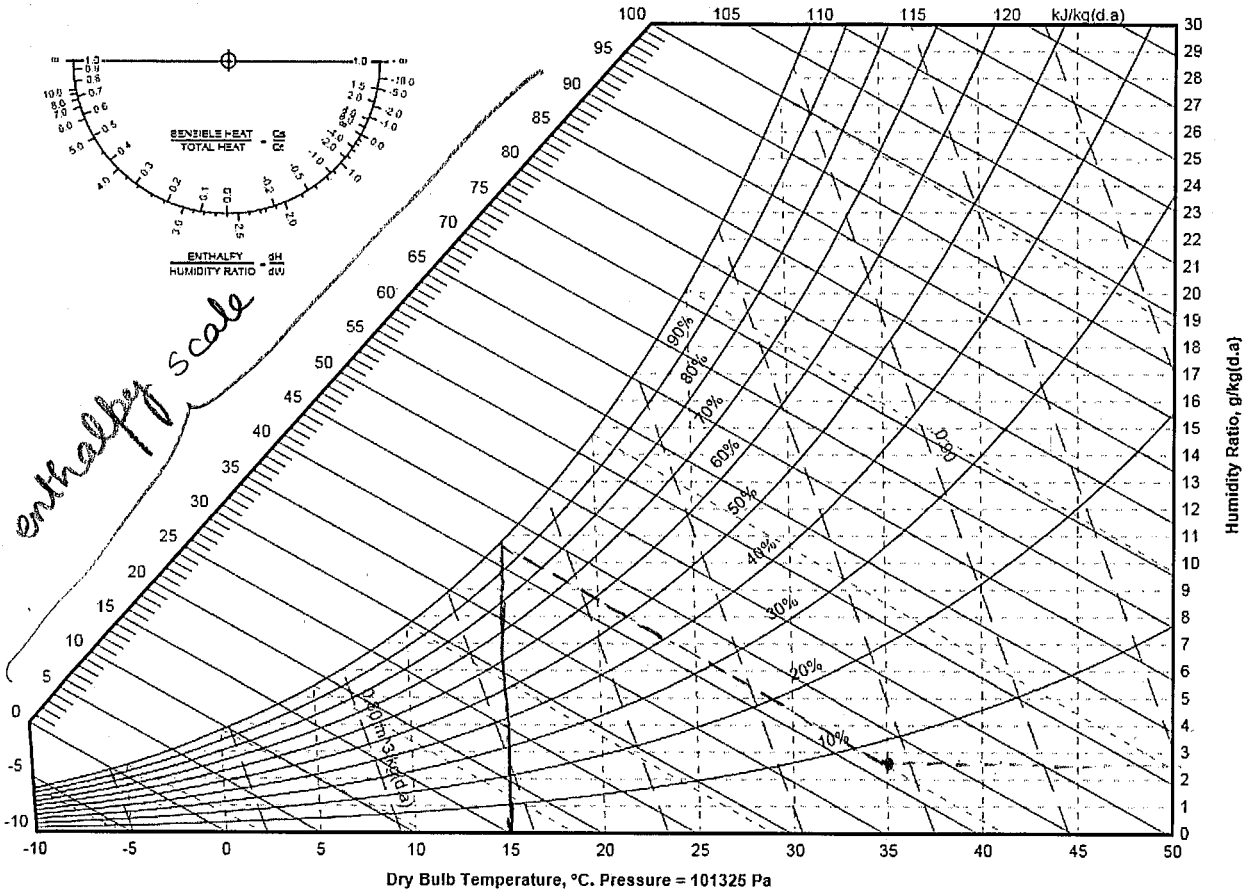


1. **Problem 1. (20 Points)** You plan to dry your wet clothes by hanging them in your room and opening windows on the opposite sides of the room so that air can flow over the clothes. The air enters at 35 °C with a wet bulb temperature of 15 °C. Assume your room is adiabatic, which means that there is no heat flow into or out of the room. Consider only the initial time when the clothes are wet and drying occurs at a constant rate.



