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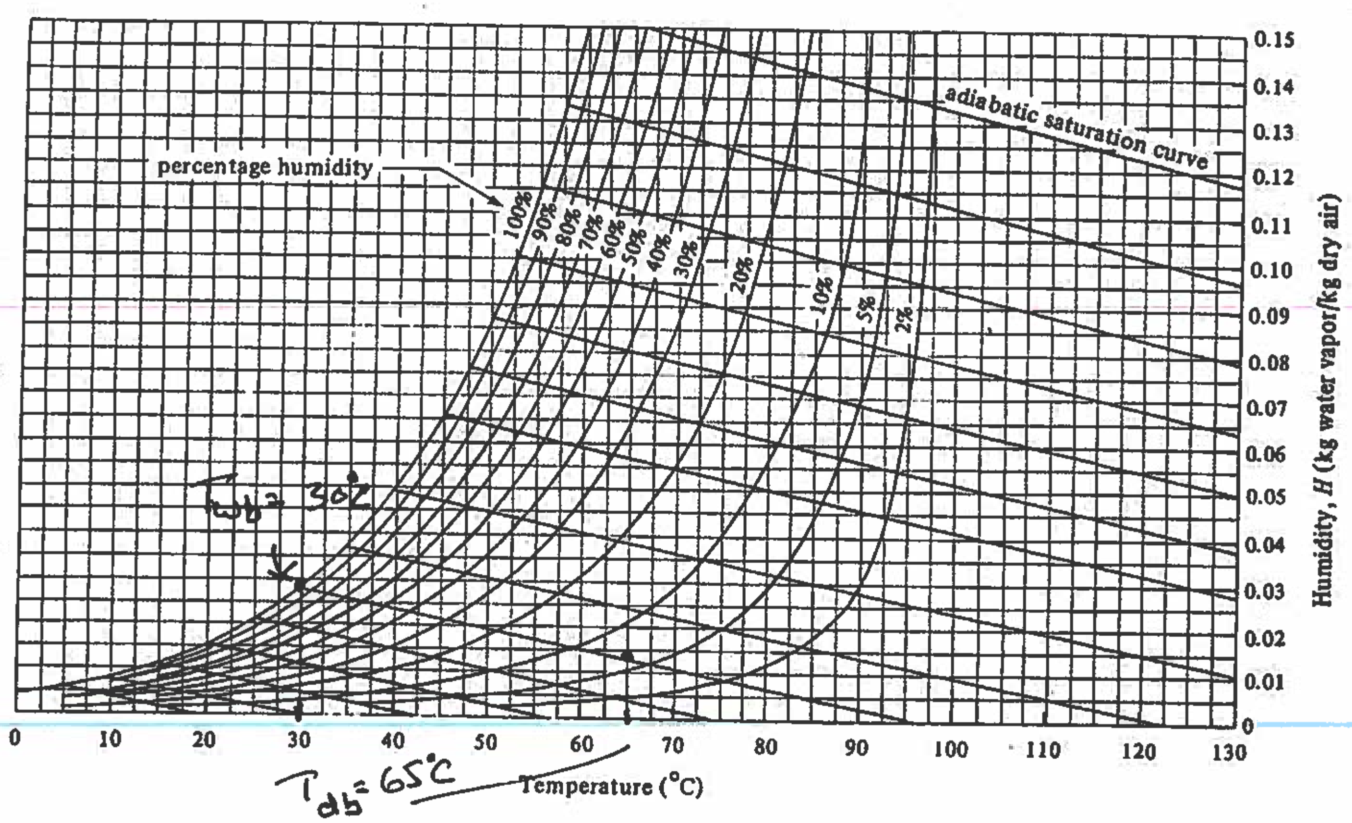
Problem 1. (20 Points) Wet wood particles are dried in a pan (the sides and bottom are insulated) by an air stream that is flowing parallel to the pan.

a) The air is at 65°C with a wet bulb temperature of 30°C. Using the Humidity Chart below, find the humidity of the air (kg water vapor/ kg dry air).

