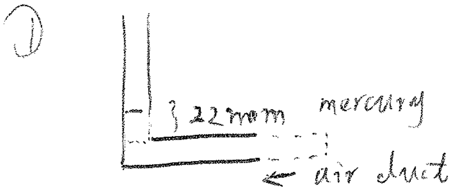
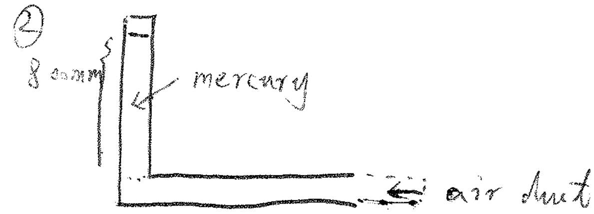
CBE 20255 HW3 solution

1.

Open - ended manometer



Sealed manometer



Pressure balance on open-ended manometer:

$$P_{atm} + P^{①}_{mercury} = P_{air\ duct}$$

Pressure balance on sealed manometer:

$$\underbrace{P_{atm}}_{=\,0 \text{ as it is sealed}} + P^{②}_{mercury} = P_{air\ duct}$$

1) $$P_{air\ duct} = P^{②}_{mercury} = 800\,mmHg$$

Conversion from mm Hg to atm at $0^\circ C$:

$$1\ mmHg = \rho_{mercury}\, g_{earth}\, 1\,mm$$

$$= 13595\ kg/m^3 \cdot 9.807\ m/s^2 \cdot 1\,mm$$

$$= 133.3\ kg/m s^2 = 133.3\ Pa = 132.0 \times 10^{-5}\ atm$$

So $800\ mm\,Hg = 1.05\,atm$

2) As is shown previously,

$$P_{atm} + P^{①}_{mercury} = P_{air\ duct}$$

gauge pressure in the air duct

$$= P_{air\ duct} - P_{atm} = P^{①}_{mercury} = 22\ mmHg$$

Unit conversion from mmHg to Pa is shown in part 1), so

$$22\ mmHg = 2900\ Pa$$

3) $$P_{atm} = P_{air\ duct} - P^{①}_{mercury}$$

$$= 800\ mmHg - 22\ mmHg$$

$$= 778\ mmHg$$

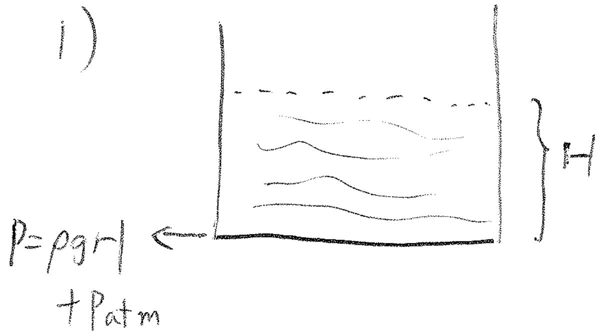
$$1\ psi = \frac{1\ lbf}{(1\ in)^2} \simeq \frac{4.4482\ N}{(0.0254\ m)^2} = 6894.757\ N/m^2 = 6894.75\ Pa$$

$$1\ mmHg = 133.3\ Pa \cdot \frac{psi}{6894.75\ Pa} = 0.0193\ psi$$

So $778\ mmHg = 15.0\ psi$

2.

1)



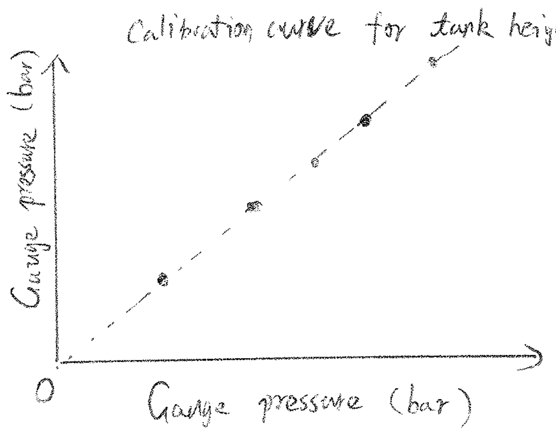
For a tank with fluid, the pressure at bottom of the tank

$$P = \rho g H + P_{atm}$$ ρ is the density of the fluid

Gauge pressure at bottom $= P - P_{atm} = \rho g H$

So Gauge pressure is proportional to height of liquid.

