

## CHAPTER SIX

**6.1 a.** AB: Heat liquid -  $-V \approx \text{constant}$

BC: Evaporate liquid -  $-V$  increases, system remains at point on vapor - liquid equilibrium curve as long as some liquid is present.  $T = 100^\circ\text{C}$ .

CD: Heat vapor -  $-T$  increases,  $V$  increases.

**b.** Point B: Neglect the variation of the density of liquid water with temperature, so  $\rho = 1.00 \text{ g/mL}$  and  $V_B = 10 \text{ mL}$

Point C:  $\text{H}_2\text{O}$  (v,  $100^\circ\text{C}$ )

$$n = \frac{10 \text{ mL}}{1 \text{ mL}} \times \frac{1.00 \text{ g}}{18.02 \text{ g}} = 0.555 \text{ mol}$$

$$P_C V_C = nRT_C \Rightarrow V_C = \frac{nRT_C}{P_C} = \frac{0.555 \text{ mol}}{1 \text{ atm}} \times \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \times \frac{373 \text{ K}}{1} = \underline{\underline{17 \text{ L}}}$$

**6.2 a.**  $P_{\text{final}} = \underline{\underline{243 \text{ mm Hg}}}$ . Since liquid is still present, the pressure and temperature must lie on the vapor-liquid equilibrium curve, where by definition the pressure is the vapor pressure of the species at the system temperature.

**b.** Assuming ideal gas behavior for the vapor,

$$m(\text{vapor}) = \frac{(3.000 - 0.010) \text{ L}}{(30 + 273.2) \text{ K}} \times \frac{\text{mol} \cdot \text{K}}{0.08206 \text{ L} \cdot \text{atm}} \times \frac{243 \text{ mm Hg}}{760 \text{ mm Hg}} \times \frac{1 \text{ atm}}{1} \times \frac{119.39 \text{ g}}{\text{mol}} = 4.59 \text{ g}$$

$$m(\text{liquid}) = \frac{10 \text{ mL}}{1 \text{ mL}} \times \frac{1.489 \text{ g}}{1} = 14.89 \text{ g}$$

$$m_{\text{total}} = m(\text{vapor}) + m(\text{liquid}) = \underline{\underline{19.5 \text{ g}}}$$

$$x_{\text{vapor}} = \frac{4.59}{19.48} = \underline{\underline{0.235 \text{ g vapor / g total}}}$$

**6.3 a.**  $\log_{10} p^* = 7.09808 - \frac{1238.71}{45 + 217} = 2.370 \Rightarrow p^* = 10^{2.370} = \underline{\underline{234.5 \text{ mm Hg}}}$

**b.**  $\ln p^* = -\frac{\Delta \hat{H}_v}{R} \frac{1}{T} + B \Rightarrow -\frac{\Delta \hat{H}_v}{R} = \frac{\ln(p_2^* / p_1^*)}{\frac{1}{T_2} - \frac{1}{T_1}} = \frac{\ln(760 / 118.3)}{\frac{1}{(77.0 + 273.2) \text{ K}} - \frac{1}{(29.5 + 273.2) \text{ K}}} = -4151 \text{ K}$

$$B = \ln(p_1^*) + \frac{\Delta \hat{H}_v / R}{T_1} = \ln(118.3) + \frac{4151 \text{ K}}{(29.5 + 273.2) \text{ K}} = 18.49$$

### 6.3 (cont'd)

$$\ln p^*(45^\circ\text{C}) = -\frac{4151}{(45 + 273.2)} + 18.49 \Rightarrow \underline{\underline{p^* = 231.0 \text{ mm Hg}}}$$

$$\frac{231.0 - 234.5}{234.5} \times 100\% = \underline{\underline{-1.5\% \text{ error}}}$$

$$\text{c. } p^* = \left( \frac{118.3 - 760}{29.5 - 77} \right) (45 - 29.5) + 118.3 = \underline{\underline{327.7 \text{ mm Hg}}}$$

$$\frac{327.7 - 234.5}{234.5} \times 100\% = \underline{\underline{39.7\% \text{ error}}}$$

**6.4** Plot  $p^*$  (log scale) vs  $\frac{1}{T + 273.2}$  (rect. scale) on semilog paper

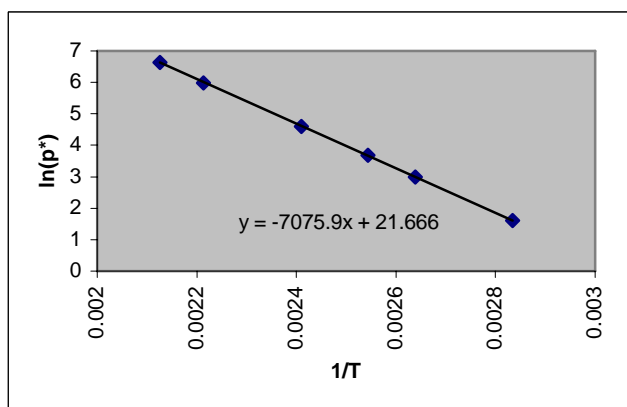
$\Rightarrow$  straight line: slope =  $-7076\text{K}$ , intercept =  $21.67$

$$\ln p^*(\text{mm Hg}) = \frac{-7076}{T(^{\circ}\text{C}) + 273.2} + 21.67 \Rightarrow \underline{\underline{p^*(\text{mm Hg}) = \exp\left[\frac{-7076}{T(^{\circ}\text{C}) + 273.2} + 21.67\right]}}$$

$$\frac{\Delta H_v}{R} = 7076\text{K} \Rightarrow \Delta \hat{H}_v = \frac{7076 \text{ K}}{\text{mol} \cdot \text{K}} \left| \frac{8.314 \text{ J}}{\text{mol} \cdot \text{K}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} \right| = \underline{\underline{58.8 \text{ kJ/mol}}}$$

**6.5**  $\ln p^* = A/T(\text{K}) + B$

T(°C)	p*(mm Hg)	1/T(K)	ln(p*)	p*(fitted)	T(°C)	p*(fitted)
79.7	5	0.002834	1.609	5.03	50	0.80
105.8	20	0.002639	2.996	20.01	80	5.12
120.0	40	0.002543	3.689	39.26	110	24.55
141.8	100	0.002410	4.605	101.05	198	760.00
178.5	400	0.002214	5.991	403.81	230	2000.00
197.3	760	0.002125	6.633	755.13	Least confidence (Extrapolated)	



6.6 a.