Using the plot and $T_{wb} = 30°C$ and $T_{db} = 65°C$ we find that $H = 0.014$ kg H_2O/kg dry air



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b) (5 points) Using the dry and wet bulb temperatures, find the rate of drying (in units of kg water/ s·m^2) for the system assuming it is a constant rate (h = 62.45 J/s·m^2·K, latent heat of vaporization = 2,433 kJ/kg)

$h = 62.45\ J/s\cdot m^2\cdot K$

$\lambda_w = 2.443 \times 10^3\ kJ/kg$

$\dot{m} = q/\lambda_w = h\Delta T/\lambda_w;\ \Delta T = 35°C$

$= \dfrac{62.45 \times 35 \times 10^{-3}\,(kJ/J)}{2.443 \times 10^3}$

$= 8.95 \times 10^{-4}\ kg/s\cdot m^2$

c) (5 points) At t = 0, the wood has a moisture content of X = 0.23 kg H_2O/kg dry wood. The equilibrium moisture content for the wood is X* = 0.04 kg H_2O/kg dry wood. If we have 1kg of wet wood at t = 0, what is the total mass of water that will be evaporated if we go to equilibrium?

$t = 0 \quad X = 0.23$ kg H_2O/kg dry wood

$t = t \quad X^* = 0.04$ " / "

$\Delta X = 0.23 - 0.04 = 0.19$ kg H_2O/kg dry wood

1 kg wet wood $= x + 0.23x \qquad x =$ kg dry wood

$x = 1/1.23 = 0.81$ kg dry wood

$\therefore \quad \Delta X \cdot x = 0.19 \times 0.81$

$= 0.15$ kg H_2O/kg wet wood

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d) (5 points) Combining parts b and c, how long will it take to dry the solids to their equilibrium water content (assume the area of the solids is the same as the area of the pan, which is 0.5 m x 0.5m)?

A = area for evaporation

= 0.5 × 0.5 = 0.25 m^2

t = time to evaporate water.

$$t = \frac{\Delta \bar{X} \cdot x}{\dot{m} \cdot A}$$

$$= \frac{0.15 \text{ kg } H_2O/\text{kg wet wood}}{8.95\times10^{-4} \frac{\text{kg } H_2O}{m^2 \cdot s} \cdot 0.25 \text{ m}^2}$$

$$= 6.7 \times 10^2 \text{ s} = 11 \text{ min}$$

Problem 2 (30 points):

It is desired to separate hydrogen chloride gas from a nitrogen stream using a trayed tower absorber with water as the absorbent. The water is initially pure with a flowrate of $L=1.5L_{min}$. The vapor stream enters at a flowrate of 50 mol/h and is 99.7% N_2. It is desired to achieve an exit gas concentration of 99.9% N_2.

a) Find L, the flowrate of absorbent. (10 points)

$99.7\%\ N_2 = 0.3\%\ HCl = 0.003 = 3\cdot10^{-3} = y$ (+2 for pt on eq line)

$Y = \frac{y}{1-y} = \frac{3\cdot10^{-3}}{1-3\cdot10^{-3}} = 3\cdot10^{-3} \Rightarrow X = .09$ (from graph)

$99.9\%\ N_2 = 0.1\%\ HCl = .001 = 1\cdot10^{-3} = y$

$Y = \frac{1\cdot10^{-4}}{1-1\cdot10^{-4}} = 1\cdot10^{-4} \Rightarrow X = 0$ Pts: $(0, 1\cdot10^{-3}), (.09, 3\cdot10^{-3})$

+2 for point on axis

+2 slope calculation

$m = \frac{3\cdot10^{-3} - 1\cdot10^{-3}}{.09 - 0}$

$m = .0222 = \left(\frac{L}{V}\right)_{min}$

$= .0222\cdot50 = L_{min}$

$= 1.11$ mol/hr (+2 for L_{min})

