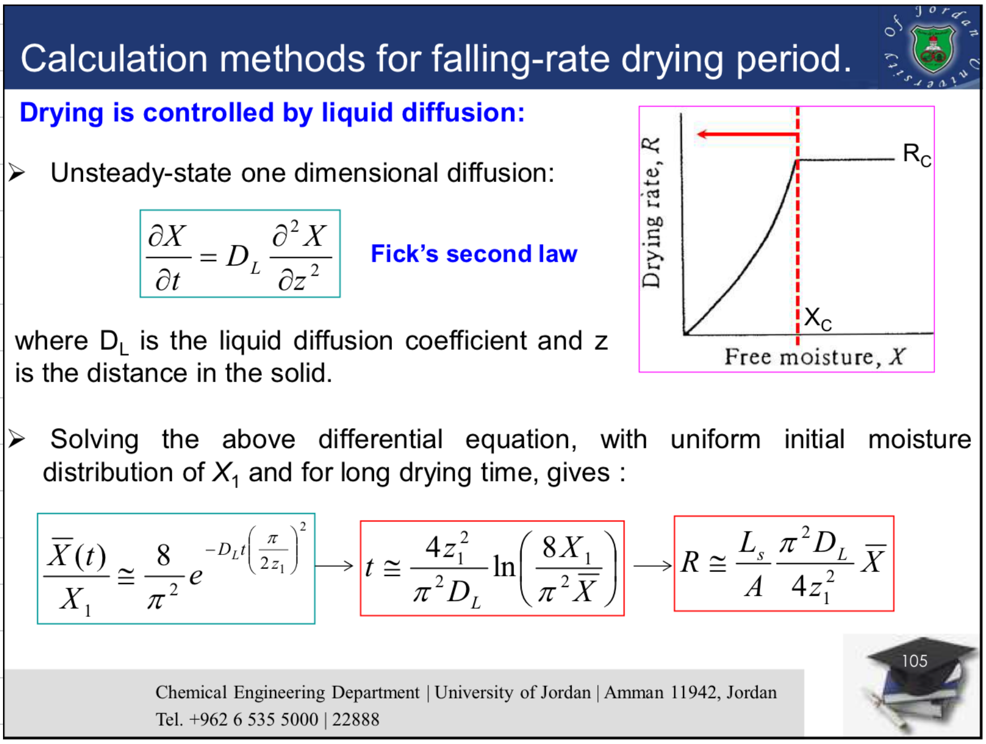
① $X_1 = X_{T1} - X^* = .9 - 0.04 = 0.86$

② $\bar{X} = X_{T2} - X^* = .1 - 0.04 = 0.06$

③ from 2 sides is dried → 0.5 × 0.75 = 0.375

$$t = \frac{4z^2}{\pi^2 D_L} \ln \frac{8X_1}{\pi^2 \bar{X}} = \frac{4 \times (0.375)^2}{\pi^2 \times 1.7 \times 10^{-6}} \cdot \ln\left(\frac{8 \times 0.86}{\pi^2 \times 0.96}\right)$$

$t = 22.8$ h



Calculation methods for falling-rate drying period.

Drying is controlled by liquid diffusion:

- Unsteady-state one dimensional diffusion:

$$\frac{\partial X}{\partial t} = D_L \frac{\partial^2 X}{\partial z^2}$$

Fick's second law

where D_L is the liquid diffusion coefficient and z is the distance in the solid.

- Solving the above differential equation, with uniform initial moisture distribution of X_1 and for long drying time, gives :

$$\frac{\bar{X}(t)}{X_1} \cong \frac{8}{\pi^2} e^{-D_L t \left(\frac{\pi}{2z_1}\right)^2} \longrightarrow t \cong \frac{4z_1^2}{\pi^2 D_L} \ln\left(\frac{8X_1}{\pi^2 \bar{X}}\right) \longrightarrow R \cong \frac{L_s}{A} \frac{\pi^2 D_L}{4z_1^2} \bar{X}$$

3.7-1. ***Numerical Integration for Drying in the Falling-Rate Region.*** A wet solid is to be dried in a tray dryer under steady-state conditions from a free moisture content of $X_1 = 0.40$ kg H_2O/kg dry solid to $X_2 = 0.02$ kg H_2O/kg dry solid. The dry solid weight is 99.8 kg dry solid and the top surface area for drying is 4.645 m^2. The drying-rate curve can be represented by Fig. 33.5-1b.

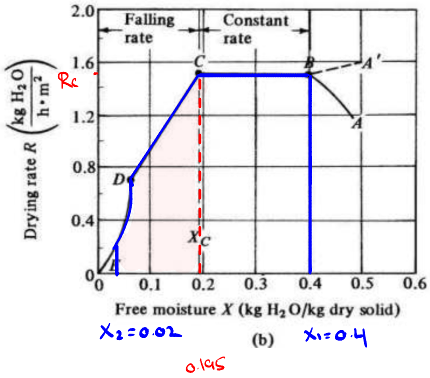
a. Calculate the time for drying using numerical integration in the falling-rate period.

b. Repeat, but use a straight line through the origin for the drying rate in the falling-rate period.

Ans. (a) t(constant rate) = 2.91 h, t(falling rate) = 6.65 h, t(total) = 9.56 h

$X_1 = 0.4 \longrightarrow X_2 = 0.02$, $L_s = 99.8$ Kg

$A = 4.645\ m^2$



$$t = \frac{L_s}{A} \int_{X_2}^{X_1} \frac{dX}{R_c}$$

① Constant rate $0.4 \rightarrow 0.195$

$$t = \frac{99.8}{4.645} \times \frac{0.4 - 0.195}{1.51} = 2.91\,h$$

② Falling rate $0.195 \rightarrow 0.02$

X	R	1/R
0.195	1.51	0.663
0.15	1.21	0.826
0.1	0.9	1.111
0.065	0.71	1.408
0.05	0.37	2.703
0.04	0.27	3.703
0.03	0.181	5.525
0.02	0.107	9.346