T(°C)	1/T(K)	$p^*$ (mm Hg) =758.9 + h <sub>right</sub> - h <sub>left</sub>
42.7	$3.17 \times 10^{-3}$	34.9
58.9	$3.01 \times 10^{-3}$	78.9
68.3	$2.93 \times 10^{-3}$	122.9
77.9	$2.85 \times 10^{-3}$	184.9
88.6	$2.76 \times 10^{-3}$	282.9
98.3	$2.69 \times 10^{-3}$	404.9
105.8	$2.64 \times 10^{-3}$	524.9

b. Plot is linear,  $\ln p^* = -\frac{\Delta \hat{H}_v}{RT} + B \Rightarrow \ln p^* = \frac{-5143.8 K}{T} + 19.855$

At the normal boiling point,  $p^* = 760 \text{ mmHg} \Rightarrow \underline{\underline{T_b = 116^\circ \text{C}}}$

$$\Delta \hat{H}_v = \frac{8.314 \text{ J}}{\text{mol} \cdot \text{K}} \left| \frac{5143.8 \text{ K}}{10^3 \text{ J}} \right| = 42.8 \text{ kJ/mol}$$

c. Yes — linearity of the  $\ln p^*$  vs  $1/T$  plot over the full range implies validity.

6.7 a.  $\ln p^* = a/(T + 273.2) + b \Rightarrow y = ax + b \quad [y = \ln p^*; \quad x = 1/(T + 273.2)]$

Perry's Handbook, Table 3-8:

$$T_1 = 39.5^\circ \text{C}, \quad p_1^* = 400 \text{ mm Hg} \Rightarrow x_1 = 3.1980 \times 10^{-3}, \quad y_1 = 5.99146$$

$$T_2 = 56.5^\circ \text{C}, \quad p_2^* = 760 \text{ mm Hg} \Rightarrow x_2 = 3.0331 \times 10^{-3}, \quad y_2 = 6.63332$$

$$T = 50^\circ \text{C} \Rightarrow x = 3.0941 \times 10^{-3}$$

$$y = y_1 + \left( \frac{x - x_1}{x_2 - x_1} \right) (y_2 - y_1) = 6.39588 \Rightarrow p^*(50^\circ \text{C}) = e^{6.39588} = \underline{\underline{599 \text{ mm Hg}}}$$

b.  $50^\circ \text{C} = 122^\circ \text{F} \xrightarrow{\text{Cox chart}} p^* = \frac{12 \text{ psi}}{14.6 \text{ psi}} \left| \frac{760 \text{ mm Hg}}{14.6 \text{ psi}} \right| = \underline{\underline{625 \text{ mm Hg}}}$

c.  $\log p^* = 7.02447 - \frac{1161.0}{50 + 224} = 2.7872 \Rightarrow p^* = 10^{2.7872} = \underline{\underline{613 \text{ mm Hg}}}$

6.8 Estimate  $p^*(35^\circ \text{C})$ : Assume  $\ln p^* = \frac{a}{T(K)} + b$ , interpolate given data.

$$\left. \begin{aligned} a &= \frac{\ln(p_2^*/p_1^*)}{\frac{1}{T_2} - \frac{1}{T_1}} = \frac{\ln(200/50)}{\frac{1}{45+273.2} - \frac{1}{25+273.2}} = -6577.1 \\ b &= \ln p_1^* - \frac{a}{T_1} = \ln(50) + \frac{6577.1}{25 + 273.2} = 25.97 \end{aligned} \right\} \Rightarrow \begin{aligned} \ln[p^*(35^\circ \text{C})] &= -\frac{6577.1}{35 + 273.2} + 25.97 = 4.630 \\ p^*(35^\circ \text{C}) &= e^{4.630} = 102.5 \text{ mm Hg} \end{aligned}$$

$$\begin{aligned} \text{Moles in gas phase: } n &= \frac{150 \text{ mL}}{(35 + 273.2) \text{ K}} \left| \frac{102.5 \text{ mm Hg}}{760 \text{ mm Hg}} \right| \left| \frac{1 \text{ L}}{10^3 \text{ mL}} \right| \left| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right| \\ &= \underline{\underline{8.0 \times 10^{-4} \text{ mol}}} \end{aligned}$$

**6.9 a.**  $m = 2 \quad \pi = 2 \Rightarrow \underline{F = 2 + 2 - 2 = 2}$ . Two intensive variable values (e.g., T & P) must be specified to determine the state of the system.

**b.**  $\log p^*_{MEK} = 6.97421 - \frac{1209.6}{55 + 216} = 2.5107 \Rightarrow p^*_{MEK} = 10^{2.5107} = 324 \text{ mm Hg}$

Since vapor & liquid are in equilibrium  $p_{MEK} = p^*_{MEK} = \underline{324 \text{ mm Hg}}$

$\Rightarrow y_{MEK} = p_{MEK} / P = 324/1200 = \underline{0.27} > 0.115$  The vessel does not constitute an explosion hazard.

**6.10 a.** The solvent with the lower flash point is easier to ignite and more dangerous. The solvent with a flash point of 15°C should always be prevented from contacting air at room temperature. The other one should be kept from any heating sources when contacted with air.

**b.** At the LFL,  $y_M = 0.06 \Rightarrow p_M = p^*_M = 0.06 \times 760 \text{ mm Hg} = 45.60 \text{ mm Hg}$

Antoine  $\Rightarrow \log_{10} 45.60 = 7.87863 - \frac{1473.11}{T + 230} \Rightarrow T = \underline{6.85^\circ \text{C}}$

**c.** The flame may heat up the methanol-air mixture, raising its temperature above the flash point.

**6.11 a.** At the dew point,

$p^*(\text{H}_2\text{O}) = p(\text{H}_2\text{O}) = 500 \times 0.1 = 50 \text{ mm Hg} \Rightarrow \underline{T = 38.1^\circ \text{C}}$  from Table B.3.

**b.**  $V_{\text{H}_2\text{O}} = \frac{30.0 \text{ L}}{(50 + 273) \text{ K}} \times \frac{500 \text{ mm Hg}}{760 \text{ mm Hg}} \times \frac{1 \text{ mol}}{22.4 \text{ L (STP)}} \times \frac{0.100 \text{ mol H}_2\text{O}}{\text{mol}} \times \frac{18.02 \text{ g}}{\text{mol}} \times \frac{1 \text{ cm}^3}{\text{g}} = \underline{1.34 \text{ cm}^3}$