- a. (5 points) What is the inlet air humidity in g moisture per kg dry air and RH percentage?

$H = 2.5 \text{ g/kg dry air}$ (+2.5)

$RH < 10\%$. (7-10% accepted) (+2.5)

- b. (5 points) What will be the equilibrium temperature of the cloth? Explain your answer.

+2.5 { The setup replicates wet-bulb temperature experiment. The wet cloth will saturate the air around it, lowering its temp. to T_w . Cloth, in equilibrium with air will also be at T_w

$T_{cloth} = 15^\circ\text{C}$ (+2.5)

- c. (10 points) Calculate the rate of drying. The heat transfer coefficient is $h = 62.45 \text{ J/s-m}^2\text{-K}$, and the latent heat of vaporization of water at the equilibrium temperature is $\lambda = 2400 \text{ kJ/kg}$.

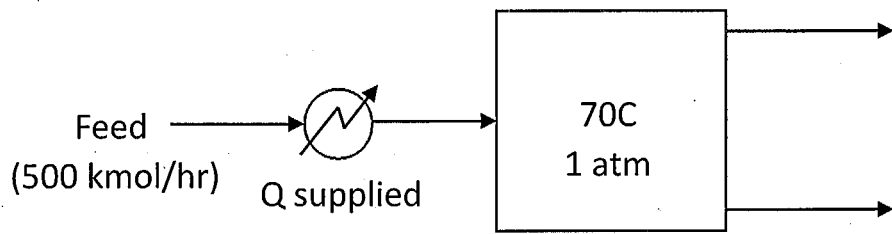
energy balance: $A \cdot h (T_{air} - T_{cloth}) = \lambda N_w \cdot A \quad (+4)$

$N_w \text{ (drying rate)} = \frac{62.45 \times (35 - 15)}{2400 \times 10^3} \frac{\cancel{\text{J}}}{\cancel{\text{m}^2} \times \cancel{\text{J}}} \frac{\text{kg}}{\cancel{\text{s}}}$

+3 for correct temp
35 & 15 C

$= \underbrace{5.2 \times 10^{-4}}_{+1} \underbrace{\text{kg/m}^2\text{s}}_{+2}$

2. **Problem 2. (30 Points)** An ethanol-benzene mixture containing 30 mol% ethanol undergoes flash distillation at 70 °C and 1 atm, as shown in the figure below. The surroundings are at 27 °C.