Calibration curve level in m vs. pressure in bar:



2) Calibration-curve-predicted height

$$H_1 = \frac{P}{\rho_1 g}$$

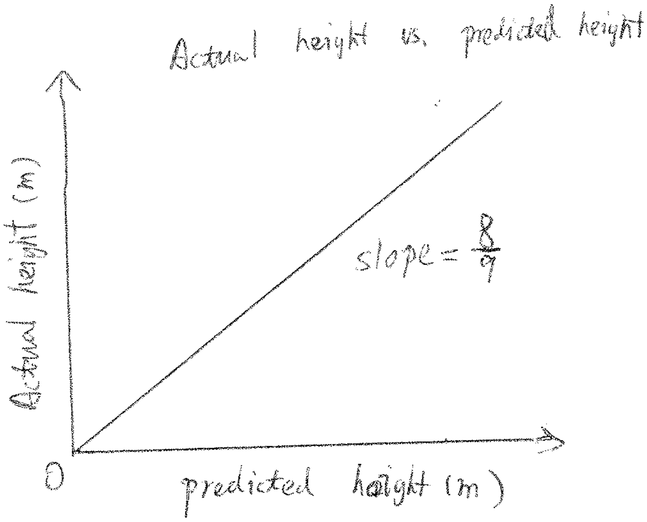
Actural fluid height

$$H_2 = \frac{P}{\rho_2 g}$$

$$\frac{\rho_1}{\rho_2} = \frac{0.900}{0.800} \longrightarrow \frac{H_1}{H_2} = \frac{P}{\rho_1 g} \cdot \frac{\rho_2 g}{P} = \frac{\rho_2}{\rho_1} = \frac{0.900}{0.800} = \frac{9}{8}$$

So actual height

$$H_2 = \frac{8}{9} H_1 \quad \text{predicted height}$$



3) When the tank is 10 m, the actual gauge pressure is

$$\cancel{P = \rho_2 g H = \frac{10\,m}{0.800 kg/L \cdot 9.807 m/s^2}}$$

$$P = \rho_2 g H = 0.800 kg/L \cdot 9.807 m/s^2 \cdot 10\,m \cdot \frac{1000 L}{m^3}$$

$$= 78456\, kg/ms^2 = 78456\, Pa \cdot \frac{1\, bar}{10^5 Pa} = 0.78\, bar$$

The Bourdon gauge reads $\boxed{0.78\, bar.}$

The calibration curve is $P = \rho_1 g H_{predicted}$

$$H_{predicted} = \frac{P}{\rho_1 g} = \frac{78456\, kg/(m\, s^2)}{0.900 kg/L \cdot 9.807 m/s^2} = \boxed{8.9\, m}$$

The calibration curve say it is 8.9m ...

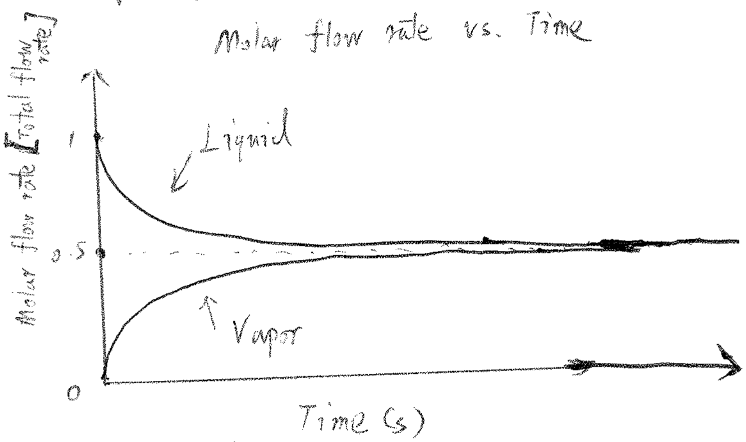
3.

