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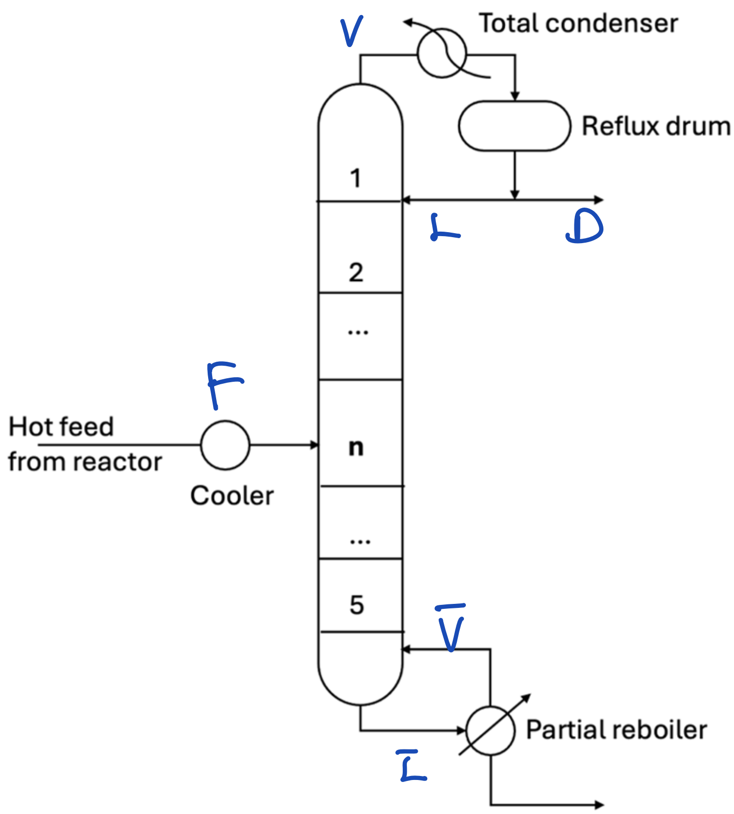
Problem 1. (25 points)

You are a chemical engineer at Bear Chemical, responsible for overseeing a distillation column used to separate a methanol-water mixture. Last night, a powerful storm swept through the town, causing unexpected disturbances to the system. Your task is to analyze and troubleshoot the issue.

- The column has 5 plates, a total condenser and a partial reboiler.
- A cooling chamber (or cooler) is used to cool down the feed before entering the column to prevent combustion and improve the purity of distillate.
- The pressure indicator shows a normal reading of 101 kPa.
- A feed of 100 kmol/h of 50 mol% methanol was sent to the n-th tray, the optimal location for the feed.
- The column is designed to produce distillate of 90 mol% methanol and bottoms of 10 mol% methanol, with a reflux ratio of 1.



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5 pts

(a) Fill out *Table 1* for the normal operation with only numbers. Show your calculation below the table.

Stream	molar flow rate (kmol/h)	methanol fraction (mol%)
+1 Feed (F)	100	50%
+1 Bottoms (B)	50	10%
+1 Distillate (D)	50	90%
+1 Overhead vapor (V)	100	