$L = 1.5L_{min} = 1.5(1.11)$

$L = 1.67$ mol/hr

+2 for answer

b) Find N, the total number of stages needed for this separation using a graphical analysis method. Use the equilibrium plot on the next page. List two assumptions inherent in this solution method. (10 points)

Operating Line: $Y = \frac{L}{V}X + Y_1 - X_0(L/V)$ (with $X_0 = 0$) +2 formula

$Y_1 = 1\cdot10^{-4},\ X_0 = 0$

$Y = \frac{1.67}{50}X + 1\cdot10^{-3}$

$Y = .0334X + 1\cdot10^{-3}$

+2 equation

$3\cdot10^{-3} = .0334X_N + 1\cdot10^{-3}$

$X_N = .06$

+2 X_N value

See plot

Assumptions

1. Constant L, V
2. Isothermal
3. Isobaric
4. Only HCl is absorbed

+2 for assumptions (1 each)

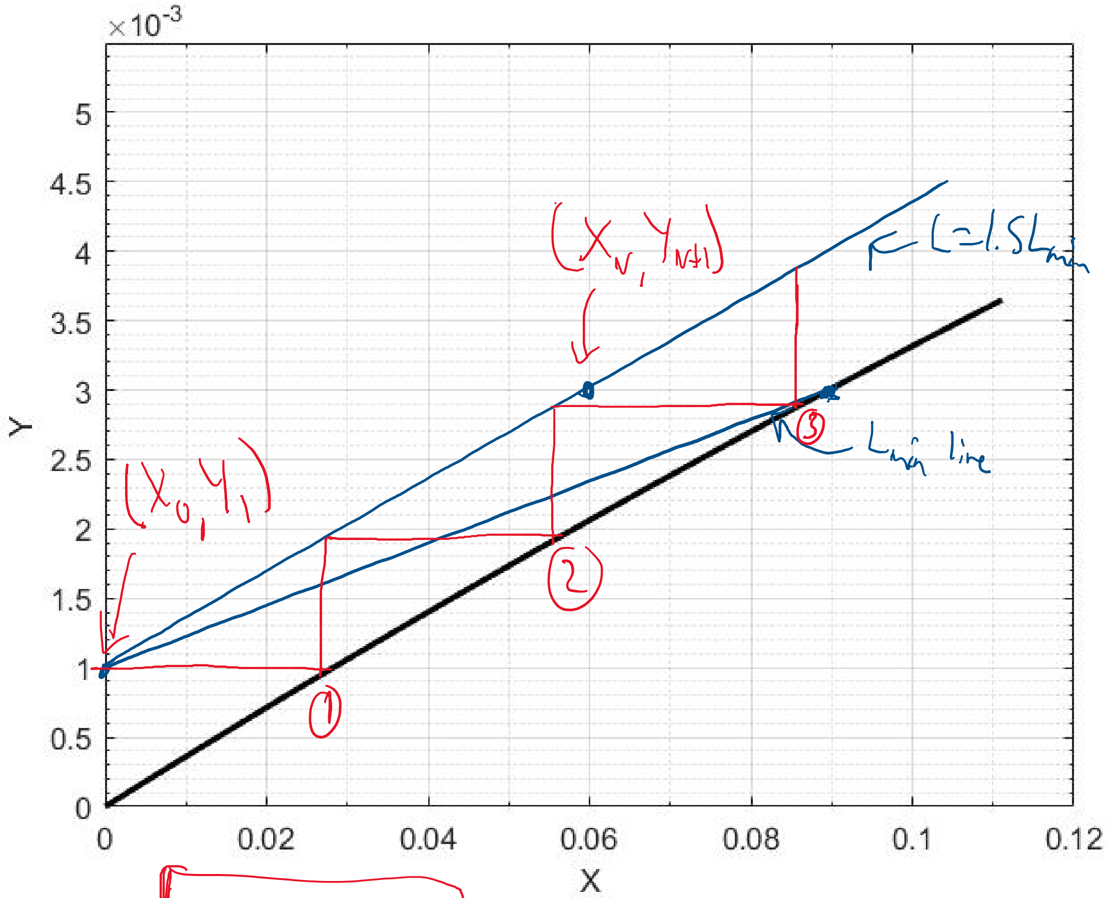
c) Use the Kremser method to find the total number of stages. How does your answer compare to part (b)? Assume that K=0.0364. (10 points)

