You may work in groups for these homeworks. Turn in one solution per group, including the names of all that work on the homework problems in your group. All problems are from Wankat's book

1. Problem 3. D1
2. Problem 3. D2
3. Problem 4. A2
4. Problem 4. D1
A very large distillation column is separating p-xylene (more volatile) from o-xylene. The column has two feeds (similar to Figure 4-17, but without the side stream). Both feeds are saturated liquids. Feed 1 is 42 mol % p-xylene, $F_1 = 90 \text{ kmol/hr}$. Feed 2 is 9 mol % p-xylene, $F_2 = 20 \text{ kmol/hr}$. The bottoms product should be 97 % o-xylene and the distillate product should be 99% p-xylene. Find the flow rates $D$ and $B$.

\[ Z_{p_x} = 0.42 \]
\[ F_1 = 90 \frac{\text{kmol}}{\text{hr}} \]
\[ F_2 = 20 \frac{\text{kmol}}{\text{hr}} \]

\[ X_D = 0.99 \text{ p-xylene} \]
\[ X_B = 0.03 \text{ p-xylene} \]

\[ \bar{Z}_1 F_1 + \bar{Z}_2 F_2 = X_D D + X_B B \]

Overall:
\[ F_1 + F_2 = D + B \]

\[ \bar{Z}_1 F_1 + \bar{Z}_2 F_2 = X_D D + X_B B \]

\[ \bar{Z}_1 F_1 + \bar{Z}_2 F_2 = \frac{X_D}{X_D} D + \frac{X_B}{X_D} B \]

From overall:
\[ D = F_1 + F_2 - B \]

\[ F_1 + F_2 = \frac{X_D}{X_D} D + \frac{X_B}{X_D} B \]

\[ B = \left[ \frac{Z_1 F_1 + Z_2 F_2}{X_D} - \left( F_1 + F_2 \right) \right] \frac{1}{X_B (X_D - 1)} \]

\[ B = 72.1875 \frac{\text{kmol/hr}}{} \]
\[ D = 37.8125 \frac{\text{kmol/hr}}{} \]

\[ 0.92(90) + 0.09(20) \approx 0.99 \left( 37.8125 \right) + 0.05(72.1875) \]

\[ 37.6 \approx 39.60 \]
A distillation column separating ethanol from water is shown. Pressure is 1 kg/cm². Instead of having a reboiler, steam (pure water vapor) is injected directly into the bottom of the column to provide heat. The injected steam is a saturated vapor. The feed is 30 wt % ethanol and is at 20 °C. Feed flow rate is 100 kg/min. Reflux is a saturated liquid. We desire a distillate concentration of 60 wt % ethanol and a bottoms product that is 5 wt % ethanol. The steam is input at 100 kg/min. What is the external reflux ratio, L/D?

\[ Q_{\text{col}} = 0 \]

\[ V_1 \]

\[ L \]

\[ D, X_D \]

\[ F, z \]

\[ y_s, S \]

\[ x_s, B, x_B \]

\[ F = 100 \text{ kg/min} \]

\[ Z = 0.3 \text{ (wt. %) ethanol} \]

\[ T = 20 \text{°C} \]

\[ h_f \]

\[ S = 100 \text{ kg/hr} \]

\[ y_s = 0 \]

\[ x_s, B, x_B \]

\[ h_B \]

\[ P = 1 \text{ Kg} \]

\[ \text{cm}² \]

\[ = 0.98066 \text{ bar} \]

**Find:** \( \frac{L}{D} = R \)

\[ \text{Find } \ D \] and \( B \)

\[ m_B \text{ Overall} \frac{S + F}{\text{Ethanol}} m_B = \frac{S + X s}{X_D + X_B B} \]

\[ D = F - B + S \]
\[
\begin{align*}
\frac{N}{X_0} F &= F + S - B + \frac{X_8 B_{X_0}}{X_0} = (F + S) + (\frac{X_8}{X_0} - 1) B \\
B &= \left[ \frac{N}{X_0} F - (F + S) \right] \left( \frac{X_8}{X_0} - 1 \right) ^{-1} \\
B &= 163.63 \text{ Kg/min} \\
D &= 36.36 \text{ Kg/min}
\end{align*}
\]