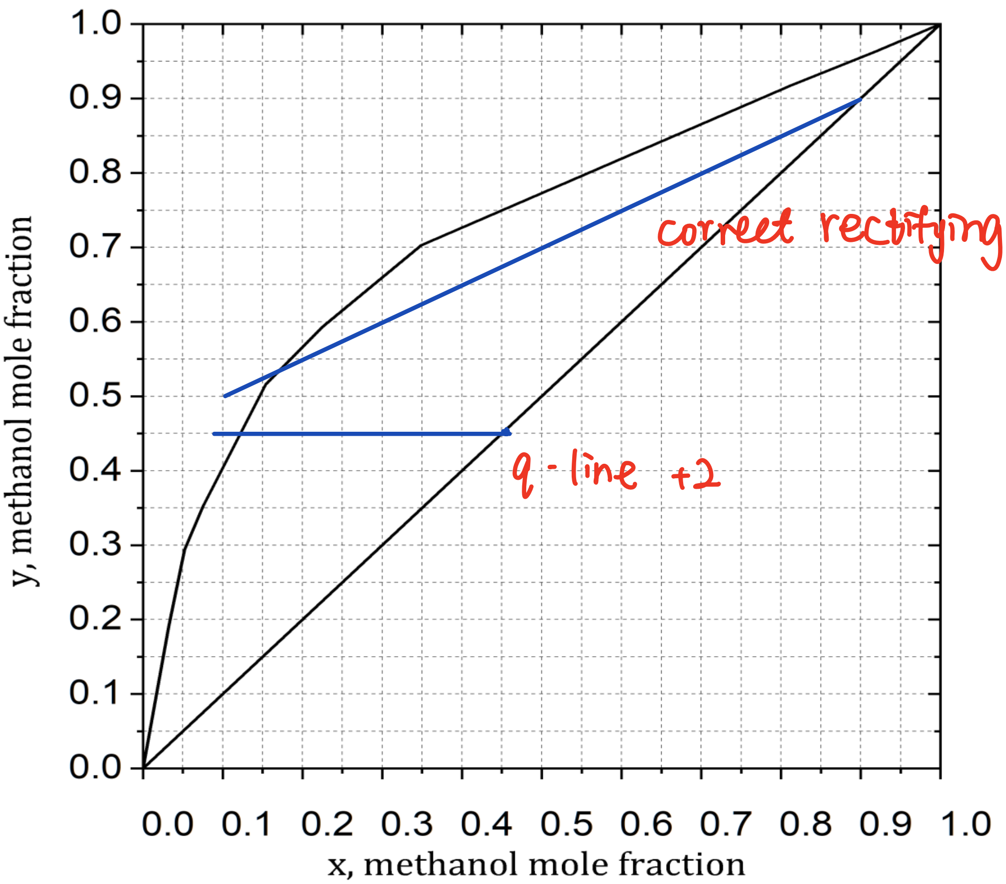
$$\boxed{\begin{cases} z_F F = x_D D + x_B B \\ F = D + B \end{cases}} \quad \begin{cases} 0.5 \times 100 = 0.9D + 0.1B \\ 100 = D + B \end{cases} \Rightarrow \begin{cases} B = 50 \\ D = 50 \end{cases} \quad V = L + D = RD + D = 2D$$

correct eqn. +1

(b) Use the chart provided. Is it possible for the feed to be saturated vapor? Show on the graph and explain with one sentence.

$$\frac{L}{V} = \frac{1}{2}$$

5 pts



No. because q-line can't intersect w/ rectifying line below the equilibrium line +1