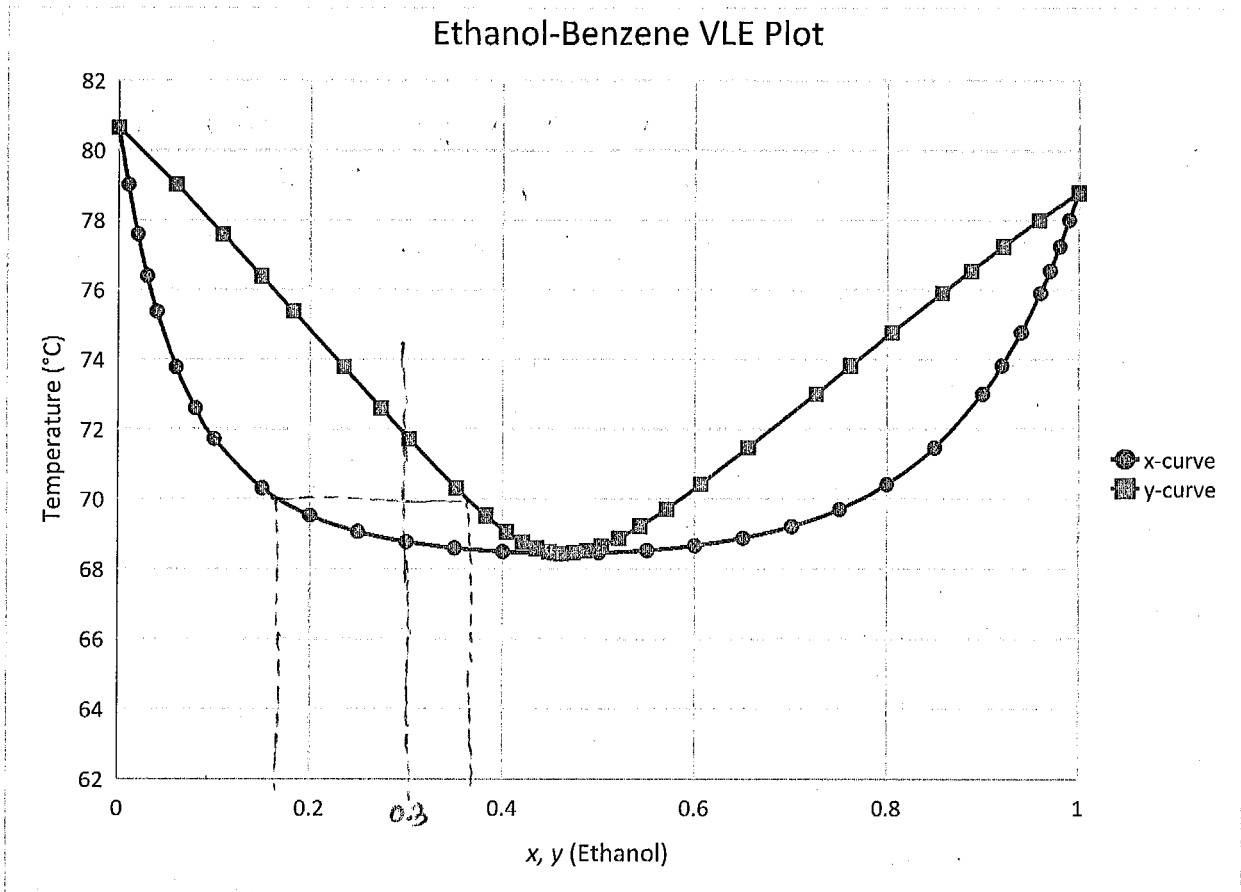


- a. (5 points) What are the feed dew point and bubble point temperatures?

From plot (follow vertical line from feed point)

$T_{bubble} \sim 69^\circ\text{C} \quad +2.5$

$T_{dew} \sim 72^\circ\text{C} \quad +2.5$



- b. (10 points) What are the compositions and flow rates of the exiting vapor and liquid phases?

From graph, vapor composition $y \sim 0.36$ (+2.5)
 liquid composition $x \sim 0.16$ (+2.5)

Doing mole balance

$$F = V + L \Rightarrow 500 = V + L \quad (+2)$$

$$Fz_i = Vy_i + Lx_i \Rightarrow (500)(0.3) = V(0.36) + L(0.16) \quad (+2)$$

$$\text{Solving, } \left. \begin{aligned} V &= 350 \text{ kmol/hr} \\ L &= F - V = 150 \text{ kmol/hr} \end{aligned} \right\} (+1)$$

Graphical approach also accepted

c. (5 points) What is an azeotrope? At what composition does this mixture behave as an azeotrope?

A mixture is azeotrope when liquid & gas phases have same composition ($x=y$) (+2.5)

This mixture is azeotrope at $x=y \approx 0.45$ (+2.5)

d. (10 points) Steam at 150 °C is used to transfer Q. Calculate Q and the second-law efficiency of the process given the following information.