1) During start-up, vapor flow rate goes from zero to asymptotically half of total molar flow rate.

As Total molar flow rate = liquid flow rate + vapor flow rate

Liquid flow rate = Total flow rate − vapor flow rate

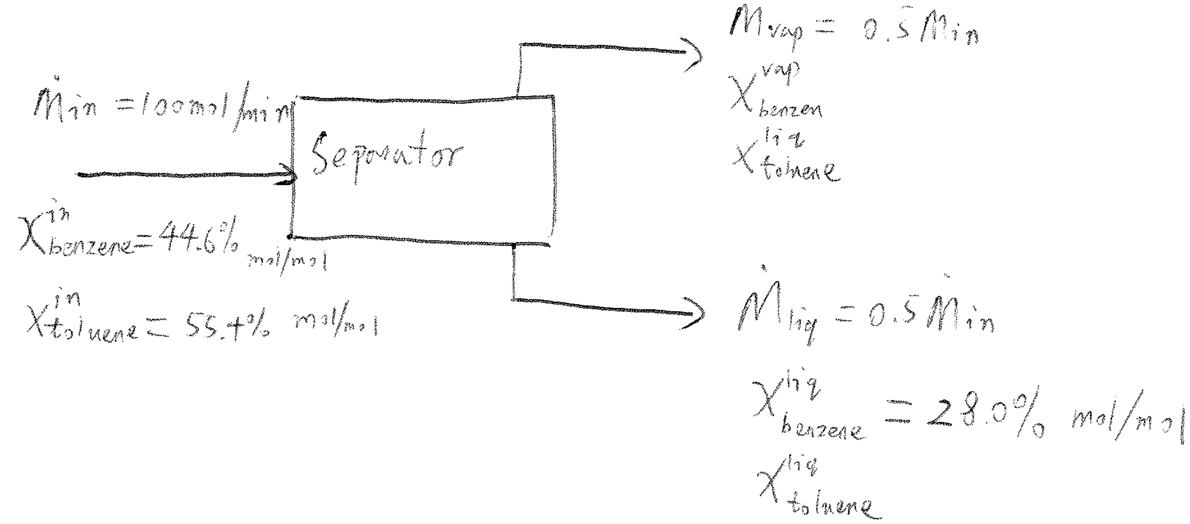
Liquid flow rate should go from whole total flow rate to asymptotically half of total flow rate.



2) The process is Continous as there are continuous inlet and outlet.

3) It is transient when first started up and ~~to~~ becomes steady-state when vapor pressure attains a constant flow rate.

4)



5) Mole balance is valid as there is no reaction in the process.

Mole balance on benzene:

$$\dot{M}_{in} X^{in}_{benzene} = \dot{M}_{vap} X^{vap}_{benzene} + \dot{M}_{liq} X^{liq}_{benzene}$$

Mole balance on toluene:

$$\dot{M}_{in} X^{in}_{toluene} = \dot{M}_{vap} X^{vap}_{toluene} + \dot{M}_{liq} X^{liq}_{toluene}$$