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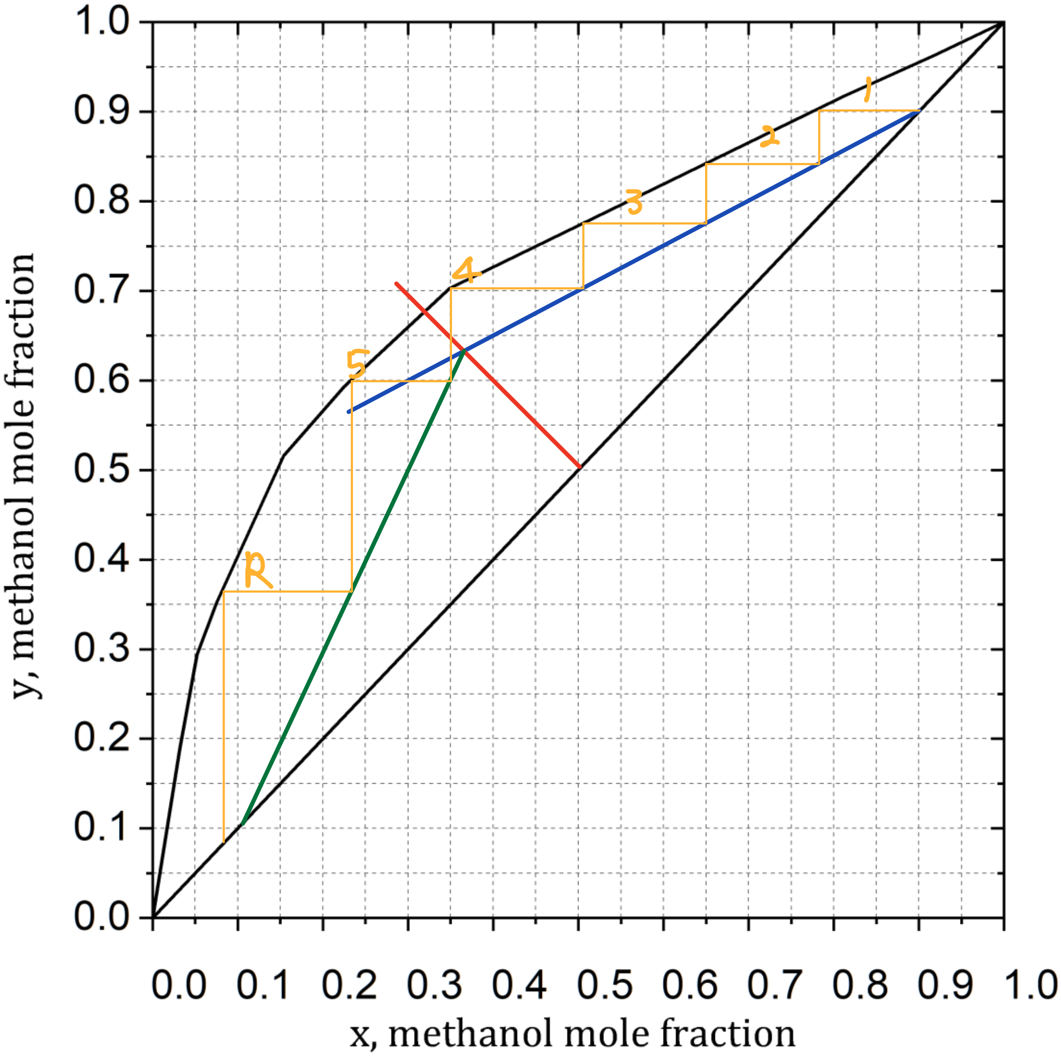
6pts (c) If the feed enters the column with a 50% vaporized fraction. Determine the total number of theoretical stages and the optimal feed stage number.