**c.** (iv) (the gauge pressure)

**6.12 a.**  $T_1 = 58.3^\circ\text{C}$ ,  $p_1^* = 755 \text{ mm Hg} - (747 - 52)\text{mm Hg} = 60 \text{ mm Hg}$   
 $T_2 = 110^\circ\text{C}$ ,  $p_2^* = 755 \text{ mm Hg} - (577 - 222)\text{mm Hg} = 400 \text{ mm Hg}$

$$\ln p^* = \frac{a}{T(K)} + b$$

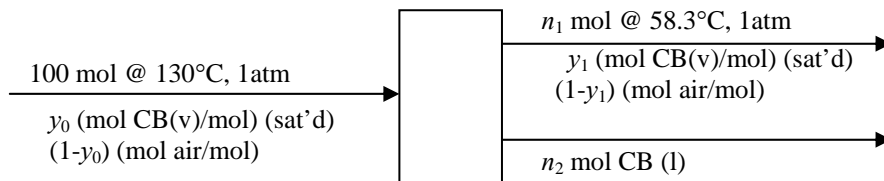
$$a = \frac{\ln(p_2^*/p_1^*)}{\frac{1}{T_2} - \frac{1}{T_1}} = \frac{\ln(400/60)}{\frac{1}{110+273.2} - \frac{1}{58.3+273.2}} = -4661.4$$

$$b = \ln p_1^* - \frac{a}{T_1} = \ln(60) + \frac{4661.4}{58.3 + 273.2} = 18.156$$

$$\ln p^* = \frac{-4661.4}{T} + 18.156 \quad \xrightarrow{T=130^\circ\text{C}=403.2 \text{ K}}$$

$$\ln p^*(130^\circ\text{C}) = 6.595 \Rightarrow p^*(130^\circ\text{C}) = e^{6.595} = \underline{\underline{731.4 \text{ mm Hg}}}$$

**b.** Basis: 100 mol feed gas    CB denotes chlorobenzene.



Saturation condition at inlet:  $y_o P = p_{\text{CB}}^*(130^\circ\text{C}) \Rightarrow y_o = \frac{731 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.962 \text{ mol CB/mol}$

Saturation condition at outlet:  $y_1 P = p_{\text{CB}}^*(58.3^\circ\text{C}) \Rightarrow y_1 = \frac{60 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.0789 \text{ mol CB/mol}$

Air balance:  $100(1 - y_o) = n_1(1 - y_1) \Rightarrow n_1 = (100)(1 - 0.962)/(1 - 0.0789) = 4.126 \text{ mol}$

Total mole balance:  $100 = n_1 + n_2 \Rightarrow n_2 = 100 - 4.126 = 95.87 \text{ mol CB(l)}$

% condensation:  $\frac{95.87 \text{ mol CB condensed}}{(0.962 \times 100) \text{ mol CB feed}} \times 100\% = \underline{\underline{99.7\%}}$

- c. Assumptions:** (1) Raoult's law holds at initial and final conditions;  
 (2) CB is the only condensable species (no water condenses);  
 (3) Clausius-Clapeyron estimate is accurate at  $130^\circ\text{C}$ .

**6.13**  $T = 78^\circ\text{F} = 25.56^\circ\text{C}$ ,  $P_{\text{bar}} = 29.9 \text{ in Hg} = 759.5 \text{ mm Hg}$ ,  $h_r = 87\%$

$$y_{\text{H}_2\text{O}} P = 0.87 p^*(25.56^\circ\text{C}) \xrightarrow{\text{Table B.3}} y_{\text{H}_2\text{O}} = \frac{0.87(24.559 \text{ mm Hg})}{759.5 \text{ mm Hg}} = \underline{\underline{0.0281 \text{ mol H}_2\text{O/mol air}}}$$

Dew Point:  $p^*(T_{dp}) = y p = 0.0281(759.5) = 21.34 \text{ mm Hg} \xrightarrow{\text{Table B.3}} \underline{\underline{T_{dp} = 23.2^\circ\text{C}}}$

### 6.13 (cont'd)

$$\underline{h_m} = \frac{0.0281}{1 - 0.0281} = 0.0289 \text{ mol H}_2\text{O/mol dry air}$$

$$\underline{h_a} = \frac{0.0289 \text{ mol H}_2\text{O}}{\text{mol dry air}} \left| \frac{18.02 \text{ g H}_2\text{O}}{\text{mol H}_2\text{O}} \right| \frac{\text{mol dry air}}{29.0 \text{ g dry air}} = \underline{0.0180 \text{ g H}_2\text{O/g dry air}}$$

$$\underline{h_p} = \frac{h_m}{p^*(25.56^\circ\text{C})/[P - p^*(25.56^\circ\text{C})]} \times 100\% = \frac{0.0289}{24.559/[759.5 - 24.559]} \times 100\% = \underline{86.5\%}$$

**6.14 Basis I:** 1 mol humid air @ 70° F (21.1° C), 1 atm,  $h_r = 50\%$

$$\underline{h_r = 50\%} \Rightarrow y_{\text{H}_2\text{O}} P = 0.50 p_{\text{H}_2\text{O}}^*(21.1^\circ\text{C})$$

$$\xrightarrow{\text{Table B.3}} y_{\text{H}_2\text{O}} = \frac{0.50 \times 18.765 \text{ mm Hg}}{760.0 \text{ mm Hg}} = 0.012 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

$$\underline{\text{Mass of air:}} \frac{0.012 \text{ mol H}_2\text{O}}{\text{mol}} \left| \frac{18.02 \text{ g}}{1 \text{ mol}} \right| + \frac{0.988 \text{ mol dry air}}{\text{mol}} \left| \frac{29.0 \text{ g}}{1 \text{ mol}} \right| = 28.87 \text{ g}$$

$$\underline{\text{Volume of air:}} \frac{1 \text{ mol}}{\text{mol}} \left| \frac{22.4 \text{ L (STP)}}{1 \text{ mol}} \right| \frac{(273.2 + 21.1)\text{K}}{273.2\text{K}} = 24.13 \text{ L}$$

$$\underline{\text{Density of air}} = \frac{28.87 \text{ g}}{24.13 \text{ L}} = \underline{1.196 \text{ g/L}}$$

**Basis II:** 1 mol humid air @ 70° F (21.1° C), 1 atm,  $h_r = 80\%$

$$\underline{h_r = 80\%} \Rightarrow y_{\text{H}_2\text{O}} P = 0.80 p_{\text{H}_2\text{O}}^*(21.1^\circ\text{C})$$

$$\xrightarrow{\text{Table B.3}} y_{\text{H}_2\text{O}} = \frac{0.80 \times 18.765 \text{ mm Hg}}{760.0 \text{ mm Hg}} = 0.020 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

$$\underline{\text{Mass of air:}} \frac{0.020 \text{ mol H}_2\text{O}}{\text{mol}} \left| \frac{18.02 \text{ g}}{1 \text{ mol}} \right| + \frac{0.980 \text{ mol dry air}}{\text{mol}} \left| \frac{29.0 \text{ g}}{1 \text{ mol}} \right| = 28.78 \text{ g}$$

$$\underline{\text{Volume of air:}} \frac{1 \text{ mol}}{\text{mol}} \left| \frac{22.4 \text{ L (STP)}}{1 \text{ mol}} \right| \frac{(273.2 + 21.1)\text{K}}{273.2\text{K}} = 24.13 \text{ L}$$

$$\underline{\text{Density of air}} = \frac{28.78 \text{ g}}{24.13 \text{ L}} = \underline{1.193 \text{ g/L}}$$