	Feed	Vapor	Liquid
Enthalpy (kJ/mol)	18	25	20
Entropy (J/mol-K)	30	42	32

Energy Balance: $Q + Fh_f = Vh_v + Lh_l$ (+2)

$$Q = (25)(350 \times 10^3) + (20)(150 \times 10^3) - (500 \times 10^3)(18)$$

$$= 2.75 \times 10^6 \text{ kJ/hr}$$
 (+1)

$\eta = \frac{W_{min}}{LW + W_{min}}$ (+2)

where $W_{min} = \sum_{out} mb - \sum_{in} mb$ (+2)

$$LW = \sum_{in} \left[mb + Q \left(1 - \frac{T_0}{T_{in}} \right) \right] - \sum_{out} \left[mb + Q \left(1 - \frac{T_0}{T_{out}} \right) \right]$$

$$= Q \left(1 - \frac{T_0}{T_{in}} \right) + \sum_{in} mb - \sum_{out} mb$$
 (+2)

Calculating $LW = (2.75 \times 10^9) \left[1 - \frac{300}{423} \right] + (500 \times 10^3) \left[18 \times 10^3 - (300)(30) \right]$

$$- (350 \times 10^3) \left[25 \times 10^3 - (300)(42) \right] - (150 \times 10^3) \left[20 \times 10^3 - (300)(32) \right]$$

$$= (0.8 \times 10^9) + (4.5 \times 10^9) - (4.34 \times 10^9) - (1.56 \times 10^9)$$

$$= -0.6 \times 10^9 \text{ kJ/hr} < 0$$

System will have $\eta > 100 \rightarrow$ unphysical } +1 for explanation
 work output is greater than work input
 or entropy is -ve [NOTE: from thermo, the total entropy of universe + system must be +ve always]

Problem 3. (20 Points) SO₂ contained in air is absorbed into pure water. A column with 6 stages operating at 50% efficiency is used. The feed molar flow rate of the air, which contains 5x10⁻⁶ vol% SO₂, is 100 kmol/h. The molar flow rate of the pure water is 500 kmol/h. The geometric average of the equilibrium constant, K, is 2 at the operating conditions of the column.

a. (5 points) What is the value of the effective absorption factor?

$$A = \frac{L}{\sqrt{K}}$$

Assume $A_e = A$

→ dilute solute and assume no air dissolving into water or water evaporating into air

∴ L, V constant throughout column

→ avg. K given

$$A = \frac{(500 \text{ kmol/h})}{\left(\frac{100 \text{ kmol}}{h}\right)(2)}$$

$$A = A_e = 2.5$$

b. (10 points) The EPA requires a maximum SO₂ mole composition in air of $y = 0.075 \times 10^{-6}$ (i.e., 75 ppb). Will the column successfully meet these EPA standards? Briefly explain 2 assumptions used in your calculations.

$$\text{Vol\%} = \text{mol\%} \rightarrow y_{in} = \frac{5 \times 10^{-6}}{100} = 5 \times 10^{-8}$$

% → fraction →

Inlet mole fraction already meets EPA standards, so yes

Assumptions

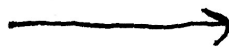
- 1.) Constant L, V (dilute solute)
- 2.) No air dissolved in water or water evaporating in air
- 3.) Ideal gas for air (mol% = vol%)
- 4.) No degradation of column over time from SO₂

c. (5 points) Assuming the column always operates at 50% efficiency, explain how you could change at least 3 different parameters to reduce the SO₂ concentration even further.

Changed parameter

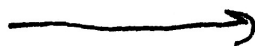
Explanation

1.) Increase P



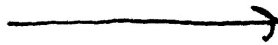
Decrease K (increases A_e)
 $K_i = \frac{y_i}{x_i} = \frac{P_i^{sat}}{P}$