$$\frac{0.15 - 0.195}{2}(0.663 + 0.826) + \frac{0.1 - 0.15}{2}(0.826 + 1.11)$$

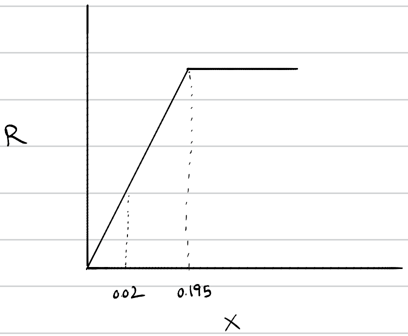
$$+ \frac{0.065 - 0.1}{2}(1.11 + 1.408) + \frac{0.05 - 0.065}{2}(1.4 + 2.7)$$

$$+ \ldots\ldots\ldots\ldots = -0.309$$

$$t = -\frac{99.8}{4.645} \times -0.309 = 6.64h$$

$t_{total} = 6.64 + 2.91 = 9.55h$

b-



$t = 2.91 \longrightarrow$ Constant Rate

$$t = \frac{L_s}{A} \times \frac{X_c}{R_c} \ln \frac{X_c}{X_2} = \frac{99.8}{4.645} \times \frac{0.195}{1.51} \ln \frac{0.195}{0.02}$$

$t = 6.32\,h$

total time $= 6.32 + 2.91 = 9.22h$

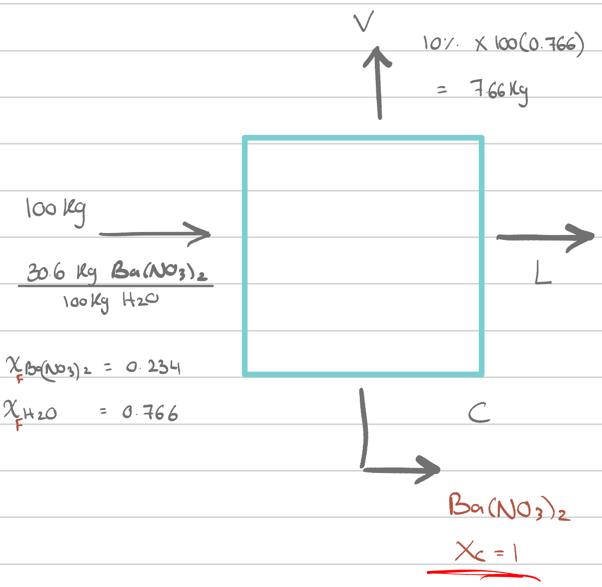
5- Crystallization

29.1-1. *Crystallization of $Ba(NO_3)_2$*. A hot solution of $Ba(NO_3)_2$ from an evaporator contains 30.6 kg $Ba(NO_3)_2$/100 kg H_2O and goes to a crystallizer, where the solution is cooled and $Ba(NO_3)_2$ crystallizes. On cooling, 10% of the original water present evaporates. For a feed solution of 100 kg total, calculate the following:

a. The yield of crystals if the solution is cooled to 290 K (17°C), where the solubility is 8.6 kg $Ba(NO_3)_2$/100 kg total water.

b. The yield if the solution is cooled instead to 283 K, where the solubility is 7.0 kg $Ba(NO_3)_2$/100 kg total water.

Ans. (a) 17.47 kg $Ba(NO_3)_2$ crystals



10% × 100(0.766) = 7.66 kg

100 kg

$\frac{30.6 \text{ kg } Ba(NO_3)_2}{100 \text{ kg } H_2O}$

$x_{F\,Ba(NO_3)_2} = 0.234$

$x_{F\,H_2O} = 0.766$

$Ba(NO_3)_2$

$X_c = 1$

a- C?

$T_2 = 17°C$

$S = \frac{8.6 \text{ Kg } Ba(NO_3)_2}{100 \text{ Kg } H_2O}$

$X_{LS} = \frac{8.6}{108.6} = 0.079$

$X_{WS} = 1 - 0.079 = 0.92$

Mass Balance :

$F = V + L + C$

Component Balance :

$F x_F = L x_L + C$

$100 = 7.66 + L + C$

$100(0.234) = L \times 0.079 + C$

$L = 74.853$ $\quad$ $C = 17.48 \text{ kg}$

b- $S = 7 \text{Kg } Ba(NO_3)_2 / 100 \text{ } H_2O$

$X_{LS} = 0.0654$

$100 = 7.66 + L + C$

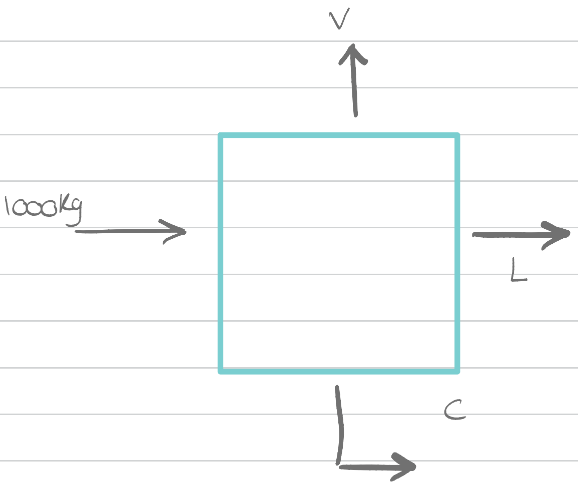
$100(0.234) = L \times 0.0654 + C$

$L = 73.7 \text{ Kg}$ $\quad$ $C = 18.58 \text{ Kg}$

29.1-2. *Dissolving and Subsequent Crystallization.* A batch of 1000 kg of KCl is dissolved in sufficient water to make a saturated solution at 363 K, where the solubility is 35 wt % KCl in water. The solution is cooled to 293 K, at which temperature its solubility is 25.4 wt %.

a. What is the weight of water required for the solution and the weight of the crystals of KCl obtained?
b. What is the weight of the crystals obtained if 5% of the original water evaporates on cooling?