**Basis III:** 1 mol humid air @ 90° F (32.2° C), 1 atm,  $h_r = 80\%$

$$\underline{h_r = 80\%} \Rightarrow y_{\text{H}_2\text{O}} P = 0.80 p_{\text{H}_2\text{O}}^*(32.2^\circ\text{C})$$

$$\xrightarrow{\text{Table B.3}} y_{\text{H}_2\text{O}} = \frac{0.80 \times 36.068 \text{ mm Hg}}{760.0 \text{ mm Hg}} = 0.038 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

**6.14 (cont'd)**

$$\text{Mass of air: } \frac{0.038 \text{ mol H}_2\text{O}}{1 \text{ mol}} \left| \frac{18.02 \text{ g}}{1 \text{ mol}} \right| + \frac{0.962 \text{ mol dry air}}{1 \text{ mol}} \left| \frac{29.0 \text{ g}}{1 \text{ mol}} \right| = 28.58 \text{ g}$$

$$\text{Volume of air: } \frac{1 \text{ mol}}{1 \text{ mol}} \left| \frac{22.4 \text{ L (STP)}}{1 \text{ mol}} \right| \left| \frac{(273.2 + 32.2)\text{K}}{273.2\text{K}} \right| = 25.04 \text{ L}$$

$$\text{Density} = \frac{28.58 \text{ g}}{25.04 \text{ L}} = \underline{\underline{1.141 \text{ g/L}}}$$

Increase in  $T \Rightarrow$  increase in  $V \Rightarrow$  decrease in density

Increase in  $h_r \Rightarrow$  more water (MW = 18), less dry air (MW = 29)

$\Rightarrow$  decrease in  $m \Rightarrow$  decrease in density

Since the density in hot, humid air is lower than in cooler, dryer air, the buoyancy force on the ball must also be lower. Therefore, the statement is wrong.

**6.15 a.**  $h_r = 50\% \Rightarrow y_{\text{H}_2\text{O}} P = 0.50 p_{\text{H}_2\text{O}}^*(90^\circ\text{C})$

$$\xrightarrow{\text{Table B.3}} y_{\text{H}_2\text{O}} = \frac{0.50 \times 525.76 \text{ mm Hg}}{760.0 \text{ mm Hg}} = 0.346 \text{ mol H}_2\text{O} / \text{mol}$$

$$\text{Dew Point: } y_{\text{H}_2\text{O}} P = p^*(T_{\text{dp}}) = 0.346(760) = 262.9 \text{ mm Hg} \xrightarrow{\text{Table B.3}} \underline{\underline{T_{\text{dp}} = 72.7^\circ\text{C}}}$$

$$\text{Degrees of Superheat} = 90 - 72.7 = \underline{\underline{17.3^\circ\text{C of superheat}}}$$

**b. Basis:**  $\frac{1 \text{ m}^3 \text{ feed gas}}{\text{m}^3} \left| \frac{10^3 \text{ L}}{\text{m}^3} \right| \left| \frac{273\text{K}}{363\text{K}} \right| \left| \frac{\text{mol}}{22.4 \text{ L (STP)}} \right| = 33.6 \text{ mol}$

$$\text{Saturation Condition: } y_1 = \frac{p_{\text{H}_2\text{O}}^*(25^\circ\text{C})}{P} = \frac{23.756}{760} = 0.0313 \text{ mol H}_2\text{O/mol}$$

$$\text{Dry air balance: } 0.654(33.6) = n_1(1 - 0.0313) \Rightarrow n_1 = 22.7 \text{ mol}$$

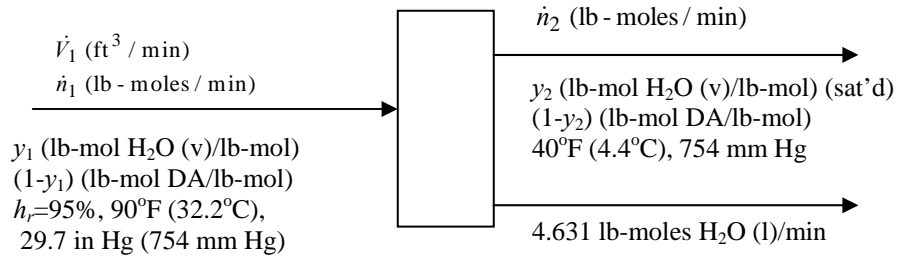
$$\text{Total mol balance: } 33.6 = 22.7 + n_2 \Rightarrow \underline{\underline{n_2 = 10.9 \text{ mol H}_2\text{O condense/m}^3}}$$

**c.**  $y_{\text{H}_2\text{O}} P = p^*(90^\circ\text{C}) \Rightarrow P = \frac{p^*(90^\circ\text{C})}{y_{\text{H}_2\text{O}}} = \frac{525.76 \text{ mmHg}}{0.346} = 1520 \text{ mm Hg} = \underline{\underline{2.00 \text{ atm}}}$

**6.16**  $T = 90^\circ\text{F} = 32.2^\circ\text{C}$ ,  $p = 29.7\text{ in Hg} = 754.4\text{ mm Hg}$ ,  $h_r = 95\%$

Basis: 10 gal water condensed/min

$$\dot{n}_{\text{condensed}} = \frac{10\text{ gal H}_2\text{O}}{\text{min}} \left| \frac{1\text{ ft}^3}{7.4805\text{ gal}} \right| \left| \frac{62.43\text{ lb}_m}{\text{ft}^3} \right| \left| \frac{1\text{ lb-mol}}{18.02\text{ lb}_m} \right| = 4.631\text{ lb-mole/min}$$



95%  $h_r$  at inlet:  $y_{\text{H}_2\text{O}} P = 0.95 p^*(32.2^\circ\text{C})$

$$\xrightarrow{\text{Table B.3}} y_{\text{H}_2\text{O}} = \frac{0.95(36.068\text{ mm Hg})}{754.4\text{ mm Hg}} = \underline{\underline{0.0045\text{ lb-mol H}_2\text{O/lb-mol}}}$$

$$\text{Raoult's law: } y_2 P = p^*(4.4^\circ\text{C}) \xrightarrow{\text{Table B.3}} y_2 = \frac{6.274}{754.4} = 0.00817\text{ lb-mol H}_2\text{O/lb-mol}$$

$$\left. \begin{array}{l} \text{Mole balance: } \dot{n}_1 = \dot{n}_2 + 4.631 \\ \text{Water balance: } 0.0045\dot{n}_1 = 0.00817\dot{n}_2 + 4.631 \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \dot{n}_1 = 124.7\text{ lb-moles/min} \\ \dot{n}_2 = 120.1\text{ lb-moles/min} \end{array} \right.$$

$$\begin{aligned} \text{Volume in: } \dot{V} &= \frac{124.7\text{ lb-moles}}{\text{min}} \left| \frac{359\text{ ft}^3\text{ (STP)}}{\text{lb-moles}} \right| \left| \frac{(460+90)^\circ\text{R}}{492^\circ\text{R}} \right| \left| \frac{760\text{ mm Hg}}{754\text{ mm Hg}} \right| \\ &= \underline{\underline{5.04 \times 10^4\text{ ft}^3/\text{min}}} \end{aligned}$$

**6.17 a.** Assume no water condenses and that the vapor at  $15^\circ\text{C}$  can be treated as an ideal gas.

$$p_{\text{final}} = \frac{760\text{ mm Hg}}{(200 + 273)\text{ K}} \left| \frac{(15 + 273)\text{ K}}{(200 + 273)\text{ K}} \right| = 462.7\text{ mm Hg} \Rightarrow (p_{\text{H}_2\text{O}})_{\text{final}} = 0.20 \times 462.7 = 92.6\text{ mm Hg}$$

$p^*(15^\circ\text{C}) = 12.79\text{ mm Hg} < p_{\text{H}_2\text{O}}$ . Impossible  $\Rightarrow$  condensation occurs.