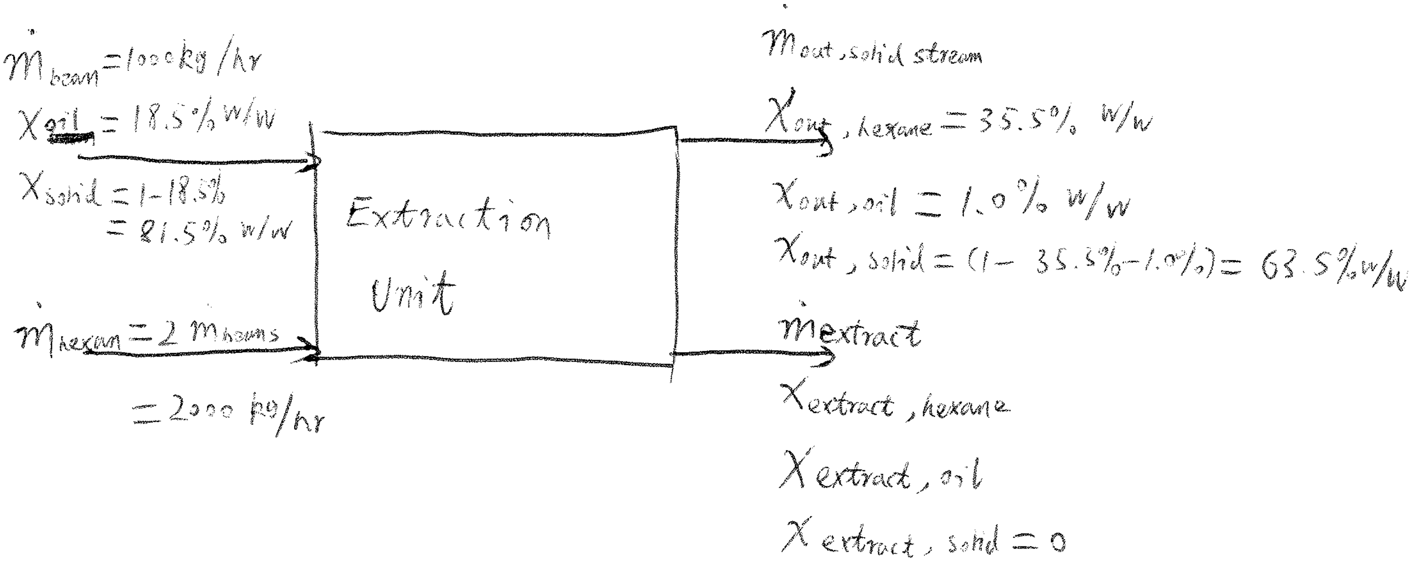
$$\rightarrow \begin{cases} 100\,mol/min \cdot 44.6\% = 100\,mol/min \cdot 0.5\, X^{vap}_{benzene} + 100\,mol/min \cdot 0.5 \cdot 28\% \cancel{(1 - X^{vap}_{benzene})} \\ 100\,mol/min \cdot 55.4\% = 100\,mol/min \cdot 0.5 \cdot \cancel{28.0\%}\, X^{vap}_{toluene} + 100\,mol/min \cdot 0.5\,(1 - 28.0\%) \end{cases}$$

By solving the above equations, we can have

$$\begin{cases} X^{vap}_{benzene} = 61.2\% \\ X_{toluene} = 38.8\% \end{cases}$$

4.

1)



You can also define the index by number, such as $\dot{m}_{I}$, $\dot{m}_{II}$, etc

2) Mass balance on total mass,

① $\dot{m}_{beam} + \dot{m}_{hexane} = \dot{m}_{out,\ solid\ stream} + \dot{m}_{extract}$

Mass balance on insoluble solid,

② $\dot{m}_{beam} X_{solid} = \dot{m}_{out,\ solid\ stream} X_{out,\ solid}$

Mass balance on hexane,

③ $\dot{m}_{hexane} = \dot{m}_{out,\ solid\ stream} X_{out,\ hexane} + \dot{m}_{extract} X_{extract,\ hexane}$

Mass balance on oil is ~~in~~dependent on ①, ②, ③

$$\begin{cases} ① \ (1000 + 2000)\ kg/hr = \dot{m}_{out,\ solid\ stream} + \dot{m}_{extract} \\ ② \ 1000\,kg/hr \cdot 81.5\% = \dot{m}_{out,\ solid\ stream} \cdot 63.5\% \\ ③ \ 2000\,kg/hr = \dot{m}_{out,\ solid\ stream} \cdot 35.5\% + \dot{m}_{extract} X_{extract,\ hexane} \end{cases}$$