Ans. (a) 1857 kg water, 368 kg crystals; (b) 399 kg crystals



$XL_{Kcl} = 0.35 \rightarrow$ @ T= 363K

$XL_{Kcl} = 0.254 \rightarrow$ @ T= 293K

a- H_2O required?

$$\frac{0.35 \text{ Kg Kcl}}{\text{Kg Solution}} = \frac{1000 \text{ Kg Kcl}}{[1000 + \underset{?}{\text{Kg } H_2O}]} \rightarrow [1000 + \overset{?}{\text{Kg } H_2O}] = 2857.14$$

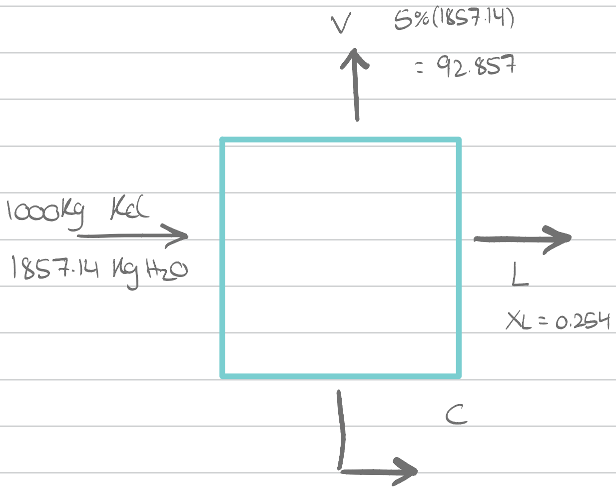
$$\text{Kg } H_2O = 1857 \text{ Kg } H_2O$$

Crystals obtained?

at 293K $$\frac{25.4 \text{ Kg Kcl}}{\text{Kg Solution}} = \frac{? \text{ Kg Kcl}}{1857 + ? \text{ Kg Kcl}}$$

= 632.32 Kg Kcl Dissolved

Kcl crystals = 1000 - 632.32 = 367.67 Kg



b- $$\overset{2857.14}{F} = \overset{92.857}{V} + L + C$$

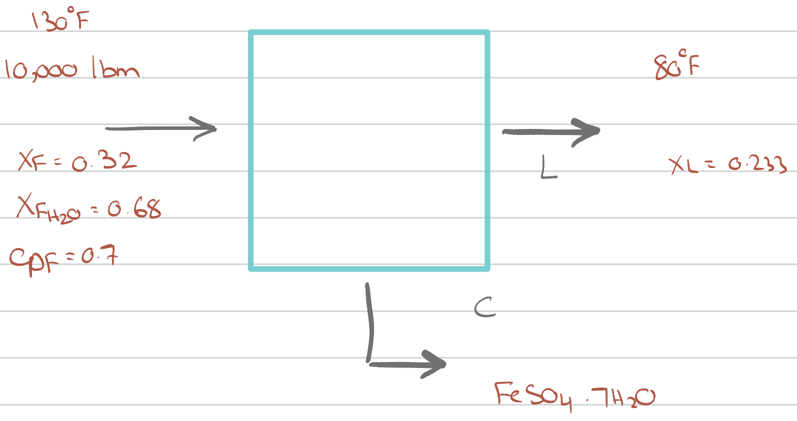
$$1000 = 0 + 0.254 L + C$$

$$L = 2365$$

$$C = 399.3 \text{ Kg}$$

29.1-4. *Heat Balance in Crystallization.* A feed solution of 10 000 lb_m at 130°F containing 47.0 lb $FeSO_4$/100 lb total water is cooled to 80°F, where $FeSO_4 \cdot 7H_2O$ crystals are removed. The solubility of the salt is 30.5 lb $FeSO_4$/100 lb total water (P1). The average heat capacity of the feed solution is 0.70 btu/$lb_m \cdot$ °F. The heat of the solution at $\boxed{18^\circ C}$ is –4.4 kcal/g mol (–18.4 kJ/mol) $FeSO_4 \cdot 7H_2O$ (P1). Calculate the yield of crystals and make a heat balance. Assume that no water is vaporized.

Ans. 2750 lb_m $FeSO_4 \cdot 7H_2O$ crystals, q = –428 300 btu (–451 900 kJ)



① $10{,}000 = L + C$

$10{,}000(0.32) = L(0.233) + 0.5467C$

$L = 7243.4$ kg $\quad C = 2756$ kg

$$h_C = -h_F = 4.4\ \cancel{kcal}/\cancel{mol} \times \frac{1000\ \cancel{cal}/\cancel{kcal}}{287.02\ \cancel{g}/\cancel{mol}} \times \frac{453.6\ \cancel{g}/lbm}{252.16\ \cancel{cal}/btu} = 28.47\ \frac{btu}{lbm}$$

$7 \cdot H_2O$ Mw = 126.11 $\qquad x_{H_2O} = 0.453$

$FeSO_4$ = 152 $\qquad x = 0.546$

②

$$q = F c_{pF}(T_2 - T_1) - C h_c$$

$$q = 10{,}000 \times 0.7(80 - 130) - 2756 \times 28.47$$

$$q = -428463.32\ Btu$$

29.1-5. ***Effect of Temperature on Yield and Heat Balance in Crystallization.*** Use the conditions given in Example 29.1-2, but the solution is cooled instead to 283.2 K, where the solubility is 30.9 kg $MgSO_4$/100 kg total water (P1). Calculate the effect on yield and the heat absorbed by using 283.2 K instead of 293.2 K for the crystallization.

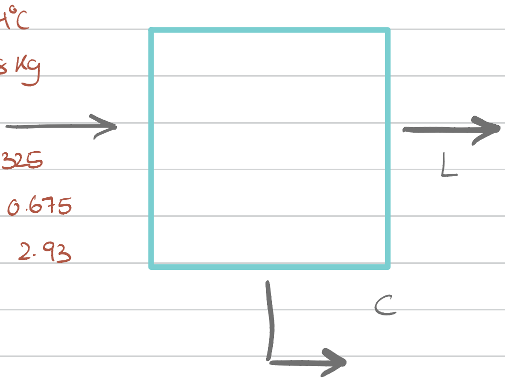
$T_1 = 54.4°C$

$F = 2268$ Kg

$X_F = 0.325$

$X_{F H_2O} = 0.675$

$C_{pF} = 2.93$



$S = \frac{30.9 \text{ kg}}{100 \text{ kg } H_2O}$

$X_L = 0.236$

$MgSO_4 \cdot 7H_2O$

$h_c = -h_s = \frac{13.31 \times 10^3 \text{ KJ/Kgmol}}{246.474 \frac{\text{Kg}}{\text{Kgmol}}} = 54$

$X_{c_1} = 0.488$

$F = L + C$

$2268 = L + C$ ①

$2268(0.325) = L(0.236) + 0.488\, C$

$\boxed{C = 801 \text{ Kg}}$ $L = 1467$ Kg

$q = F c_{pF}(T_2 - T_1) - C\, h_c$

$= 2268 \times 2.93 \times (283.2 - 327.6) - 801 \times 54$

$= \boxed{-338302.6 \text{ KJ}}$

Crystal geometry and size distribution || Seader - sec 17.1

17.1. Estimation of crystal sphericities.

Estimate sphericities of the following simple particle shapes: (a) a cylindrical needle with a height, *H*, equal to 5 times the diameter, *D*; (b) a rectangular prism of sides *a*, 2*a*, and 3*a*.