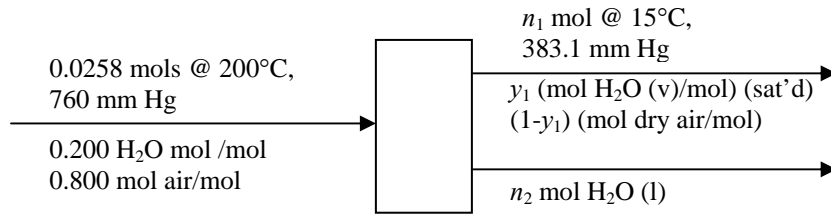
$$(p_{\text{air}})_{\text{final}} = (p_{\text{air}})_{\text{initial}} \frac{T_{\text{final}}}{T_{\text{initial}}} = (0.80 \times 760)\text{ mm Hg} \times \frac{288\text{ K}}{473\text{ K}} = 370.2\text{ mm Hg}$$

$$P = p_{\text{H}_2\text{O}} + p_{\text{air}} = 370.2 + 12.79 = \underline{\underline{383\text{ mm Hg}}}$$

**b.** Basis:  $\frac{1\text{ L}}{473\text{ K}} \left| \frac{273\text{ K}}{22.4\text{ L (STP)}} \right| \left| \frac{\text{mol}}{22.4\text{ L (STP)}} \right| = 0.0258\text{ mol}$



### 6.17 (cont'd)



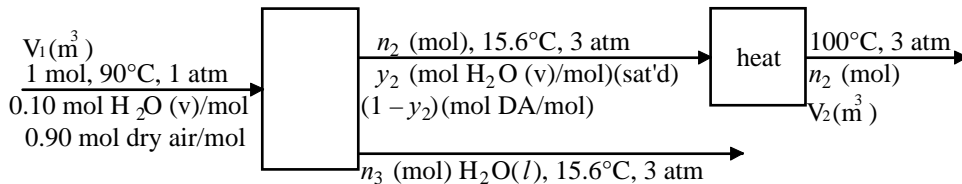
$$\text{Saturation Condition: } y_1 = \frac{p_{\text{H}_2\text{O}}^*(15^\circ\text{C})}{P} = \frac{12.79 \text{ mm Hg}}{383.1 \text{ mm Hg}} = \underline{\underline{0.03339 \text{ mol H}_2\text{O/mol}}}$$

c. Dry air balance:  $0.800(0.0258) = n_1(1 - 0.03339) \Rightarrow n_1 = 0.02135 \text{ mol}$

Total mole balance:  $0.0258 = 0.02135 + n_2 \Rightarrow n_2 = 0.00445 \text{ mol}$

Mass of water condensed =  $\frac{0.00445 \text{ mol}}{1 \text{ mol}} \times \frac{18.02 \text{ g}}{1 \text{ mol}} = \underline{\underline{0.0802 \text{ g}}}$

### 6.18 Basis: 1 mol feed



$$\text{Saturation: } y_2 = \frac{p_{\text{H}_2\text{O}}^*(15.6^\circ\text{C})}{P} \xrightarrow{\text{Table B.3}} y_2 = \frac{13.29 \text{ mm Hg}}{3 \text{ atm}} \times \frac{\text{atm}}{760 \text{ mm Hg}} = 0.00583$$

Dry air balance:  $0.90(1) = n_2(1 - 0.00583) \Rightarrow n_2 = 0.9053 \text{ mol}$

H<sub>2</sub>O mol balance:  $0.10(1) = 0.00583(0.9053) + n_3 \Rightarrow n_3 = 0.0947 \text{ mol}$

Fraction H<sub>2</sub>O condensed:  $\frac{0.0947 \text{ mol condensed}}{0.100 \text{ mol fed}} = \underline{\underline{0.947 \text{ mol condense/mol fed}}}$

$$h_r = \frac{y_2 P \times 100\%}{p^*(100^\circ\text{C})} = \frac{0.00583(3 \text{ atm})}{1 \text{ atm}} \times 100\% = \underline{\underline{1.75\%}}$$

$$V_2 = \frac{0.9053 \text{ mol}}{1 \text{ mol}} \times \frac{22.4 \text{ L (STP)}}{1 \text{ mol}} \times \frac{373\text{K}}{273\text{K}} \times \frac{1 \text{ atm}}{3 \text{ atm}} \times \frac{1 \text{ m}^3}{10^3 \text{ L}} = 9.24 \times 10^{-3} \text{ m}^3 \text{ outlet air @ } 100^\circ\text{C}$$

$$V_1 = \frac{1 \text{ mol}}{1 \text{ mol}} \times \frac{22.4 \text{ L (STP)}}{1 \text{ mol}} \times \frac{363\text{K}}{273\text{K}} \times \frac{1 \text{ m}^3}{10^3 \text{ L}} = 2.98 \times 10^{-2} \text{ m}^3 \text{ feed air @ } 90^\circ\text{C}$$

$$\frac{V_2}{V_1} = \frac{9.24 \times 10^{-3} \text{ m}^3 \text{ outlet air}}{2.98 \times 10^{-2} \text{ m}^3 \text{ feed air}} = \underline{\underline{0.310 \text{ m}^3 \text{ outlet air/m}^3 \text{ feed air}}}$$

$$\text{6.19 Liquid H}_2\text{O initially present: } \frac{25 \text{ L}}{1} \left| \frac{1.00 \text{ kg}}{\text{L}} \right| \frac{1 \text{ kmol}}{18.02 \text{ kg}} = 1.387 \text{ kmol H}_2\text{O (l)}$$

$$\text{Saturation at outlet: } y_{\text{H}_2\text{O}} = \frac{p_{\text{H}_2\text{O}}^*(25^\circ\text{C})}{P} = \frac{23.76 \text{ mm Hg}}{1.5 \times 760 \text{ mm Hg}} = 0.0208 \text{ mol H}_2\text{O/mol air}$$

$$\Rightarrow \frac{0.0208}{1 - 0.0208} = 0.0212 \text{ mol H}_2\text{O/mol dry air}$$

