1. A liquid mixture of benzene and toluene at 130° C is to be separated in a continuous single-stage equilibrium flash tank. The feed is equimolar in benzene and toluene, and the exit streams are at 652 mm Hg and 90° C. The enthalpies are calculated as a function of temperature with both liquids having an enthalpy of 0 at 0° C such that:

H of benzene liquid: 0.1356T
H of toluene liquid: 0.1674T
H of benzene vapor: 0.1045T + 33.25
H of toluene vapor: 0.1304T + 37.57

The H’s are in kJ/mole and the T is in °C.

Find the moles of the liquid and vapor products and the required heat input per one mole of feed.

a) do a degree of freedom analysis to show that the problem can be solved (do it correctly – I want unknowns and then how you’re going to solve it. Otherwise you will receive no credit for this part). (10 pts)
b) Solve for the required variables. (35 pts)

---

Diagram:

Basis: 1 mol feed

\[ \begin{align*}
&\text{B = benzene} \\
&\text{T = toluene} \\
&1 \text{ mol @ 130° C} \\
&0.5 \text{ B, 0.5 T}
\end{align*} \]

\[ \begin{align*}
&n_v \ (\text{mol vapor}) \\
&y_B(\text{mol B/mol}) \\
&(1 - y_B)(\text{mol T/mol})
\end{align*} \] in equilibrium

\[ \begin{align*}
&n_l \ (\text{mol liquid}) \\
&x_B(\text{mol B/mol}) \\
&(1 - x_B)(\text{mol T/mol})
\end{align*} \] at 90° C, 652 mm Hg

---

a) unknowns: \( n_v, n_l, y_B, x_B, Q \) (2.5 pts)

For \( n_v \) and \( n_l \), material balances; for \( x_B \) and \( y_B \), Raoult’s Law, for \( Q \), energy balance (7.5 pts)
b) \( n_V + n_L = 1 \)

Raoult's Law:

\[ y_B P = x_B P_B^* \]

\[ (1 - y_B) P = (1 - x_B) P_T^* \]

Antoine Equation. For \( T = 90 ^\circ C \) and \( P = 652 \text{ mmHg} \):

\[ P_B^*(90 ^\circ C) = 10^{[6.89272 - 1203.531/(90 + 219.888)]} = 1021 \text{ mmHg} \]

\[ P_T^*(90 ^\circ C) = 10^{[6.95805 - 1346.773/(90 + 219.693)]} = 406.7 \text{ mmHg} \]

\[ P = x_B P_B^* + (1 - x_B) P_T^* \Rightarrow x_B = \frac{P - P_T^*}{P_B^* - P_T^*} = \frac{652 - 406.7}{1021 - 406.7} = 0.399 \text{ mol B(l) / mol} \]

\[ y_B = \frac{x_B P_B^*}{P} = \frac{0.399(1021 \text{ mmHg})}{652 \text{ mmHg}} = 0.625 \text{ mol B(v) / mol} \]

Solving (1) and (2) \( \Rightarrow n_V = \frac{z_B - x_B}{y_B - x_B} = \frac{0.5 - 0.399}{0.625 - 0.399} = 0.446 \text{ mol vapor} \)

\[ n_L = 1 - n_V = 1 - 0.446 = 0.554 \text{ mol liquid} \]

Vapor pressures: 1 pt each

Mole fractions in vapor and liquid: 2 pts each

\( n_V \) and \( n_L \): 1 pt each

Solving for moles out:

\( .399*.554 = 0.221 \text{ B(l)} \)

\( .601*.554 = .333 \text{ T(l)} \)

\( .625*.446 = .279 \text{ B(v)} \)

\( .375*.446 = .167 \text{ T(v)} \)

(1 pt each)

Solving for enthalpies:

\( .1356*130=17.63 \text{ B(l) in} \)

\( .1356*90 = 12.204 \text{ B(l) out} \)

\( .1674*130 = 21.76 \text{ T(l) in} \)

\( .1674*90 = 15.1 \text{ T(l) out} \)

\( .1045*90+33.25 = 42.655 \text{ B(v) out} \)

\( .1304*90 + 37.57 = 49.31 \text{ T(v) out} \)

(1 pt each)
References: Benzene liquid at 0° C, Toluene liquid at 0° C (5 pts)

<table>
<thead>
<tr>
<th>Substance</th>
<th>n_{in}</th>
<th>H_{in}</th>
<th>n_{out}</th>
<th>H_{out}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene (l)</td>
<td>0.5</td>
<td>17.63</td>
<td>.221</td>
<td>12.204</td>
</tr>
<tr>
<td>Toluene (l)</td>
<td>0.5</td>
<td>21.76</td>
<td>.333</td>
<td>15.1</td>
</tr>
<tr>
<td>Benzene (v)</td>
<td>0</td>
<td>---</td>
<td>.279</td>
<td>42.655</td>
</tr>
<tr>
<td>Toluene (v)</td>
<td>0</td>
<td>---</td>
<td>.167</td>
<td>49.31</td>
</tr>
</tbody>
</table>

Table: 6 pts

\[
Q = (12.204 \times .221 + 15.1 \times .333 + .279 \times 42.655 + .167 \times 49.31) - (.5 \times 17.63 + .5 \times 21.76) = 27.86 - 19.69 = 8.17 \text{ kJ/mole of feed} \] (4 pts)
2. Soil contaminated with polyaromatic hydrocarbons can be treated with hot air and steam to drive out contaminants. If 30 m$^3$ of air (with water vapor) at 100 ºC and 98.6 kPa with a dew point of 30 ºC are introduced into the soil, and in the soil the gas cools to 14 ºC at a pressure of 109.1 kPa, what fraction of the water in the gas at 100 ºC condenses out in the soil? Assume the system at 14 ºC is at equilibrium. (15 pts)

at 30 ºC, $p^* = 4.24$ kPa = 31.824 mm Hg (1 pt)
at 14 ºC, $p^* = 1.60$ kPa = 11.987 mm Hg (1 pt)