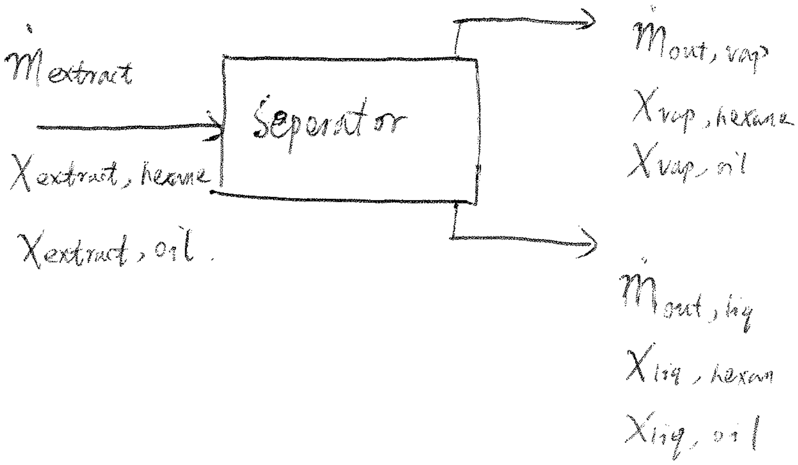
There are 3 equations and 3 unknown variables, the problem can be solved.

$$\begin{cases} \dot{m}_{out,\ solid\ stream} = \boxed{1280\ kg/hr} \\ \dot{m}_{extract} = \boxed{1720\ kg/hr} \\ X_{extract,\ hexane} = \boxed{90.0\%} \end{cases}$$

$$X_{extract,\ oil} = 1 - X_{extract,\ hexane} = \boxed{10.0\%}$$

All unknown variable are solved.

3) The hexane can be recovered by a seperator (distillation column)

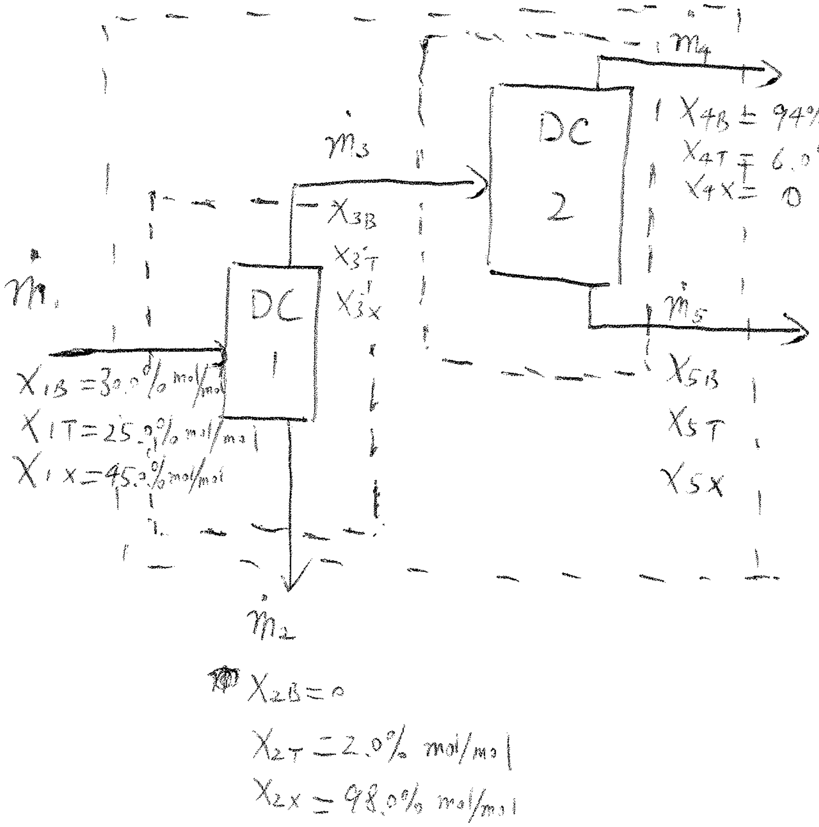


It is expected hexane has lower boiling point than soy bean oil, so the vapor stream outlet should be ~~bean oi~~ rich in hexane.

The recovered hexane can be further recycled to the extraction unit.

5.

1)



Mass balance can be done on first distillation column alone, second distillation column alone and the whole system.

2) If the flow rate into first column is known, we will have $\boxed{\text{5 unknown variables}}$ for the mass balance on the whole system : $\dot{m}_2$, $\dot{m}_4$, $\dot{m}_5$, X_{5B} , X_{5T}

We have $\boxed{\text{3 mass balance equations}}$, $\boxed{\text{2 equations}}$ of constraint (96.0% xylene collected in the bottom of 1st column and ~~94.0~~ 97.0% benzene recovered in the top of 2nd column)

We have 5 unknowns and 5 equations, so we are able to determine the three flow rates out of the overall process.