$$\text{Flow rate of dry air: } \frac{15 \text{ L(STP)}}{\text{min}} \left| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right| = 0.670 \text{ mol dry air/min}$$

$$\text{Evaporation Rate: } \frac{0.670 \text{ mol dry air}}{\text{min}} \left| \frac{0.0212 \text{ mol H}_2\text{O}}{\text{mol dry air}} \right| = 0.0142 \text{ mol H}_2\text{O/min}$$

$$\text{Complete Evaporation: } \frac{1.387 \text{ kmol}}{1} \left| \frac{10^3 \text{ mol}}{\text{kmol}} \right| \frac{\text{min}}{0.0142 \text{ mol}} \left| \frac{1 \text{ h}}{60 \text{ min}} \right| = \underline{\underline{1628 \text{ h}}} \quad (67.8 \text{ days})$$

$$\text{6.20 a. Daily rate of octane use} = \frac{\pi}{4} \cdot 30^2 \cdot (18 - 8) = \frac{7.069 \times 10^3 \text{ ft}^3}{\text{day}} \left| \frac{7.481 \text{ gal}}{\text{ft}^3} \right| = \underline{\underline{5.288 \times 10^4 \text{ gal/day}}}$$

$$(SG)_{\text{C}_8\text{H}_{18}} = 0.703 \Rightarrow \frac{5.288 \times 10^4 \text{ gal}}{\text{day}} \left| \frac{1 \text{ ft}^3}{7.481 \text{ gal}} \right| \left| \frac{0.703 \times 62.43 \text{ lb}_m}{\text{ft}^3} \right| = \underline{\underline{3.10 \times 10^5 \text{ lb}_m \text{ C}_8\text{H}_{18} / \text{day}}}$$

$$\text{b. } \Delta p = \frac{0.703 \times 62.43 \text{ lb}_m}{\text{ft}^3} \left| \frac{32.174 \text{ ft}}{\text{s}^2} \right| \left| \frac{1 \text{ lb}_f}{32.174 \frac{\text{lb}_m \cdot \text{ft}}{\text{s}^2}} \right| \left| \frac{(18-8) \text{ ft}}{1} \right| \left| \frac{1 \text{ ft}^2}{144 \text{ in}^2} \right| \left| \frac{29.921 \text{ in Hg}}{14.696 \text{ lb}_f / \text{in}^2} \right| = \underline{\underline{6.21 \text{ in Hg}}}$$

$$\text{c. Table B.4: } p_{\text{C}_8\text{H}_{18}}^*(90^\circ\text{F}) = \frac{20.74 \text{ mm Hg}}{1} \left| \frac{14.696 \text{ psi}}{760 \text{ mm Hg}} \right| = 0.40 \text{ lb}_f / \text{in}^2 = p_{\text{octane}} = y_{\text{octane}} P$$

Octane lost to environment = octane vapor contained in the vapor space displaced by liquid during refilling.

$$\text{Volume: } \frac{5.288 \times 10^4 \text{ gal}}{1} \left| \frac{1 \text{ ft}^3}{7.481 \text{ gal}} \right| = 7069 \text{ ft}^3$$

$$\text{Total moles: } n = \frac{pV}{RT} = \frac{(16.0 + 14.7) \text{ psi}}{10.73 \text{ ft}^3 \cdot \text{psi} / (\text{lb} - \text{mole} \cdot ^\circ\text{R})} \left| \frac{7069 \text{ ft}^3}{(90 + 460) ^\circ\text{R}} \right| = 36.77 \text{ lb} - \text{moles}$$

$$\text{Mole fraction of C}_8\text{H}_{18}: y = \frac{p_{\text{C}_8\text{H}_{18}}}{P} = \frac{0.40 \text{ psi}}{(16.0 + 14.7) \text{ psi}} = 0.0130 \text{ lb} - \text{mole C}_8\text{H}_{18} / \text{lb} - \text{mole}$$

$$\text{Octane lost} = 0.0130(36.77) \text{ lb} - \text{mole} = \underline{\underline{0.479 \text{ lb} - \text{mole}}} (= 55 \text{ lb}_m = 25 \text{ kg})$$

d. A mixture of octane and air could ignite.

**6.21 a.** Antoine equation  $\Rightarrow p_{tol}^*(85^\circ \text{F}) = p_{tol}^*(29.44^\circ \text{C}) = 35.63 \text{ mmHg} = p_{tol}$

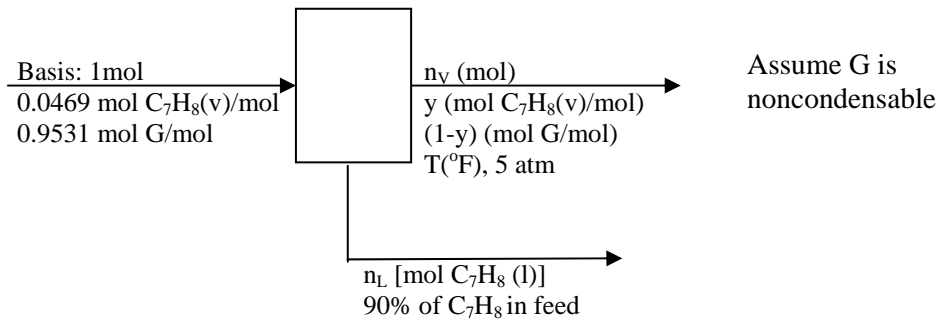
Mole fraction of toluene in gas:  $y = \frac{p_{tol}}{P} = \frac{35.63 \text{ mmHg}}{760 \text{ mmHg}} = 0.0469 \text{ lb - mole toluene / lb - mole}$

Toluene displaced  $= y n_{total} = \frac{yPV}{RT}$

$$= \frac{0.0469 \text{ lb - mole tol}}{\text{lb - mole}} \left| \frac{1 \text{ atm}}{0.7302 \frac{\text{ft}^3 \cdot \text{atm}}{\text{lb - mole} \cdot ^\circ \text{R}}} \right| \left| \frac{900 \text{ gal}}{(85 + 460)^\circ \text{R}} \right| \left| \frac{1 \text{ ft}^3}{7.481 \text{ gal}} \right| \left| \frac{92.13 \text{ lb}_m \text{ tol}}{\text{lb - mole}} \right|$$

= 1.31 lb<sub>m</sub> toluene displaced

**b.**



90% condensation  $\Rightarrow n_L = 0.90(0.0469)(1) \text{ mol C}_7\text{H}_8 = 0.0422 \text{ mol C}_7\text{H}_8(l)$

Mole balance:  $1 = n_V + 0.0422 \Rightarrow n_V = 0.9578 \text{ mol}$

Toluene balance:  $0.0469(1) = y(0.9578) + 0.0422 \Rightarrow y = 0.004907 \text{ mol C}_7\text{H}_8 / \text{mol}$

Raoult's law:  $p_{tol} = yP = (0.004907)(5 \times 760) = 18.65 \text{ mmHg} = p_{tol}^*(T)$