$yP = p^*(@T)$

going in: $y = 4.24/98.6 = .043$ (2 pts)
coming out: $y = 1.6/109.1 = .0147$ (2 pts)

Let $n_1$ equal moles coming in, $n_2$ moles of water condensing and $n_3$ moles coming out.

going in: total moles = 98.6 * 30.0 m$^3$/((8.314 * 373 K) = .954 kmol = $n_1$ (2 pts)

Two balances:

$.954 = n_2 + n_3$ (overall) (1 pt)
$.041 = .0147 * n_3 + n_2$ (water) (1 pt)

$n_2 = .027$  $n_3 = .927$ (1 pt each)

Fraction condensed = $0.027/.041 = .658$ (3 pts)
3. (15 pts) In a proposed low pollution vehicle burning H₂ and O₂, the gases are to be stored in tanks at 136 atm(abs). The vehicle has to operate from 20 K to 327 K.

a) A practical operating range requires that 681 moles of hydrogen be stored. How large must the hydrogen tank be?

b) The H₂/O₂ ratio is 2/1 on a molar basis. How large must the oxygen tank be?

Cannot use ideal gas law (pressure too high). Use $V = \frac{znRT}{P}$

Find $T_r$ and $P_r$ for both H₂ and O₂ and look up $z$

H₂: $T_c = 33 + 8 = 41 \quad T_r = \frac{327}{41} = 7.97$
$P_c = 12.8 + 8 = 20.8 \quad P_r = \frac{136}{20.8} = 6.54$
$z = 1.07$ (7 pts – 2 pts for $T_c$ and $P_c$)

O₂: $T_r = \frac{327}{154.4} = 2.12$
$P_r = \frac{136}{49.7} = 2.74$
$z = .98$ (3 pts)

a) $V = \frac{znRT}{P} = 1.07 \times 681 \times .0821 \times 327/136 = 143.8$ L (2 pts)

b) $V = .98 \times 681/2 \times .0821 \times 327/136 = 65.88$ L (3 pts)
4. Methanol is contained in a large tank under a pressure of 3.1 bar absolute. A valve is opened on the bottom of the tank, the methanol drains through a 1-cm inside diameter tube whose outlet is 7.00 m below the surface. The pressure at the outlet of the discharge pipe is 1 atm. What is the methanol discharge velocity and flow rate in L/min when the discharge valve is fully opened? (15 pts)

\[
\begin{align*}
\text{Point 1 - surface of fluid} & : P_1 = 3.1 \text{ bar}, \ z_1 = +7 \text{ m}, \ u_1 = 0 \text{ (m/s)} \\
\text{Point 2 - discharge pipe outlet} & : P_2 = 1 \text{ atm}, \ z_2 = 0 \text{ (m)}, \ u_2 = ? \\
\frac{\Delta P}{\rho} & = (1.013 - 3.1) \text{ bar} \times \frac{10^5 \text{ N}}{\text{m}^2 \cdot \text{bar}} \times \frac{1}{0.792 \times 10^3 \text{ kg}} = -263.5 \text{ m}^2/\text{s}^2 \\
g\Delta z & = \frac{9.8066 \text{ m}}{\text{s}^2} \times (-7 \text{ m}) = -68.6 \text{ m}^2/\text{s}^2
\end{align*}
\]

\[
\text{Bernoulli equation} \Rightarrow \frac{\Delta u^2}{2} = -\frac{\Delta P}{\rho} - g\Delta z = (263.5 + 68.6) \text{ m}^2/\text{s}^2 = 332.1 \text{ m}^2/\text{s}^2
\]

\[
u^2 = 2(332.1 \text{ m}^2/\text{s}^2) = 664.2 \text{ m}^2/\text{s}^2 \Rightarrow u_2 = 258 \text{ m/s}
\]

\[
\dot{V} = \frac{\pi (1.00^2)}{4} \frac{2580 \text{ cm}}{1 \text{ s}} \times \frac{1 \text{ L}}{10^3 \text{ cm}^3} \times \frac{60 \text{ s}}{1 \text{ min}} = 122 \text{ L/min}
\]
Closed Book (15 pts)

1. As the temperature increases, what happens to the dew point pressure of a vapor mixture? As the pressure decreases, what happens to the bubble point temperature of a liquid mixture? (4 pts)

   increases, decreases

2. If the relative humidity at 100 °C and 2 atm is 60 %, what is the mole fraction of the water? What is the partial pressure of the water? (5 pts)

   vapor pressure of water at 100 degrees C = 1 atm
   \[ \frac{.6}{1 \text{ atm}} = y \]  
   \[ y = .3 \]  
   \[ yP = .6 \text{ atm} \]

3. A system and its surroundings are at the same temperature, there is a turbine in the process, and velocities and height are constant. What is the energy balance? (2 pts)

   \[ -W = \Delta H \]

4. Liquid water is at 10 bar and 35° C. Where in the steam table do you find the enthalpy? saturated water at 35° C (2 pts)

5. The solubility of NaCl at 50° C is 42 g NaCl/100 g of water. What is the mass fraction? 42/142 (2 pts)