$A = \frac{L}{KV} = \frac{1.67}{.0364\cdot50} = .918$ (+2 equation, +2 A value)

$\phi =$ fraction not absorbed $= \frac{1\cdot10^{-3}}{3\cdot10^{-3}} = .333$ (+2 equation, +1 value)

Look at Kremser Plot $\Rightarrow$ **3 stages**

+3 correct stage #



3 stages

+2 correct # of stages

~~1.~~ **Question 3 (20 points): Isothermal Flash of a Ternary Mixture:** You have a mixture of methane (CH_4), n-pentane (C_5H_{12}), and n-nonane (C_9H_{20}) that you would like separate in an isothermal flash at 69°C and 1 bar. The feed stream comes in with $z_{methane} = 0.4$, $z_{pentane} = 0.2$, and $z_{nonane} = 0.4$. The saturation pressure of n-pentane at these conditions is 2.75 bar. The partition coefficients are $K_{methane} = \infty$, $K_{pentane} = 2.75$, and $K_{nonane} = 0$.

a. What simplifying assumption arises when $K_{nonane} = 0$ and $K_{methane} = \infty$? Why is this the case for the given mixture? (5 points)

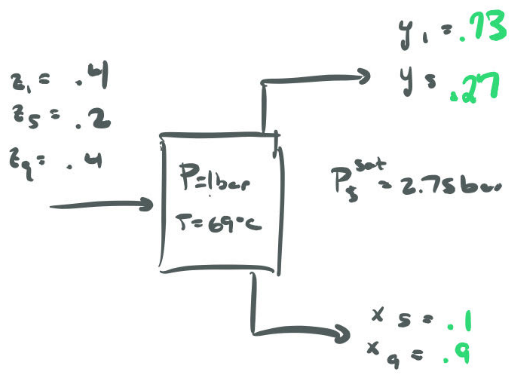
b. Determine expressions for $\Psi = V/F$, and $(1 - \Psi) = L/F$ in terms of the mole fraction of pentane in the liquid outlet, x_5. (10 points)

c. Solve for the compositions of the vapor and liquid outlet streams. **Hint:** The quadratic formula is $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$. (5 points)

Solution Part A:

Methane is by far the lightest component, nonane is by far the heaviest. The given Ks mean that can assume methane is going to be completely in the vapor phase, nonane is purely in the liquid phase, with pentane partitioning into each.

Solution to Part B and C:



$\frac{V}{F} = .56$

$\frac{L}{F} = .44$

$K_5 = 2.75 \qquad K_1 = \infty \qquad K_9 = 0$

$y_5 = x_5(2.75) \qquad F = L + V$

$F z_1 = V y_1 \qquad F z_9 = L x_9 \qquad F z_5 = V y_5 + L x_5$

B soln

$$\frac{V}{F} = \frac{z_1}{y_1} = \frac{.4}{1-y_5} = \frac{.4}{1-2.75x_5}$$

$$\frac{L}{F} = \frac{z_9}{x_9} = \frac{.4}{1-x_5}$$

$$\frac{V}{F} + \frac{L}{F} = 1 \rightarrow 1 = \frac{.4}{1-2.75x_5} + \frac{.4}{1-x_5}$$