Antoine equation:

$$T = \frac{B - C(A - \log_{10} p^*)}{A - \log_{10} p^*} = \frac{1346.773 - 219.693(6.95805 - \log_{10} 18.65)}{6.95805 - \log_{10} 18.65} = 17.11^\circ \text{C} = \underline{\underline{62.8^\circ \text{F}}}$$

**6.22 a.** Molar flow rate:  $\dot{n} = \frac{\dot{V}P}{RT} = \frac{100 \text{ m}^3}{\text{h}} \left| \frac{\text{kmol} \cdot \text{K}}{82.06 \times 10^{-3} \text{ m}^3 \cdot \text{atm}} \right| \left| \frac{2 \text{ atm}}{(100 + 273) \text{ K}} \right| = \underline{\underline{6.53 \text{ kmol} / \text{h}}}$

**b.** Antoine Equation:

$$\log_{10} p_{Hex}^*(100^\circ \text{C}) = 6.88555 - \frac{1175.817}{100 + 224.867} = 3.26601$$

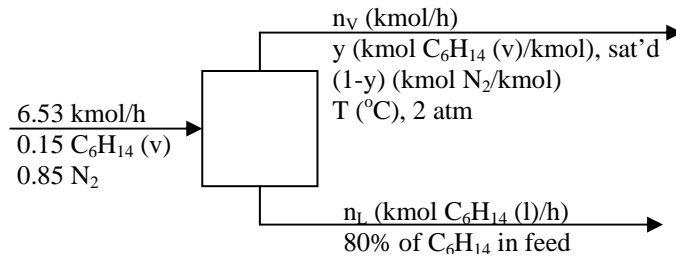
$$\Rightarrow p^* = 1845 \text{ mm Hg}$$

$$p_{Hex} = y_{Hex} \cdot P = \frac{0.150(2.00) \text{ atm}}{\text{atm}} \left| \frac{760 \text{ mm Hg}}{\text{atm}} \right| = 228 \text{ mm Hg} < p_{Hex}^* \Rightarrow \text{not saturated}$$

$$p_{Hex}^*(T) = 228 \text{ mm Hg} \Rightarrow \log_{10} 228 = 6.88555 - \frac{1175.817}{T + 224.867} = 2.35793 \Rightarrow T = \underline{\underline{34.8^\circ \text{C}}}$$

## 6.22 (cont'd)

c.



80% condensation:  $n_L = 0.80(0.15)(6.53 \text{ kmol/h}) = 0.7836 \text{ kmol C}_6\text{H}_{14}(\text{l})/\text{h}$

Mole balance:  $6.53 = n_V + 0.7836 \Rightarrow n_V = 5.746 \text{ kmol/h}$

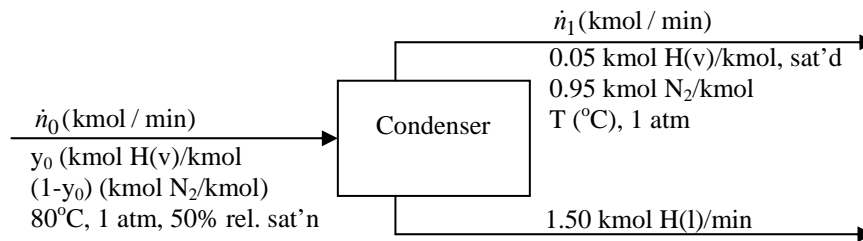
Hexane balance:  $0.15(6.53) = y(5.746) + 0.7836 \Rightarrow y = 0.03409 \text{ kmol C}_6\text{H}_{14} / \text{kmol}$

Raoult's law:  $p_{\text{Hex}} = yP = (0.03409)(2 \times 760 \text{ mmHg}) = 51.82 \text{ mmHg} = p_{\text{Hex}}^*(T)$

Antoine equation:  $\log_{10} 51.82 = 6.88555 - \frac{1175.817}{T + 224.867} \Rightarrow T = \underline{\underline{2.52^\circ\text{C}}}$

## 6.23 Let H=n-hexane

a.



50% relative saturation at inlet:  $y_o P = 0.500 p_H^*(80^\circ\text{C})$

Table B.4  $\Rightarrow y_o = \frac{(0.500)(1068 \text{ mmHg})}{760 \text{ mmHg}} = 0.703 \text{ kmol H} / \text{kmol}$

Saturation at outlet:  $0.05P = p_H^*(T_1) \Rightarrow p_H^*(T_1) = 0.05(760 \text{ mmHg}) = 38 \text{ mmHg}$

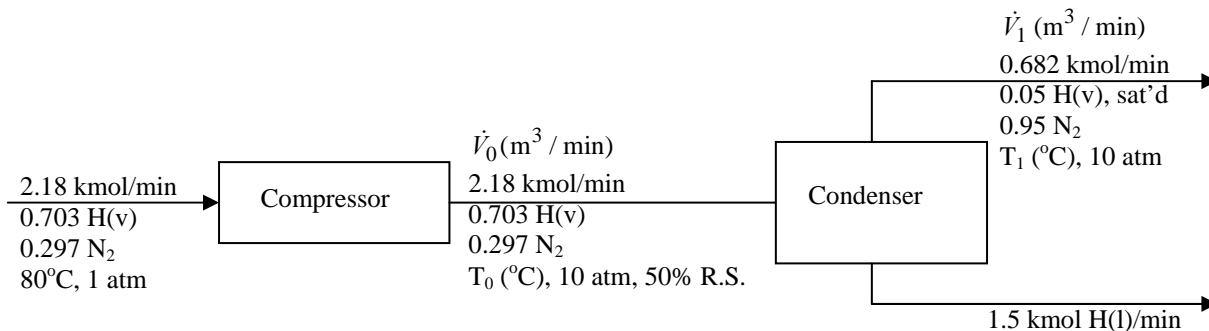
Antoine equation:  $\log_{10} 38 = 6.88555 - \frac{1175.817}{T_1 + 224.867} \Rightarrow T_1 = \underline{\underline{-3.26^\circ\text{C}}}$

Mole balance:  $\dot{n}_0 = \dot{n}_1 + 1.50$   
N<sub>2</sub> balance:  $(1 - 0.703)\dot{n}_0 = 0.95\dot{n}_1$   $\Rightarrow \begin{cases} \dot{n}_0 = 2.18 \text{ kmol/min} \\ \dot{n}_1 = 0.682 \text{ kmol/min} \end{cases}$

N<sub>2</sub> volume:  $\dot{V}_{N_2} = \frac{(0.95)0.682 \text{ kmol}}{\text{min}} \left| \frac{22.4 \text{ m}^3 (\text{STP})}{\text{kmol}} \right| = \underline{\underline{14.5 \text{ SCMM}}}$