$$\frac{q}{q-1} = \frac{0.5}{0.5-1} = -1$$



q-line +1

rectifying +1

stripping +1

thereotical stages N = 6 +2

optimal feed stage number

n = 4 +1

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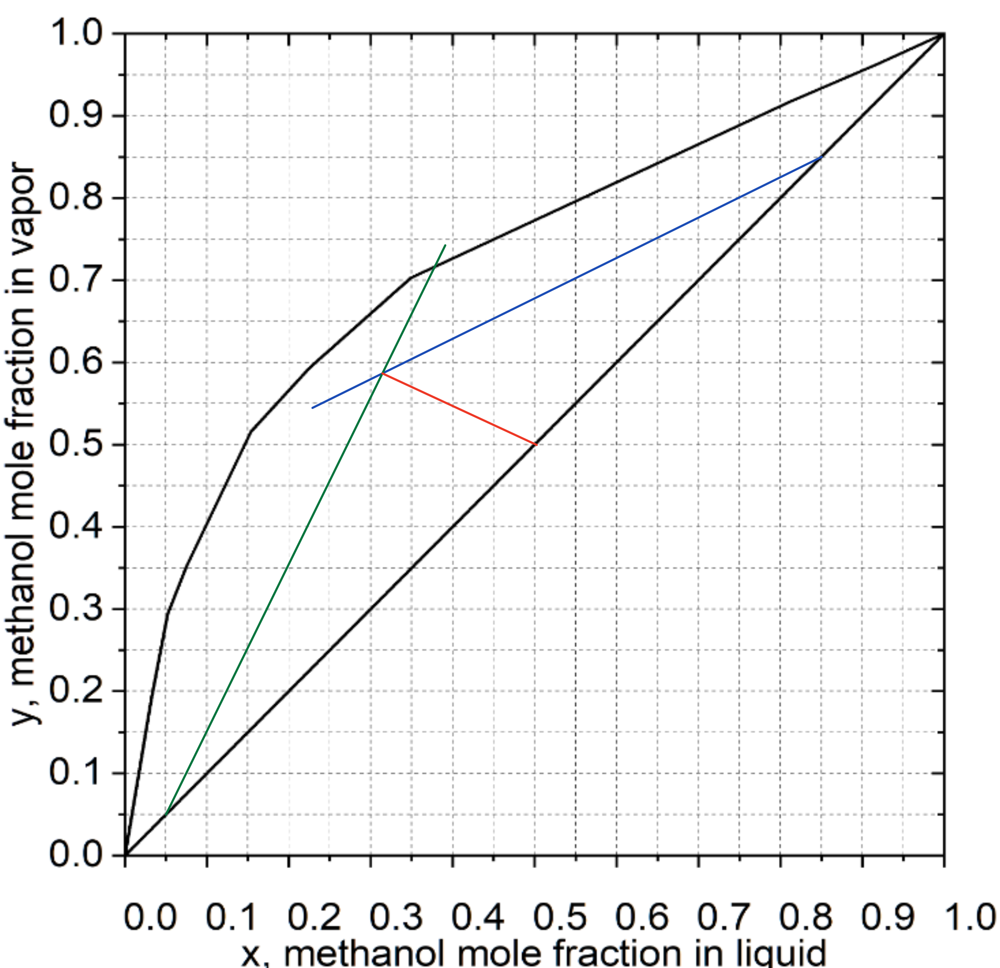
6pts

(d) You inspect the column and confirm that all plates are functioning well and the feed is entering at the optimal location. However, different data is reported in Table 2 for the abnormal operation. Based on Table 2, estimate the vaporized fraction (in percent) of the feed using the figure below.

Stream	molar flow rate (kmol/h)	methanol fraction (mol%)
Feed (F)	100	50
Bottoms (B)	43.75	5
Distillate (D) √	56.25	85
Overhead vapor (V) √	112.5	
Boilup vapor ($\bar{V}$)	43.75	

Table 2. Table 1. Records of the abnormal operation



$\frac{V-D}{V}$

$\frac{L}{V} = \frac{56.25}{112.5} = \frac{1}{2}$ → rectifying line (+2)

$\frac{V_B+1}{V_B} = \frac{\bar{V}/B+1}{\bar{V}/B} = \frac{1+1}{1} = 2$ → stripping line (+2)

q line

$\frac{q}{q-1} = -0.45$ (+1)

$q = 0.31$

vaporized fraction $= 1-q$

$= 69\%$ (+1)