3) Mass balance of benzene on DC1:

① $\dot{m}_1 X_{1B} = \dot{m}_3 X_{3B}$

________ of toluene:

② $\dot{m}_1 X_{1T} = \dot{m}_2 X_{2T} + \dot{m}_3 X_{3T}$

________ of xylene:

③ $\dot{m}_1 X_{1X} = \dot{m}_2 X_{2X} + \dot{m}_3 X_{3X}$

We have one more equation of constraint,

$$\dot{m}_1 X_{1X} \cdot 96\% = \dot{m}_2 X_{2X}$$

Asume $\dot{m}_1 = 100$ mol/hr

$$\begin{cases} 100 \cdot 30.0\% = \dot{m}_3 X_{3B} \\ 100 \cdot 25.0\% = \dot{m}_2 \cdot 2.0\% + \dot{m}_3 X_{3T} \\ 100 \cdot 45.0\% = \dot{m}_2 \cdot 98.0\% + \dot{m}_3 X_{3X} \\ 100 \cdot 45.0\% \cdot 96.0\% = \dot{m}_2 \cdot 98.0\% \end{cases}$$

There are 4 unknown variables and 4 equations. They can be solved.

$$\begin{cases} \dot{m}_2 = 44.1 \text{ mol/hr} \\ \dot{m}_3 = 55.9 \text{ mol/hr} \\ \boxed{\begin{array}{l} X_{3B} = 53.7\% \\ X_{3T} = 43.1\% \\ X_{3X} = 3.2\% \end{array}} \end{cases}$$

4) Mass balance of benzene on DC 2:

$$\dot{m}_3 X_{3B} = \dot{m}_4 X_{4B} + \dot{m}_5 X_{5B}$$

——— of toluene:

$$\dot{m}_3 X_{3T} = \dot{m}_4 X_{4T} + \dot{m}_5 X_{5T}$$

——— of xylene:

$$\dot{m}_3 X_{3X} = \dot{m}_5 X_{5X}$$

We have one more equation of constraint,

$$\dot{m}_3 X_{3B} \cdot 97.0\% = \dot{m}_4 X_{4B}$$

From part 4), we know

$$\begin{cases} X_{3B} = 53.7\% \\ X_{3T} = 43.1\% \\ X_{3X} = 3.2\% \end{cases}$$

Again, assume $\dot{m}_1 = 100$ mol/hr, then $\dot{m}_3 = 55.9$ mol/hr

We have

$$\begin{cases} 55.9 \cdot 53.7\% = \dot{m}_4 \cdot 94.0\% + \dot{m}_5 X_{5B} \\ 55.9 \cdot 43.1\% = \dot{m}_4 \cdot 6.0\% + \dot{m}_5 X_{5T} \\ 55.9 \cdot 3.2\% = \dot{m}_5 X_{5X} \\ 55.9 \cdot 53.7\% \cdot 97.0\% = \dot{m}_4 \cdot 94.0\% \end{cases}$$

4 Unknowns and 4 equations, we can solve it

$$\begin{cases} \dot{m}_4 = 31.0 \text{ mol/hr} \\ \dot{m}_5 = 24.9 \text{ mol/hr} \\ \boxed{\begin{array}{l} X_{5X} = 7.2\% \\ X_{5B} = 3.5\% \\ X_{5T} = 89.3\% \end{array}} \end{cases}$$

5) Fraction of benzene recovered

$$= \frac{\dot{m}_4 X_{4B}}{\dot{m}_1 X_{1B}} = \frac{31.0 \text{ mol/hr} \cdot 94\%}{100 \text{ mol/hr} \cdot 30.0\%} = 97.1\%$$

Fraction of toluene recovered

$$= \frac{\dot{m}_5 X_{5T}}{\dot{m}_1 X_{1T}} = \frac{24.9 \text{ mol/hr} \cdot 89.3\%}{100 \text{ mol/hr} \cdot 25.0\%} = 88.9\%$$