**EB:**

Overall:

\[
F h_F + S h_S + Q_C = D h_D + B h_B + Q_{C01}
\]

Condenser:

\[
V_i h_i + Q_C = L h_D + D h_D = (L + D) h_D
\]

All mass:

\[
V_i = (L + D) L (L + D) h_i + Q_C = (L + D) h_D
\]

From Fig 2-4 p18

\[
\text{Subcooling: } h_F = 9.2 \text{ Kcal/kg} \\
\text{h}_{S} = 640 \text{ Kcal/kg} \\
\text{h}_{D} = 70 \text{ Kcal/kg} \\
\text{h}_{B} = 95 \text{ Kcal/kg} \\
\text{h}_{i} = 410 \text{ Kcal/kg}
\]

From overall EB

\[
F h_F + S h_S + Q_C = D h_D + B h_B
\]

\[
F h_F + S h_S - D (R + 1) (h_i - h_D) = D h_D + B h_B
\]

\[
F h_F + S h_S - D h_D - B h_B = R + 1
\]

\[
\frac{D (h_D - h_i)}{3.78} R = 2.786
\]

\[
Q_C = \frac{-46,809 \text{ Kcal}}{\text{m}^3}\]
vapor lines, because they represent all possible liquid and vapor systems that can be in equilibrium at a pressure of 1 atm. Any point below the saturated liquid curve represents a subcooled liquid (liquid below its boiling point) whereas any point above the saturated vapor curve would be a superheated vapor. Points between the two saturation curves represent streams consisting of both liquid and vapor. If allowed to separate, these streams will give a liquid and vapor in equilibrium. Liquid temperature; therefore, these streams will occur for $x_{Eth} = 0.2$.

Even more information can be obtained from this type of diagram, as illustrated for ethanol and water. Figures 2-3. Again, the isotherms shown in Figure 2-3 are used to determine weight fraction varies. Because the temperature, these points are connected. The vapor and liquid curves represent two-phase saturated liquid curves generated using the auxiliary line with the ordinate $x_{Eth} = 0.2$.

**Figure 2-4.** Enthalpy-composition diagram for ethanol-water at a pressure of 1 kg/cm² (Bosnjakovic, Technische Thermodynamik, T. Steinkopff, Leipzig, 1935)

Chapter 2 Flash Distillation

2.3 Graphs
D1. A continuous, steady-state distillation column with a total condenser and a partial reboiler is separating methanol from water at one atmosphere (See Table 2.7 for data). The feed rate is 100 kg mole per hour. The feed is 55 mole % methanol and 45 mole % water. We desire a distillate product that is 90 mole % methanol and a bottoms product that is 5 mole % methanol. Assume CMO.
   a. If the external reflux ratio \( L/D \) = 1.25 plot the top operating line.
   b. If the boilup ratio \( V/B \) = 2.0 plot the bottom operating line.
   c. Step off stages starting at the bottom with the partial reboiler. Use the optimum feed stage. Report the optimum feed stage and the total number of stages.
   d. Plot the feed line. Calculate its slope. Calculate \( q \). What type of feed is this?

Assume CMO

\[ X_D = 0.9 \text{ mole} \]

\[ n+1: \frac{L}{R+1} X_N + \frac{X_D}{R+1} \]

\[ n+1: \frac{L}{R+1} X_N = \frac{B}{V} X_B \]

\[ Y_{n+1} = \frac{L}{R+1} X_N = \frac{B}{V} X_B \]

\[ F = 100 \text{ kmol/hr} \]

\[ \bar{F} = 0.55 \text{ mole fraction} \]

\[ Y_{m+1} = \frac{L}{V} X_B = \frac{B}{V} X_B \]

\[ X_B = 0.05 \text{ mole fraction} \]

\[ \frac{L}{D} = R = 1.25 \]

\[ \text{Rectifying section} \]

\[ \frac{L}{R+1} = \frac{0.9}{2.25} = 0.4 \]

\[ \frac{V}{B} = 2.0 \]