$\Psi = \frac{6}{D_p}\left(\frac{V_p}{S_p}\right)$

a- $\frac{6}{D_p}\left(\frac{\frac{\pi}{4}D^2 \cdot 5D}{\pi D \cdot 5D + \frac{\pi}{2}D^2}\right)$

$\frac{6}{D_p}\left(\frac{5\frac{\pi}{4}D^3}{\frac{11\pi}{2}\cancel{D^2}}\right) = \frac{15}{11}\frac{D}{D_p} =$

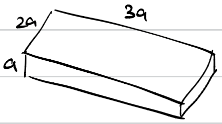
$D_p \propto D$

$\frac{\pi D_p^3}{6} = \frac{\pi}{4}D^2 \cdot 5D$

$\frac{D_p}{D} = \sqrt[3]{\frac{15}{2}}$

$\Psi = 0.696$

b-



$a \times 2a \times 3a$

$\Psi = \frac{6}{D_p} \cdot \left(\frac{V}{S}\right) = \frac{6}{D_p}\left(\frac{6a^3}{2(a\times 2a + a\times 3a + 2a\times 3a)}\right)$

$= \frac{6}{D_p} \cdot \frac{6a^3}{4a^2 + 6a^2 + 12a^2}$

$= \frac{6}{D_p} \cdot \frac{6a^{\cancel{3}}}{22\cancel{a^2}} = \frac{18}{11}\frac{a}{D_p}$

$\frac{\pi}{6}D_p^3 = 6a^3$

$\frac{a}{D_p} = \sqrt[3]{\frac{\pi}{36}}$

$\Psi = 0.725$

17.7. Screen analysis and average diameters.

A screen analysis for a sample of Glauber's salt from a commercial crystallizer is as follows, where the crystals can be assumed to have a uniform sphericity and volume shape factor.

provided

U.S. Screen	Mass Retained, gm
14	0.0
16	0.9
18	25.4
20	111.2
25	113.9
30	225.9
35	171.7
40	116.5
45	55.1
50	31.5
60	8.7
70	10.5
80	4.4
	875.7

calculated

$\frac{.9}{875.7}$ $\frac{25.4}{875.7}$ $\frac{111.2}{875.7}$ $\frac{1139}{875.7}$

$\frac{0.029}{1.09}$ 0.029×1.09 $\frac{0.029}{1.092^2}$ $\frac{0.029}{1.092^3}$

	Differential Analysis						
% Mass retained	Average Particle Size, mm	Mass Fraction, xi	x/Dp	xDp	x/Dp^2	x/Dp^3
0.00						
0.10	1.290	0.0010	0.0008	0.0013	0.0006	0.0005
2.90	1.090	0.0290	0.0266	0.0316	0.0244	0.0224
12.70	0.925	0.1270	0.1373	0.1175	0.1484	0.1604
13.01	0.780	0.1301	0.1668	0.1015	0.2138	0.2741
25.80	0.655	0.2580	0.3938	0.1690	0.6013	0.9180
19.61	0.550	0.1961	0.3565	0.1078	0.6482	1.1785
13.30	0.463	0.1330	0.2876	0.0615	0.6219	1.3447
6.29	0.390	0.0629	0.1613	0.0245	0.4137	1.0607
3.60	0.328	0.0360	0.1098	0.0118	0.3354	1.0241
0.99	0.275	0.0099	0.0361	0.0027	0.1314	0.4777
1.20	0.231	0.0120	0.0519	0.0028	0.2247	0.9727
0.50	0.196	0.0050	0.0256	0.0010	0.1308	0.6673
100.00		1.0000	1.7543	0.6330	3.4945	8.1012

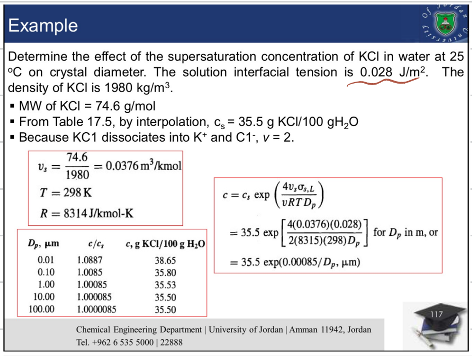
① $D_s = \frac{1}{\sum \frac{x_i}{D_{pi}}} = \frac{1}{1.7543} = 0.57\text{ mm}$

② $D_w = \sum x_i D_{pi} = 0.633 = 0.633\text{ mm}$

③ $D_N = \frac{\sum x_i/D_{pi}^2}{\sum x_i/D_{pi}^3} = \frac{3.4945}{8.1012} = 0.431\text{ mm}$

④ $D_v = \frac{1}{\left(\sum \frac{x_i}{D_{pi}^3}\right)^{1/3}} = \frac{1}{(8.1012)^3} = 0.498\text{ mm}$

Nucleation || Seader - sec 17.3.2



Example

Determine the effect of the supersaturation concentration of KCl in water at 25 °C on crystal diameter. The solution interfacial tension is 0.028 J/m². The density of KCl is 1980 kg/m³.