$$2.5(1-x_5)(1-2.75x_5) = 1-x_5 + 1-2.75x = 2-3.75x_5$$

$$(1-x_5)(1-2.75x_5) = .8 - 1.5x_5$$

$$1 - x_5 - 2.75x_5 + 2.75x_5^2 = .8 - 1.5x_5$$

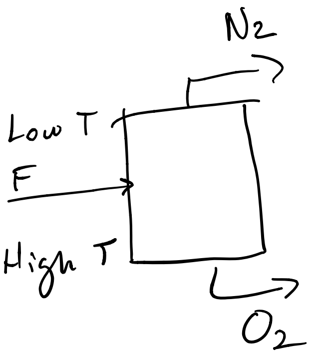
C.

$$.2 - 2.25x_5 + 2.75x_5^2 = 0 \rightarrow \text{Use QF} \rightarrow \boxed{x_5 = 0.10}$$

$$y_5 = .275$$

Problem 4. (30 points) The liquefaction of air is frequently accomplished by throttling air through a valve from 200+ bar to 1 bar in a process known as Linde Liquefaction. The resulting liquid air is fed into a cryogenic distillation column. You can assume that the liquid feed is saturated. We can also assume the composition of air is 20% Oxygen and 80% Nitrogen. The boiling point of O_2 is -183 °C and the boiling point of N_2 is -196 °C. We are interested in obtaining a stream of oxygen that is 95% pure and a stream of nitrogen that is 99% pure.

a. (5 points) Which component is the light key, why (Explain in a sentence or two)?



Since N_2 boils at a lower temperature. We know it must be purified at the top of the column making it the light key.

b. (10 points) Given you have a feed rate of 100 kmol/day, find the flow rate of distillate and bottoms.

$$x_{N_2}^{F} F = x_{N_2}^{B} B + x_{N_2}^{D} D$$

$$F = B + D$$

$$(0.8)(100) = (0.05)B + (0.99)(100 - B)$$

$$80 = 0.05B - 0.99B + 99$$

$$-19 = -.94B \longrightarrow B = 20.212 \text{ kmol/Day} \rightarrow D = 79.787 \text{ kmol/day}$$

c. (5 points) What is the minimum reflux ratio?

See graph 1 (for slope)

$$\text{Slope} = \frac{R}{R+1} \Rightarrow R = \frac{\text{Slope}}{1 - \text{Slope}}$$

$$R_{min} = \frac{0.211}{1 - 0.211} = 0.267$$

d. (10 points) Assuming that the column operates at $4R_{min}$ and has a partial reboiler, how many stages do we need? What stage does the feed enter on?