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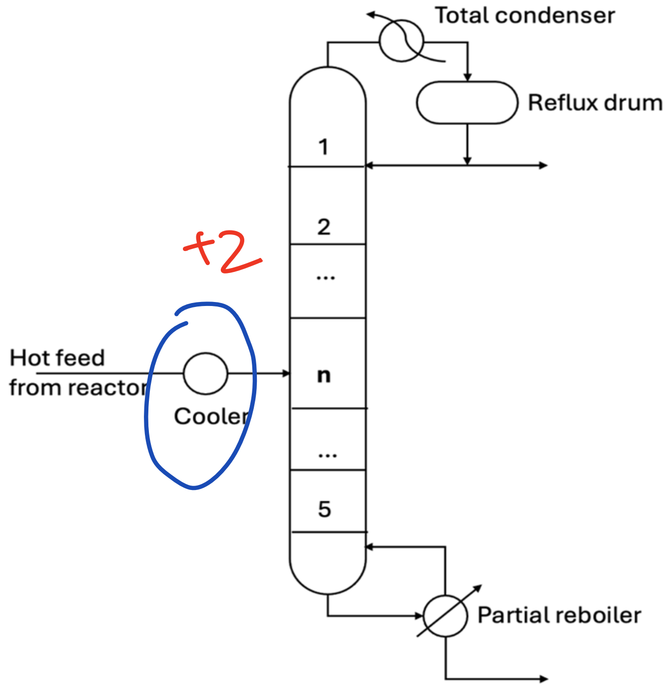
3 pts (e) Compare your result in part (c) and (d), circle the part of the schematic where failure most likely occurs and explain with one sentence.



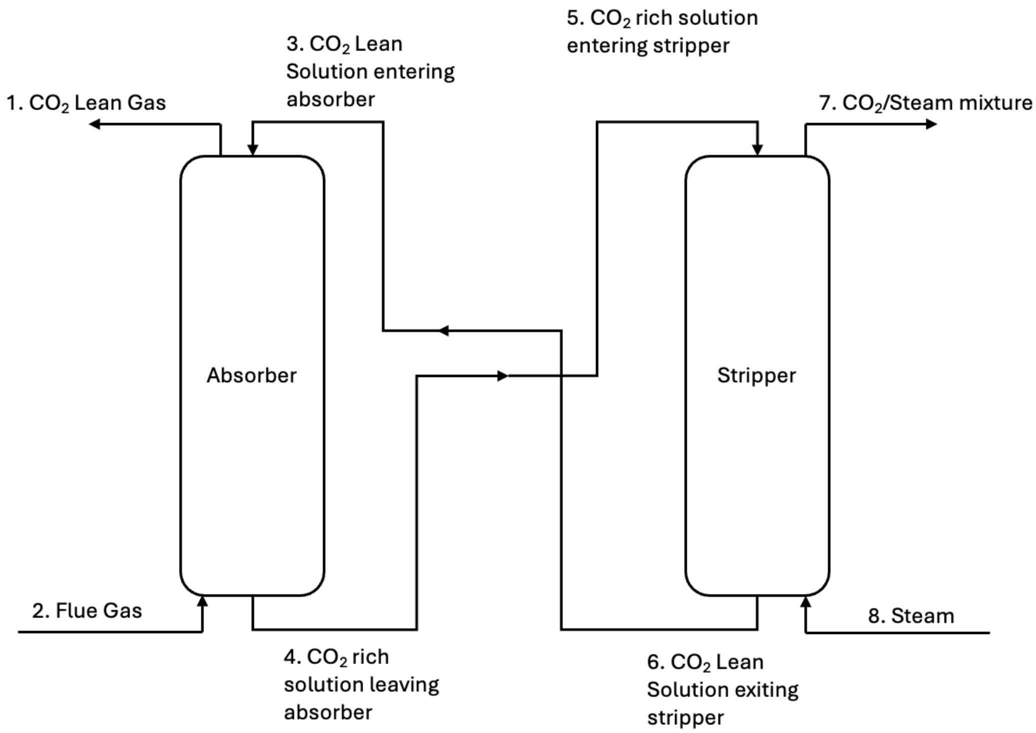
trouble shoot:

① reflux ratio R=1 the same

② boilup ratio $\bar{V}/B = 1$ the same

only possible variance: the feed vaporizd fraction (1-q) increased, which implies cooler failed to cool down the hot feed +1

You are tasked to design a carbon capture system that uses an amine solution in the absorber to absorb the CO_2. The Absorber is coupled with a stripper that uses steam to regenerate the absorbant. A set-up is shown below.