- MW of KCl = 74.6 g/mol
- From Table 17.5, by interpolation, c_s = 35.5 g KCl/100 gH_2O
- Because KC1 dissociates into K^+ and $C1^-$, $v = 2$.

$$v_s = \frac{74.6}{1980} = 0.0376\,\text{m}^3/\text{kmol}$$
$$T = 298\,\text{K}$$
$$R = 8314\,\text{J/kmol-K}$$

$$c = c_s \exp\left(\frac{4 v_s \sigma_{s,L}}{v R T D_p}\right)$$
$$= 35.5 \exp\left[\frac{4(0.0376)(0.028)}{2(8315)(298)D_p}\right] \text{ for } D_p \text{ in m, or}$$
$$= 35.5 \exp(0.00085/D_p, \mu\text{m})$$

D_p, µm	c/c_s	c, g KCl/100 g H_2O
0.01	1.0887	38.65
0.10	1.0085	35.80
1.00	1.00085	35.53
10.00	1.000085	35.50
100.00	1.0000085	35.50

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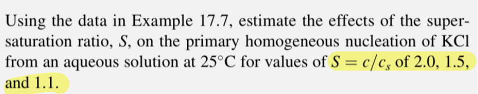


Using the data in Example 17.7, estimate the effects of the supersaturation ratio, S, on the primary homogeneous nucleation of KCl from an aqueous solution at 25°C for values of $S = c/c_s$ of 2.0, 1.5, and 1.1.

$$B^\circ = c \times \exp\left(\frac{16\pi \times \sigma^3 \times v_s^2 \cdot N_a}{3v^2 (RT)^3 \ln(c/c_s)^2}\right)$$

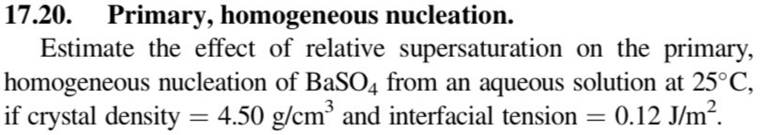
① $c/c_s = 2$

$$B^\circ = 10^{30} \times \exp\left(\frac{-16\pi \times 0.028^3 \times 0.0376^2 \times 6.022\times10^{26}}{3\times 2^2 \times (8315\times(25+273.15))^3 \times \ln(2)^2}\right)$$

① $B^\circ = 2.23 \times 10^{25}$

② For $c/c_s = 1.5$ $B^\circ = 2.55 \times 10^{16}$

③ For $c/c_s = 1.1$ $B^\circ = 0$



17.20. Primary, homogeneous nucleation.

Estimate the effect of relative supersaturation on the primary, homogeneous nucleation of $BaSO_4$ from an aqueous solution at 25°C, if crystal density = 4.50 g/cm³ and interfacial tension = 0.12 J/m².

$$\frac{M_w}{\rho} = \frac{233.4}{4.5\times1000} = 0.0518$$

0.12

6.22×10^{26}

$$B^\circ = c \times \exp\left(\frac{16\pi \times \sigma^3 \times v_s^2 \cdot N_a}{3v^2 (RT)^3 \ln(c/c_s)^2}\right)$$

2 8315 298

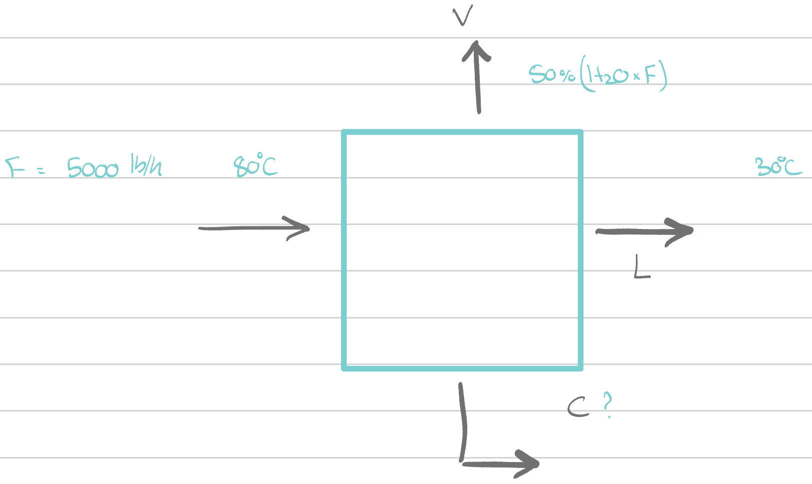
$c/c_s = S \rightarrow$ Try 50, 40, 30

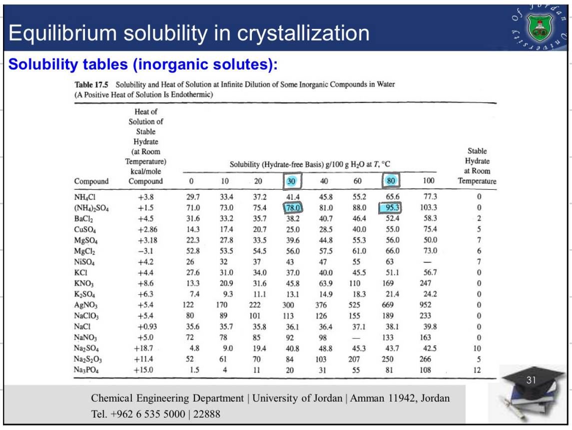
S	B°
50	1.25×10^{8}
40	2.34×10^{5}
30	10.64

Crystal growth || Seader - sec 17.3.3

17.9. Crystallization by cooling and evaporation.

Five thousand lb/h of a saturated aqueous solution of $(NH_4)_2SO_4$ at 80°C is cooled to 30°C. At equilibrium, what is the amount of crystals formed in lb/h? If during the cooling process, 50% of the water is evaporated, what amount of crystals is formed in lb/h?