See graph 2

$4R_{min} = 1.07$

Rect line

$$y = \frac{1.07}{1+1.07} x + \frac{1}{1.07+1} x_D$$

Since sat liquid we can find the y value where this line crosses the q line

↳ this is b.c. there is only one x val

$$y_{qline} = 0.517(0.8) + .483(0.99)$$

$$y_{qline} = .4136 + .4782 = 0.89$$

$(0.8, 0.89)$

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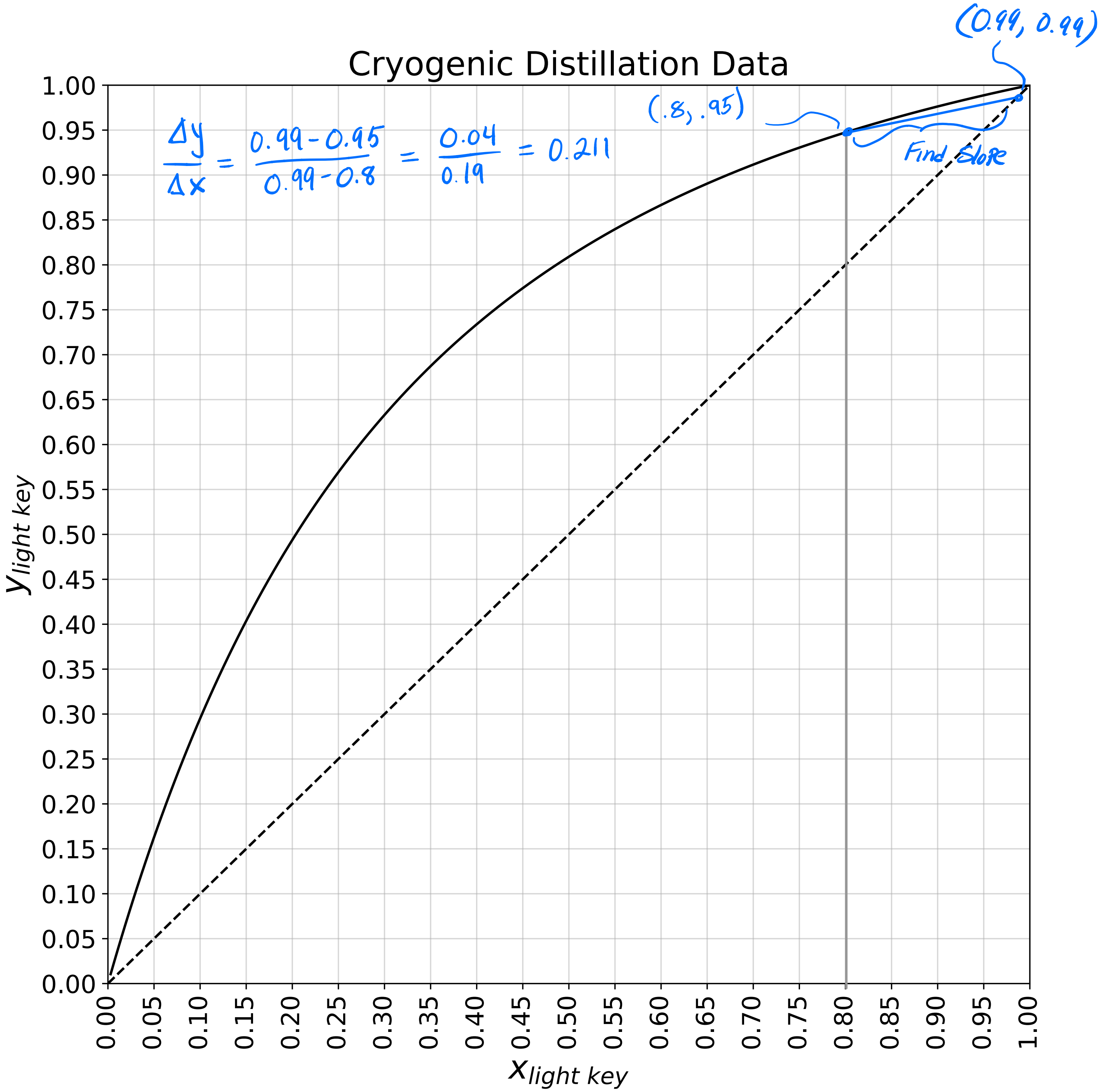

Cryogenic Distillation Data
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
$y_{light\ key}$
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00
$x_{light\ key}$
(0.99, 0.99)
(.8, .95)
Find Slope
$\frac{\Delta y}{\Delta x} = \frac{0.99-0.95}{0.99-0.8} = \frac{0.04}{0.19} = 0.211$