\[ \text{intercept} = -\frac{B(X_B)}{V} = -\frac{0.05}{2} = -0.025 \]

\[ \text{or better let } y_{m+1} = 1 \]

\[ \frac{y_B}{1 + \frac{B}{V} X_B} \frac{V}{L} = X_B = 0.683 \]

\[ \text{plot } \theta = 1.4 \text{ line} \]

\[ L = V + B \]

\[ \frac{L}{B} = \frac{V}{B} + 1 \]

\[ \frac{V}{B} = \frac{L - V}{V} = B \]

\[ \frac{B}{V} = \frac{L - V}{V} - 1 \Rightarrow \frac{L}{V} = 1 + \frac{B}{V} = 1 + 0.5 = 1.5 \]

\[ \frac{V}{V} = 2 \frac{L}{V} = \frac{2}{3} \]
c) y stage + Preboiler.

Optimum Feed stage is #2

d) Feed line

\[ Y = \frac{9}{8-1} \times -\frac{ZF}{8-1} \]

\[
\frac{\text{Slope}}{.55 - 1.0} = -0.99 \approx 1
\]

\[
50 \times 9 = 8 = 8 - 1.5 \Rightarrow 8 \approx 0.5
\]

\[
50:50 \quad V:L
\]
**Table 2-7. Vapor-Liquid Equilibrium Data for Methanol Water (p = 1 atm) (mole %)**

<table>
<thead>
<tr>
<th>Methanol Liquid</th>
<th>Methanol Vapor</th>
<th>Temp., °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>2.0</td>
<td>13.4</td>
<td>96.4</td>
</tr>
<tr>
<td>4.0</td>
<td>23.0</td>
<td>93.5</td>
</tr>
<tr>
<td>6.0</td>
<td>30.4</td>
<td>91.2</td>
</tr>
<tr>
<td>8.0</td>
<td>36.5</td>
<td>89.3</td>
</tr>
<tr>
<td>10.0</td>
<td>41.8</td>
<td>87.7</td>
</tr>
<tr>
<td>15.0</td>
<td>51.7</td>
<td>84.4</td>
</tr>
<tr>
<td>20.0</td>
<td>57.9</td>
<td>81.7</td>
</tr>
<tr>
<td>30.0</td>
<td>66.5</td>
<td>78.0</td>
</tr>
<tr>
<td>40.0</td>
<td>72.9</td>
<td>75.3</td>
</tr>
<tr>
<td>50.0</td>
<td>77.9</td>
<td>73.1</td>
</tr>
<tr>
<td>60.0</td>
<td>82.5</td>
<td>71.2</td>
</tr>
<tr>
<td>70.0</td>
<td>87.0</td>
<td>69.3</td>
</tr>
<tr>
<td>80.0</td>
<td>91.5</td>
<td>67.6</td>
</tr>
<tr>
<td>90.0</td>
<td>95.8</td>
<td>66.0</td>
</tr>
<tr>
<td>95.0</td>
<td>97.9</td>
<td>65.0</td>
</tr>
<tr>
<td>100.0</td>
<td>100.0</td>
<td>64.5</td>
</tr>
</tbody>
</table>

Source: Perry et al. (1963), p. 13-5

Data: \( p_w = 1.00 \text{ g/cm}^3, p_{m,L} = 0.7914 \text{ g/cm}^3, MW_w = 18.01, MW_m = 32.04 \). Assume vapors are ideal gas.

**D2.**

If \( z = 0.4, p = 1 \text{ atm}, \) and \( T_{\text{drum}} = 77 \degree \text{ C} \), find \( V/F, x_m \), and \( y_m \).

Data: \( p_{FL} = 37 \text{ kPa} \), \( C_{FL, w} = 18.0 \text{ kcal} / \text{mol} \cdot \text{K} \), \( C_{FL, m} = 14 \text{ kcal} / \text{mol} \cdot \text{K} \), \( CP_{FL, w} = 7.88 \text{ kcal} / \text{mol} \cdot \text{K} \). Both \( CP_{FL, w} \) and \( CP_{FL, m} \) are given in Table 2-7.