Equilibrium solubility in crystallization

Solubility tables (inorganic solutes):

Table 17.5 Solubility and Heat of Solution at Infinite Dilution of Some Inorganic Compounds in Water (A Positive Heat of Solution Is Endothermic)

Compound	Heat of Solution of Stable Hydrate (at Room Temperature) kcal/mole Compound	Solubility (Hydrate-free Basis) g/100 g H_2O at T, °C								Stable Hydrate at Room Temperature
		0	10	20	30	40	60	80	100	
NH_4Cl	+3.8	29.7	33.4	37.2	41.4	45.8	55.2	65.6	77.3	0
$(NH_4)_2SO_4$	+1.5	71.0	73.0	75.4	78.0	81.0	88.0	95.3	103.3	0
$BaCl_2$	+4.5	31.6	33.2	35.7	38.2	40.7	46.4	52.4	58.3	2
$CuSO_4$	+2.86	14.3	17.4	20.7	25.0	28.5	40.0	55.0	75.4	5
$MgSO_4$	+3.18	22.3	27.8	33.5	39.6	44.8	55.3	56.0	50.0	7
$MgCl_2$	−3.1	52.8	53.5	54.5	56.0	57.5	61.0	66.0	73.0	6
$NiSO_4$	+4.2	26	32	37	43	47	55	63	—	7
KCl	+4.4	27.6	31.0	34.0	37.0	40.0	45.5	51.1	56.7	0
KNO_3	+8.6	13.3	20.9	31.6	45.8	63.9	110	169	247	0
K_2SO_4	+6.3	7.4	9.3	11.1	13.1	14.9	18.3	21.4	24.2	0
$AgNO_3$	+5.4	122	170	222	300	376	525	669	952	0
$NaClO_3$	+5.4	80	89	101	113	126	155	189	233	0
$NaCl$	+0.93	35.6	35.7	35.8	36.1	36.4	37.1	38.1	39.8	0
$NaNO_3$	+5.0	72	78	85	92	98	—	133	163	0
Na_2SO_4	+18.7	4.8	9.0	19.4	40.8	48.8	45.3	43.7	42.5	10
$Na_2S_2O_3$	+11.4	52	61	70	84	103	207	250	266	5
Na_3PO_4	+15.0	1.5	4	11	20	31	55	81	108	12

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$X_F = 0.488 \times 5000 = 2439.8$ lb $(NH_4)_2SO_4$

$= 2560$ lb H_2O

$V = 50\% \, (2560) = 1280.08$

@ 30°C → 78 g/100g H_2O

@ 80°C → 95.3 g/100g H_2O

water in solution

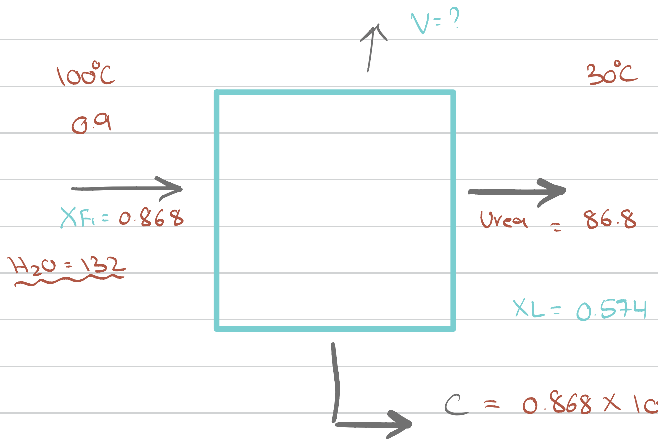
$\frac{78}{100} \times 1280.08 = 998.46$ Kg

$C = 2439.8 - 998.46 = \boxed{1441.33 \text{ Kg}}$

17.12. Crystallization by cooling and evaporation.

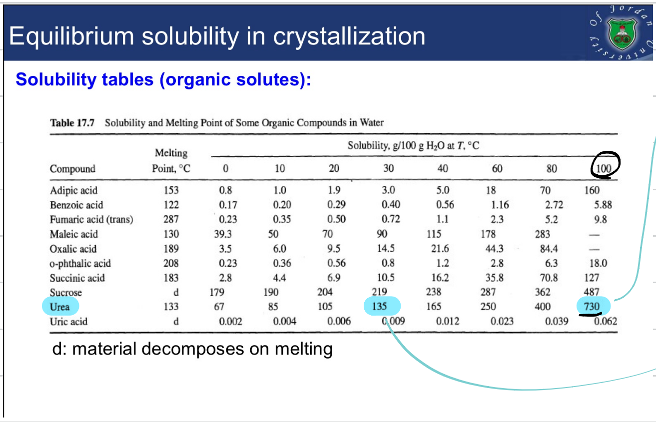
Urea is to be crystallized from an aqueous solution that is 90% saturated at 100°C. If 90% of the urea is to be crystallized in the anhydrous form and the final solution temperature is to be 30°C, what fraction of the water must be evaporated?

Basis 1000 Kg Feed



$L = \frac{86.8}{0.574} = 151.22$

$C = 0.868 \times 1000 \times 0.9 = 781.2$



Equilibrium solubility in crystallization

Solubility tables (organic solutes):

Table 17.7 Solubility and Melting Point of Some Organic Compounds in Water

Compound	Melting Point, °C	Solubility, g/100 g H_2O at T, °C 0	10	20	30	40	60	80	100
Adipic acid	153	0.8	1.0	1.9	3.0	5.0	18	70	160
Benzoic acid	122	0.17	0.20	0.29	0.40	0.56	1.16	2.72	5.88
Fumaric acid (trans)	287	0.23	0.35	0.50	0.72	1.1	2.3	5.2	9.8
Maleic acid	130	39.3	50	70	90	115	178	283	—
Oxalic acid	189	3.5	6.0	9.5	14.5	21.6	44.3	84.4	—
o-phthalic acid	208	0.23	0.36	0.56	0.8	1.2	2.8	6.3	18.0
Succinic acid	183	2.8	4.4	6.9	10.5	16.2	35.8	70.8	127
Sucrose	d	179	190	204	219	238	287	362	487
Urea	133	67	85	105	135	165	250	400	730
Uric acid	d	0.002	0.004	0.006	0.009	0.012	0.023	0.039	0.062

d: material decomposes on melting

@ 100°C → 730 g/100g H_2O Feed 90% saturated

730×0.9 = 657 g/100g H_2O

@ 30°C → 135 g/100g H_2O

Water evaporated ?

H_2O Balance

(151.22 − 86.8) = 64.42 Kg in L

132 − 64.42 = 67.58 Kg

Fraction water $= \frac{67.58}{132} = \boxed{0.512}$

17.11. Continuous vacuum crystallization.

A concentrate from an evaporation system is 5,870 lb/h of 35 wt% $MgSO_4$ at 180°F and 25 psia. It is mixed with 10,500 lb/h of saturated aqueous recycle filtrate of $MgSO_4$ at 80°F and 25 psia. The mixture is sent to a vacuum crystallizer, operating at 85° F and 0.58 psia, to produce steam and a magma of 25 wt% crystals and 75 wt% saturated solution. Determine the lb/h of water evaporated and the maximum production of crystals in tons/day (dry basis).