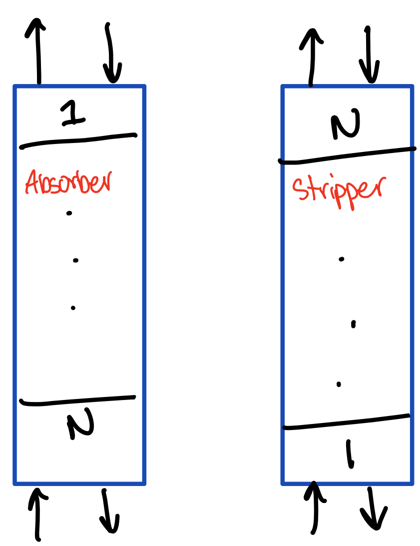


Note: Stream 6 and 3 have the same composition & Streams 4 and 5 have the same composition

A. Label streams 1-8 on the Absorber and Stripper (i.e. Y_0, Y_{N+1}, X_1 etc).

+0.5 pts for each correct label

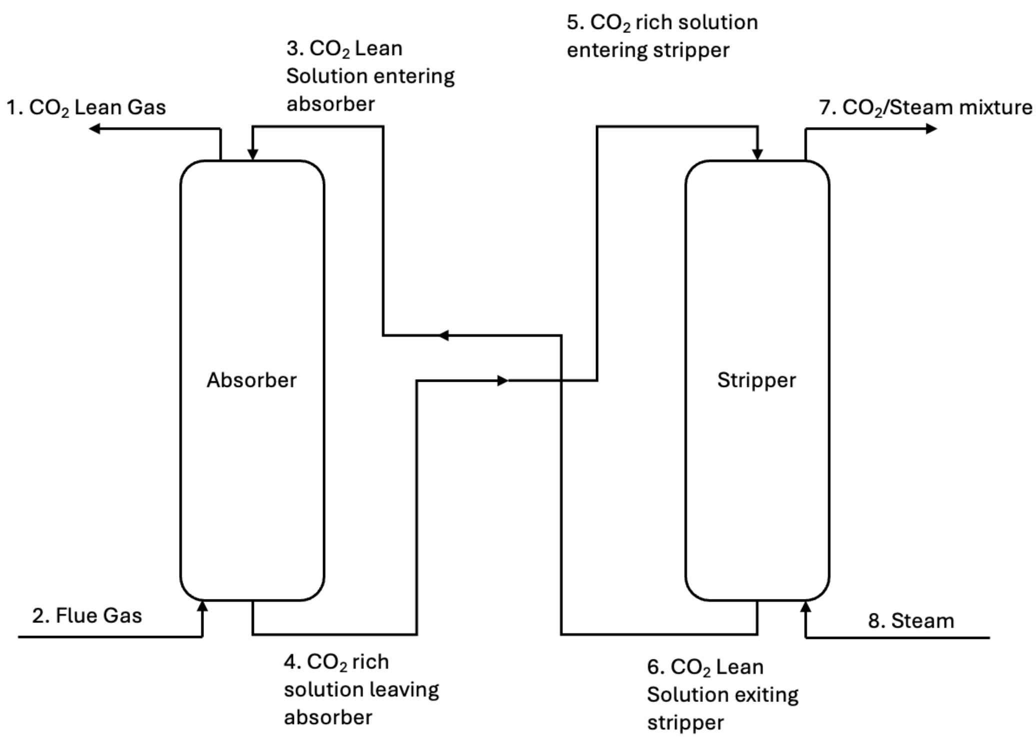
Stream	Label
1	Y_1
2	Y_{N+1}
3	X_0
4	X_N
5	X_{N+1}
6	X_1
7	Y_N
8	Y_0



The CO_2 rich gas enters the absorber with 14.9 mol% (y) CO_2 at a flow rate of 10 kmol/s. The amine solution enters the absorber with a CO_2 concentration of 3.9 mol% (x) at a flow rate of 13.91 kmol/s. The recovery of CO_2 is 71.4%.