2.) Decrease T



Decrease K (increases A_e)
 $\log_i^{sat} \approx A - \frac{B}{C+T}$

3.) Increase # stages



More opportunity for separations

4.) Increase L



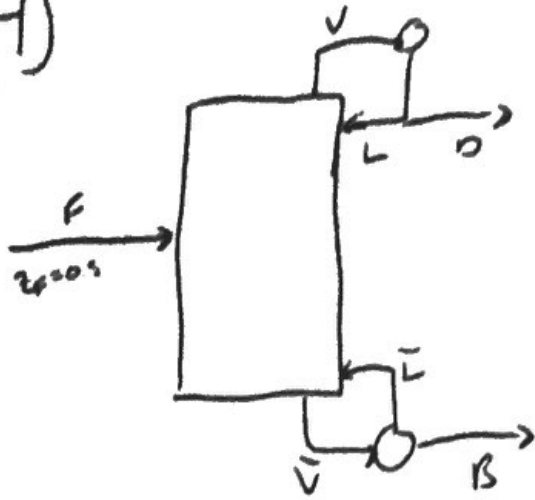
A_e increased

5.) Use a solvent w/ higher affinity for SO₂ →

6.) Multiple columns in series →

Lower K (higher A_e)
 More opportunity for separations

(4)



$F = 100 \text{ kmol/h}$
 $z_F = 0.5$

$R/R_{min} = 4/3$

$R/R_{min} = 2$

$0.9 z_F F = x_D D$

$x_D = 0.8$

$C_{HD} = V \cdot \eta / \text{kmol}$

$C_{strip} = 810 / \text{strip} \cdot \text{hr}$

(a) D, B, x_B

(+1) $D = 0.9 \frac{z_F F}{x_D} = 0.9 \frac{0.5}{0.8} (100 \text{ kmol/hr})$

(+0.5) $D = 56.25 \text{ kmol/hr}$

(+1) $B = F - D = 100 - 56.25$

(+0.5) $B = 43.75 \text{ kmol/hr}$

(+1) $x_B = \frac{z_F F - x_D D}{B} = 0.1 z_F \frac{F}{B} = (0.1)(0.5) \left(\frac{100}{43.75} \right)$

(+1) $x_B = 0.114$

(b) Determine R_{min}

q-line has slope: $\frac{0.8}{0.8-1} = -4$, and begins on 45° line @ $\frac{q}{q-1}$

$y=x=0.5$. It therefore intersects w/ equilibrium curve @

$$(y, x) = (0.64, 0.48)$$

R_{min} line can't reach this point w/o crossing equilibrium line, so

R_{min} line tangent to eq. line @

$$(y, x) = (0.7, 0.6)$$

$$\text{slope} = \frac{0.8-0.7}{0.8-0.6} = \frac{1}{2} = \frac{R_{min}}{R_{min}+1} \Rightarrow \boxed{R_{min} = 1}$$

(c) N, feed stage location

$$R/R_{min} = 4/3$$

$$\text{slope} = \frac{4/3}{7/3} = 4/7$$

stepping off on chart

: from bottom: 16 steps

+ reboiler.

Feed stage: 2nd stage

from bottom

$$R/R_{min} = 2$$

$$\text{slope} = \frac{2}{2+1} = 2/3$$

stepping off on chart from bottom:

9 stages + reboiler

Feed stage: 1st stage

from bottom (above reboiler)

Partial credit

(d) which R/R_{min} is cheaper?

$$V = (R+1) D \quad (+2)$$

$$\textcircled{+1} \quad V_1 = \left(\frac{7}{3}\right) D \quad N_1 = 16$$

$$\textcircled{+1} \quad V_2 = (3) D \quad N_2 = 9$$

$$\textcircled{+2} \quad C_1 = \left(\frac{7}{3} D\right) \$1/\text{kwhl} + (16) \$10/\text{stage}\cdot\text{hr} =$$

$$C_1 = \$291.25/\text{hr}$$

P.O.E.
ok.