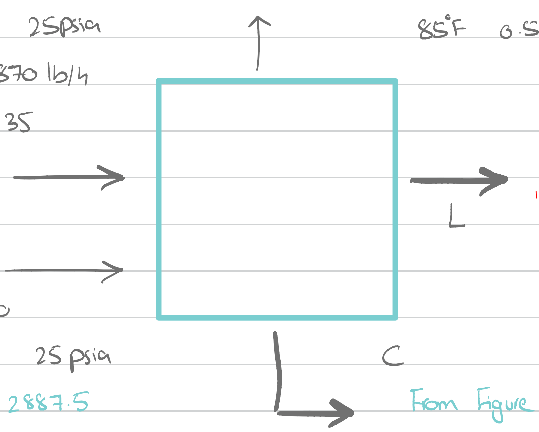
V=?

180°F 25psia

$MgSO_4 = 2054.5$ kg , $F_1 = 5870$ lb/h

$H_2O = 3815.5$ kg , $X_F = 0.35$

85°F 0.58 psia



F_2

R= 10,500

80°F 25 psia

$MgSO_4 = 2887.5$

$H_2O = 7612.5$

$M = \overset{0.25M}{C} + \overset{0.75M}{L}$

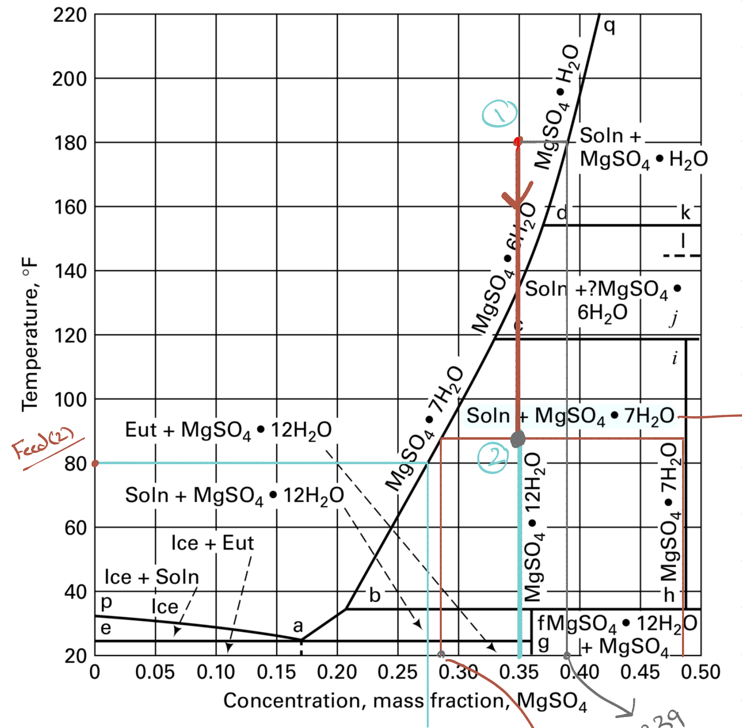
$C = 0.25(C+L)$

$C - 0.25C = 0.25L \rightsquigarrow \frac{0.75}{0.25}C = L$

From Figure $MgSO_4 \cdot 7H_2O$

$X = \frac{Mw\ MgSO_4}{Mw\ total}$

$= \frac{120.4}{246.4} = 0.488$



$MgSO_4 \cdot 7H_2O$

$MgSO_4$ in H_2O

0.275

For Feed (2)

$X_L = 0.28$

$MgSO_4$ in water

$MgSO_4$ Balance

$2054.5 + 2887.5 = 0.488C + 0.28L$

$4942 = 0.488C + 0.28L$

$\hookrightarrow \frac{0.75C}{0.25}$

C= 3721 lb/h L= 11,164

$3721 \frac{lb}{h} \times \frac{24h}{1day} \times \frac{ton}{2000lb}$

$\boxed{= 44.652 \frac{ton}{day}}$

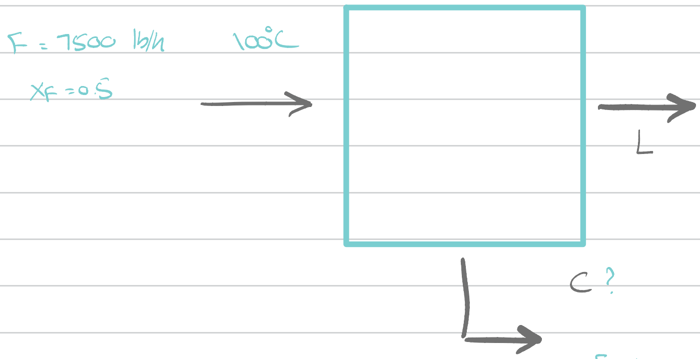
V=?

$5870 + 10,500 = V + 11164 + 3721$

$\boxed{V = 1485\ lb/h}$

17.10. Crystallization by cooling.

7,500 lb/h of a 50 wt% aqueous solution of $FeCl_3$ at 100°C is cooled to 20°C. At 100°C, the solubility of the $FeCl_3$ is 540 g/100 g of water. At 20°C, the solubility is 91.8 g/100 g water, and crystals of $FeCl_3$ are the hexahydrate. At equilibrium at 20°C, determine the lb/h of crystals formed.