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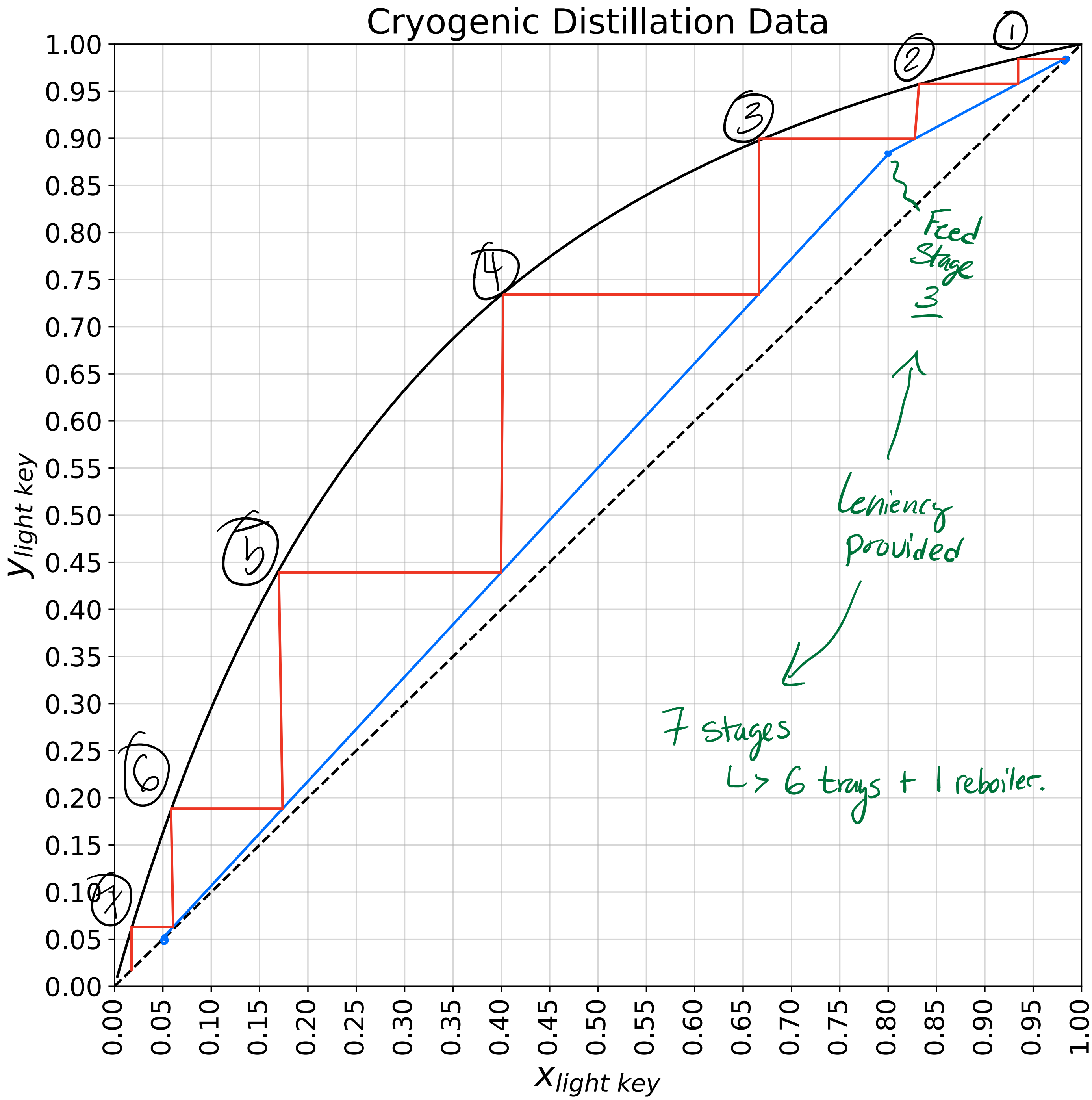
Cryogenic Distillation Data
$y_{light\ key}$
$x_{light\ key}$
Feed Stage 3
Leniency provided
7 stages
L> 6 trays + 1 reboiler.

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Incorrect Mass Balance

$$X_{O_2}F = X_{O_2}D + X_{O_2}B$$

$$20 = (0.95)D + (0.01)B$$

$$B = 100 - D$$

$$20 = .95D + 1 - 0.01D$$

$$19 = 0.94D$$

$$D = 20.2 \text{ kmol/Day}$$

$$B = 79.8 \text{ kmol/Day}$$