B. Calculate the mole ratio of CO_2 in the flue gas (stream 2), the CO_2 lean gas (stream 1), the CO_2 lean amine solution (stream 3), and the CO_2 rich amine solution (stream 4).

		X	Y
Y_1	Stream 1		0.05
Y_{N+1}	Stream 2		0.175
X_0	Stream 3	0.041	
X_N	Stream 4	0.118	



Note: Stream 6 and 3 have the same composition & Streams 4 and 5 have the same composition

$X = \frac{x}{1-x}$ $\quad Y = \frac{y}{1-y}$ +1 point for correct eqn

$X_0 = \frac{0.039}{1-0.039} = 0.041$ +1 point

$Y_{N+1} = \frac{0.149}{1-0.149} = 0.175$ +1 point

71.4% recovery

$Y_1 = Y_{N+1}(1 - \text{Recovery}) = 0.175(1-0.714) = 0.05$ +1

X_N requires MB:

$Y_{N+1}V' + X_0 L' = Y_1 V' + X_N L'$ +2 for MB

$X_N = X_0 + V'/L' (Y_{N+1} - Y_1)$ +1 for using V' & L'

$V' = V_{N+1}(1 - Y_{N+1}) = 10(1-0.175) = 8.25$ kmol/s +1

$L' = L_0(1 - X_0) = 13.91(1-0.041) = 13.34$ kmol/s +1

$X_N = 0.041 + \left(\frac{8.25}{13.34}\right)(0.175 - 0.05) = 0.118$

+1

CO_2 Balance on absorber

$$Y_{N+1}V' + X_0 L' = Y_1 V' + X_N L'$$

$$X_N = (Y_1 - Y_{N+1})\frac{V'}{L'} + X_0 \quad (1)$$

$$V' = V_{N+1}(1 - y_{N+1}) = V_{N+1}(1 - 0.149) \quad (2)$$

$$= 10(0.851) = 8.51 \ \frac{\text{kmol}}{\text{s}}$$

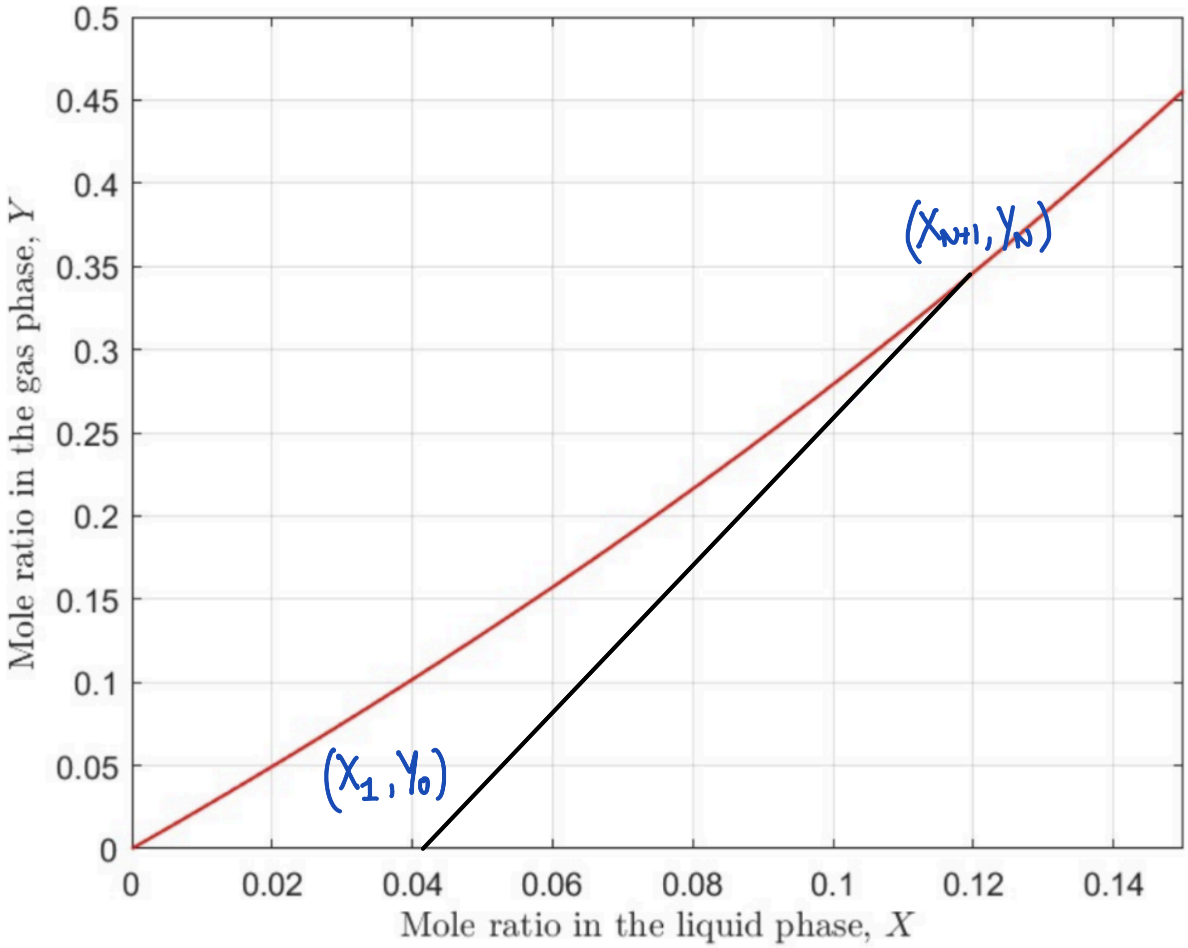
$$L' = L_0(1 - x_0) = 13.91(1 - 0.039) = 13.37 \ \frac{\text{kmol}}{\text{s}} \quad (3)$$