**D3.** We are separating the feed using a multistage distillation column. The feed is a mixture of methanol and water. Use the equilibrium data to calculate the required number of stages.

**D4.** We have a feed that is sent to the distillation column. The feed contains 30.0 mole % methanol. Find the vapor flow rate of the feed.

**D5.** We have a feed that is sent to the distillation column. The feed contains 30.0 mole % methanol. Find the vapor flow rate of the feed.

**D6.** A feed that is sent to the distillation column contains 30.0 mole % methanol. Find the vapor flow rate of the feed.

**D7.** A feed that is sent to the distillation column contains 30.0 mole % methanol. Find the vapor flow rate of the feed.

**D8.** You want to distill \( V/F = 2.0 \text{ mol} / \text{mol} \). The feed contains 30.0 mole % methanol. Find the vapor flow rate of the feed.

**D9.** We wish to distill \( V/F = 2.0 \text{ mol} / \text{mol} \). The feed contains 30.0 mole % methanol. Find the vapor flow rate of the feed.

**a.** What is the fraction vaporized in the first flash drum?

**b.** What are \( y_1, y_2, x_1, T_1, \) and \( T_2 \)?

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Homework
D7. a. A distillation column with a total condenser is separating acetone from ethanol. A distillate concentration of \( x_D = 0.90 \) mole fraction acetone is desired. Since CMO is valid, \( L/V = \) constant. If \( L/V = 0.8 \), find the composition of the liquid leaving the fifth stage below the total condenser.

b. A distillation column separating acetone and ethanol has a partial reboiler that acts as an equilibrium contact. If the bottoms composition is \( x_B = 0.13 \) mole fraction acetone and the boilup ratio \( V/B = 1.0 \), find the vapor composition leaving the second stage above the partial reboiler.

c. The distillation column in parts a and b is separating acetone from ethanol and has \( x_D = 0.9, x_B = 0.13, L/V = 0.8, \) and \( V/B = 1.0 \). If the feed composition is \( z = 0.3 \) (all concentrations are mole fraction of more volatile component), find the optimum feed plate location, total number of stages, and required \( q \) value of the feed. Equilibrium data for acetone and ethanol at 1 atm (Perry et al., 1963, p. 13-4) are:

<table>
<thead>
<tr>
<th>Concentration (mole fraction)</th>
<th>( x_A )</th>
<th>( y_A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.10</td>
<td>0.262</td>
</tr>
<tr>
<td>0.15</td>
<td>0.15</td>
<td>0.348</td>
</tr>
<tr>
<td>0.20</td>
<td>0.20</td>
<td>0.417</td>
</tr>
<tr>
<td>0.25</td>
<td>0.25</td>
<td>0.478</td>
</tr>
<tr>
<td>0.30</td>
<td>0.35</td>
<td>0.524</td>
</tr>
<tr>
<td>0.35</td>
<td>0.40</td>
<td>0.566</td>
</tr>
<tr>
<td>0.40</td>
<td>0.50</td>
<td>0.605</td>
</tr>
<tr>
<td>0.50</td>
<td>0.60</td>
<td>0.674</td>
</tr>
<tr>
<td>0.60</td>
<td>0.70</td>
<td>0.739</td>
</tr>
<tr>
<td>0.70</td>
<td>0.80</td>
<td>0.802</td>
</tr>
<tr>
<td>0.80</td>
<td>0.90</td>
<td>0.865</td>
</tr>
<tr>
<td>0.90</td>
<td></td>
<td>0.929</td>
</tr>
</tbody>
</table>

Rect. section:

\[
Y_{j+1} = \frac{L}{V} X_j + (1 - \frac{L}{V}) X_D
\]

Stripping section:

\[
Y_{n+1} = \left( \frac{R}{R+1} \right) Y_n + \frac{X_D}{R+1}
\]

Feed line:

\[
Y = \frac{q}{q-1} X - \left( \frac{Z_F}{q-1} \right)
\]
\[ F \quad \text{[Diagram] \quad X_D = 0.9} \]

\[ Z_F = \quad \text{[Diagram] \quad X_B = 0.13} \]