$S = \frac{91.8g}{100g\ water}$

$X_L = 0.4786$

$FeCl_3 \cdot 6H_2O$

$x = \frac{162.2}{162.2 + 6 \times 18} = 0.6$

$7500 = L + C$

$7500(0.5) = L(0.4786) + C(0.6)$

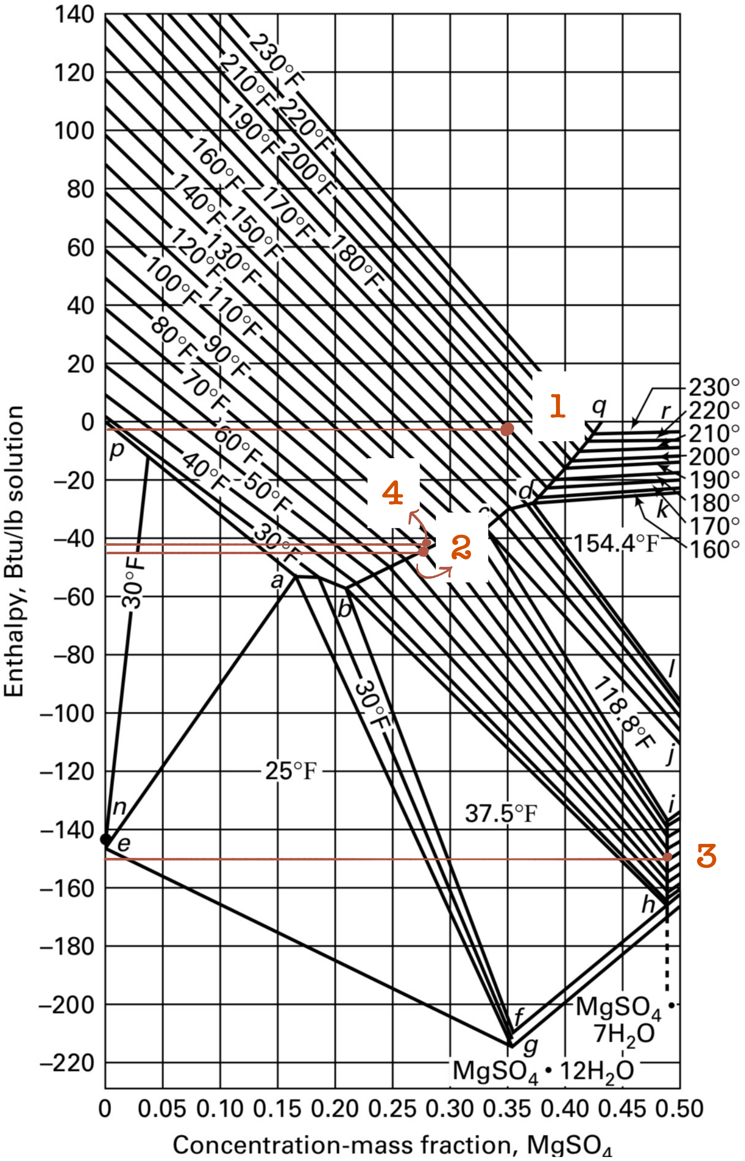
$L = 6178\ Kg$ $\boxed{C = 1322.07\ Kg}$

17.14. Heat addition to a crystallizer.

For Exercise 17.11, determine the rate at which heat must be added to the system.

Enthalpy Balance :

$$\overset{\text{Feed 1}}{m_{F_1} H_{F_1}} + \overset{\text{Feed}}{m_{F_2} H_{F_2}} + \underset{?}{\underline{Q}} = \overset{\text{Cry}}{C H_c} + \overset{\text{V}}{H_v V} + \overset{\text{L}}{H_L \cdot L}$$



① $x_{F_1} = 0.35$ @ 180°F → H = -3

② $x_{F_2} = 0.275$ @ 80°F → H = -44

③ $x_c = 0.488$ @ 85°F → H = -148

④ $x_L = 0.28$ @ 85°F → H = -43

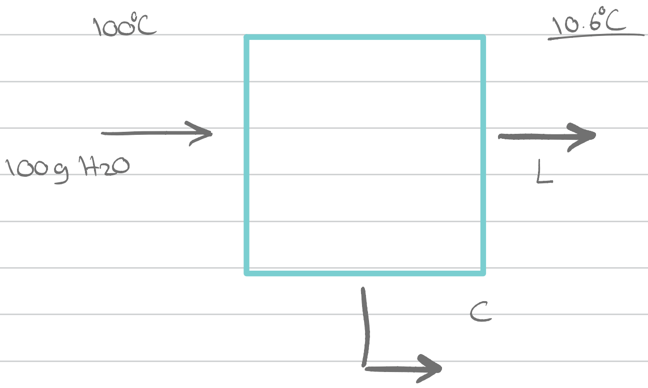
⑤ H_v at 85°F + 0.58 psia = 1099

Q = 1084334 Btu/h

17.15. Heat removal from a cooling crystallizer.

For Example 17.4, calculate the amount of heat in calories/100 grams of water that must be removed to cool the solution from 100 to 10.6°C.

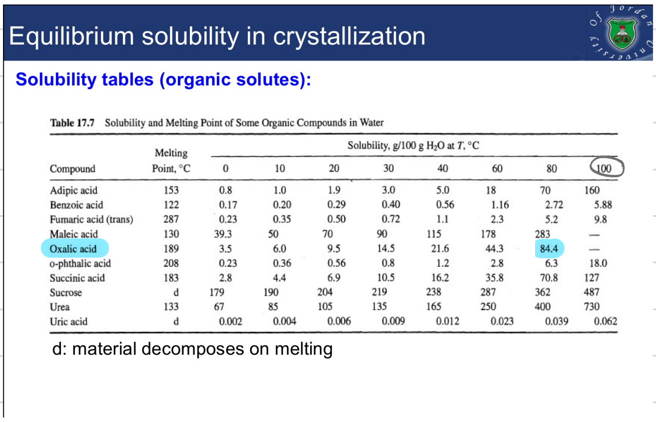
Given :- 95% of oxalic acid crystallized



$cp = \frac{0.76\ cal}{g \cdot °C}$

$Hc = 8580\ \frac{cal}{mol} \times 0.891\ mol = 7644.78\ cal$

$oxalic = \frac{80.29}{90\ g/mol} = 0.891\ mol$



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Uric acid	d	0.002	0.004	0.006	0.009	0.012	0.023	0.039	0.062

d: material decomposes on melting

$\frac{84.4\ g}{100\ g\ H_2O}$

Feed = 84.4 g Oxalic Acid × 0.95

C = 80.2

L = 4.22

$q = Fcp(T_2 - T_1) - Hc$

$= 184.4 \times 0.76(10.6 - 100) - 7644.78$

$\boxed{Q = -20173}$ heat must be removed