(2) & (3) in (1) $X_N = (0.175 - 0.05)\frac{8.51}{13.37} + 0.041$

$\underline{X_N = 0.120}$

The equilibrium curve for the conditions present in the stripper is given below.

C. Determine the minimum amount of (fresh) steam needed to regenerate the amine solution in the stripping column.



Y_0 (stream 8) is fresh steam $Y_0 = 0$ +1

X_{N+1} in stripper is same composition as X_N in absorber $X_{N+1} = 0.118$ +1

X_1 in stripper is same composition as X_0 in absorber $X_1 = 0.041$ +1

You can plot these but not necessary to solve question

$$\frac{L'}{V'_{min}} = \frac{0.34 - 0}{0.1\cancel{18}^{\,20} - 0.041} = \cancel{4.41}\ 4.30 \quad +2$$

$$L'/4.41 = V'_{min} \rightarrow \frac{13.3\cancel{4}^{\,7}}{4.\cancel{41}_{\,30}} = \boxed{3.\cancel{02}\ \text{kmol/s}} \quad 3.10\ \text{kmol/s} \quad +1$$

Can be solved without part C.

D. You decide to operate the stripper at a steam flow rate of 3.66 kmol/s. What is the composition of the vapor stream leaving the stripper? Give your answer in mole fractions.

$$\frac{L'}{V'} = \frac{13.3\cancel{4}^{7}}{3.66} = 3.6\cancel{4}^{5} \quad \text{slope of operating line } +1$$

Two ways to solve

1. Material Balance. +2 using material balance

$$Y_N = Y_0 + \frac{L'}{V'}(X_{N+1} - X_1) \quad +2 \text{ correct material balance}$$

$$Y_N = 0 + 3.64(0.\cancel{118}^{120} - 0.041) = \boxed{0.28} \quad +1$$

OR

2. Graphically / Slope

$$Y_0 = \frac{L'}{V'}(X_1) + b \quad +2$$

$$0 = 3.64(0.041) + b \rightarrow b = -0.149 \quad +2$$

$$Y_N = 3.64(0.118) - 0.149 = \boxed{0.28} \quad +1$$