A) \[ X_0 = 0.90 \quad \frac{L}{V} = 0.8 \quad \text{[Constant]} \quad \frac{L}{V} \text{is Slope} \]

\[ 0.8 = \frac{\Delta y}{\Delta x} = \frac{8}{10} \]

\[ X_S = 0.515 \quad \text{[From Top]} \]

\[ \text{[Box]} \quad \text{=} \ a \]

b) \[ X_B = 0.13 \quad \frac{V}{B} = 1.0 \quad \text{so} \quad \frac{B}{V} = 1.0 \quad \text{also!} \]

\[ \text{SO intercept of stripping line is} \left(-\frac{B}{V} \quad 0.13\right) \]

\[ \text{Intercept} = -0.13 \]

\[ X_2 \approx 0.505 \]

\[ \text{[Box]} \quad \text{=} \ b \]
N = 8 \text{ stages} + N_r

N_F = 7

\text{slope} = \frac{\frac{9}{8} - 1}{0.3 - 0.315} = \frac{0.3 - 0.315}{0.3 - 0.27} = -3.1667

\frac{q_0}{8} = 8 \kappa - \kappa

q_0(1 - \kappa) = -\kappa

q = \frac{-\kappa}{1 - \kappa} = \frac{3.1667}{1 + 3.1667} \quad \bar{q} = 0.76

Basis: 100 kg moles feed.

\[
\begin{align*}
5 \text{ kg moles Ethanol} & \times \frac{46 \text{ kg}}{\text{kg mole}} = 230 \text{ kg} \\
95 \text{ kg moles water} & \times \frac{18 \text{ kg}}{\text{kg mole}} = \frac{1710 \text{ kg}}{1940} \\
\text{EtOH wt. frac.} & = \frac{230}{1940} = 0.1186
\end{align*}
\]

Use Figure 2-4. Approximate feed stage at 97°C

\[
q = \frac{H-h_F}{H-h}
\]

\[
H = 550
\]

\[
h_F = 300
\]

\[
h = 92
\]

\[
z = 0.1186
\]

Note: Using 5 wt % gives \(h_F = 160\), \(q = \frac{550-160}{550-92} = 0.8515\)

\[
\text{Slope } = \frac{q}{q-1} = -5.74. \text{ Which are wrong!}
\]

4.D7. a. Plot top op. line: slope = \(\frac{L}{V} = 0.8\), \(x = y = x_D = 0.9\). Step off stages as shown on Figure.

b. Plot bottom op. line: slope = \(\frac{L}{V} = 1 + \frac{1}{B} = 2\), \(x = y = x_B = 0.13\). Step off stages (reboiler is an equil stage). Find \(y_2 = 0.515\).

c. Total # stages = 8 + reboiler

Optimum feed plate = 7 or 8 from top. Plot feed line. Goes through \(x = y = z = 0.3\), and intersection of two operating lines.

\[
\text{slope } = -\frac{9}{4} = -\frac{q}{q-1} \text{ gives } q = 0.692.
\]
4.D8. The equilibrium data is plotted and shown in the figure. From the Solution to 4.D7c, 
\( q = 0.692 \) and \( q/(q-1) = -9/4 \)

a. total reflux. Need 5 2/3 stages (from large graph) - 5.9 from small diagram shown.
b. \( (L/V)_{\text{min}} = \frac{9-0.462}{9-0.236} = 0.660 \) (see figure)
   \[ (L/D)_{\text{min}} = \frac{(L/V)_{\text{min}}}{1-(L/V)_{\text{min}}} = 1.941 \]

c. In 4.D7, \( L/D_{\text{act}} = \frac{L/V}{1-L/V} = \frac{8}{.2} = 4 \)
   \( L/D_{\text{act}} = (\text{Multiplier}) \times (L/D)_{\text{min}} \)
   Multiplier = \( 4/1.941 = 2.06 \)
d. Operating lines are same as in Problem 4.D7. Start at bottom of column. Reboiler is an equilibrium contact. Then use \( E_{\text{MV}} = \frac{\Delta B}{\Delta C} = 0.75 \) (illustrated for the first real stage) Stage 1 is the optimum feed stage. 11 real stages plus a partial reboiler are sufficient.