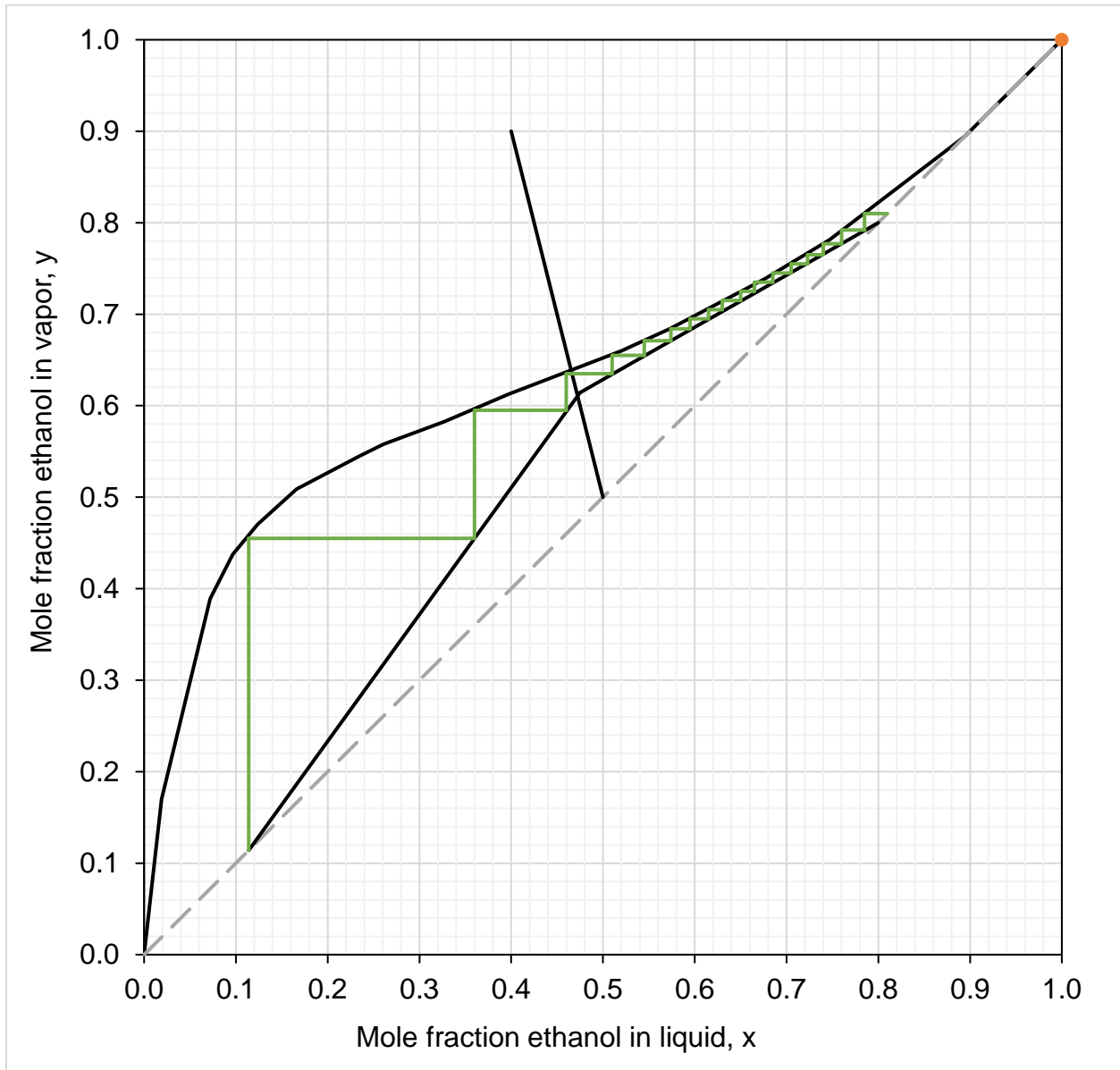
$$\textcircled{+2} \quad C_2 = (3D) \$1/\text{kwhl} + (9) \$10/\text{stage}\cdot\text{hr} =$$

$$C_2 = \$258.75/\text{hr}$$

so, $R/R_{\min} = 2$ is cheaper to operate

$\textcircled{+2}$ for justified answer.

R/Rmin = 4/3



R/Rmin = 2