### 6.23 (cont'd)

- b. Assume no condensation occurs during the compression



50% relative saturation at condenser inlet:

$$0.500 p_H^*(T_0) = 0.703(7600 \text{ mmHg}) \Rightarrow p_H^*(T_0) = 1.068 \times 10^4 \text{ mmHg} \xrightarrow{\text{Antoine}} T_0 = 187^\circ \text{C}$$

$$\text{Saturation at outlet: } 0.050(7600 \text{ mmHg}) = 380 \text{ mmHg} = p_H^*(T_1) \xrightarrow{\text{Antoine}} T_1 = \underline{\underline{48.2^\circ \text{C}}}$$

$$\text{Volume ratio: } \frac{\dot{V}_1}{\dot{V}_0} = \frac{n_1 R T_1 / P}{n_0 R T_0 / P} = \frac{n_1 (T_1 + 273.2)}{n_0 (T_0 + 273.2)} = \frac{0.682 \text{ kmol/min}}{2.18 \text{ kmol/min}} \times \frac{321 \text{ K}}{460 \text{ K}} = \underline{\underline{0.22}} \frac{\text{m}^3 \text{ out}}{\text{m}^3 \text{ in}}$$

- c. The cost of cooling to  $-3.26^\circ \text{C}$  (installed cost of condenser + utilities and other operating costs) vs. the cost of compressing to 10 atm and cooling at 10 atm.

- 6.24 a. Maximum mole fraction of nonane achieved if all the liquid evaporates and none escapes.

$$n_{\max} = \frac{15 \text{ L C}_9\text{H}_{20} (l) \quad \swarrow (SG)_{\text{nonane}} \quad 0.718 \times 1.00 \text{ kg}}{\text{L C}_9\text{H}_{20} \quad 128.25 \text{ kg}} \times \frac{\text{kmol}}{128.25 \text{ kg}} = 0.084 \text{ kmol C}_9\text{H}_{20}$$

Assume  $T = 25^\circ \text{C}$ ,  $P = 1 \text{ atm}$

$$n_{\text{gas}} = \frac{2 \times 10^4 \text{ L} \quad 273 \text{ K}}{298 \text{ K} \quad 22.4 \times 10^3 \text{ L(STP)}} \times \frac{1 \text{ kmol}}{22.4 \times 10^3 \text{ L(STP)}} = 0.818 \text{ kmol}$$

$$y_{\max} = \frac{n_{\max}}{n_{\text{gas}}} = \frac{0.084 \text{ kmol C}_9\text{H}_{20}}{0.818 \text{ kmol}} = 0.10 \text{ kmol C}_9\text{H}_{20} / \text{kmol (10 mole\%)}$$

As the nonane evaporates, the mole fraction will pass through the explosive range (0.8% to 2.9%). The answer is therefore yes.

The nonane will not spread uniformly—it will be high near the sump as long as liquid is present (and low far from the sump). There will always be a region where the mixture is explosive at some time during the evaporation.

$$\text{b. } \ln p^* = -\frac{A}{T} + B \quad T_1 = 25.8^\circ \text{C} = 299 \text{ K}, p_1^* = 5.00 \text{ mmHg}$$

$$T_2 = 66.0^\circ \text{C} = 339 \text{ K}, p_2^* = 40.0 \text{ mmHg}$$

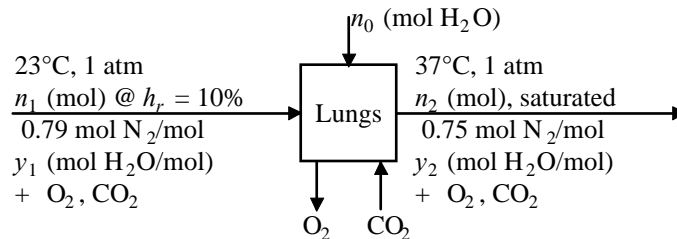
### 6.24 (cont'd)

$$-A = \frac{\ln(40.0 / 5.00)}{\frac{1}{339} - \frac{1}{299}} \Rightarrow A = 5269, \quad B = \ln(5.00) + \frac{5269}{299} = 19.23 \Rightarrow p^* = \exp\left(19.23 - \frac{5269}{T(K)}\right)$$

At lower explosion limit,  $y = 0.008 \text{ kmol C}_9\text{H}_{20} / \text{kmol} \Rightarrow p^*(T) = yP = (0.008)(760 \text{ mm Hg})$   
 $= 6.08 \text{ mm Hg} \xrightarrow[\text{Formula for } p^*]{} T = 302 \text{ K} = \underline{\underline{29^\circ\text{C}}}$

- c. The purpose of purge is to evaporate and carry out the liquid nonane. Using steam rather than air is to make sure an explosive mixture of nonane and oxygen is never present in the tank. Before anyone goes into the tank, a sample of the contents should be drawn and analyzed for nonane.

### 6.25 Basis: 24 hours of breathing



Air inhaled:  $n_1 = \frac{12 \text{ breaths}}{\text{min}} \left| \frac{500 \text{ ml}}{\text{breath}} \right| \left| \frac{1 \text{ liter}}{10^3 \text{ ml}} \right| \left| \frac{273 \text{ K}}{(23 + 273) \text{ K}} \right| \left| \frac{1 \text{ mol}}{22.4 \text{ liter(STP)}} \right| \left| \frac{60 \text{ min}}{1 \text{ hr}} \right| \left| \frac{24 \text{ hr}}{1 \text{ day}} \right|$   
 $= 356 \text{ mol inhaled/day}$

Inhaled air - 10% r.h.:  $y_1 = \frac{0.10 p^*_{\text{H}_2\text{O}}(23^\circ\text{C})}{P} = \frac{0.10(21.07 \text{ mm Hg})}{760 \text{ mm Hg}} = 2.77 \times 10^{-3} \frac{\text{mol H}_2\text{O}}{\text{mol}}$

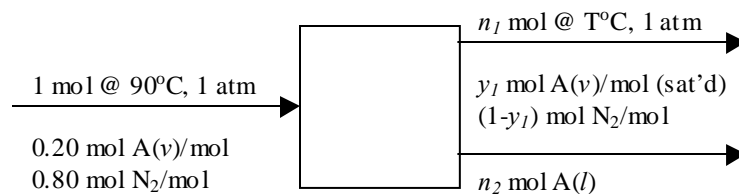
Inhaled air - 50% r.h.:  $y_1 = \frac{0.50 p^*_{\text{H}_2\text{O}}(23^\circ\text{C})}{P} = \frac{0.50(21.07 \text{ mm Hg})}{760 \text{ mm Hg}} = 1.39 \times 10^{-2} \frac{\text{mol H}_2\text{O}}{\text{mol}}$

H<sub>2</sub>O balance:  $n_0 = n_2 y_2 - n_1 y_1 \Rightarrow (n_0)_{10\% \text{ rh}} - (n_0)_{50\% \text{ rh}} = (n_1 y_1)_{50\%} - (n_1 y_1)_{10\%}$

$$= \left( 356 \frac{\text{mol}}{\text{day}} \right) \left[ (0.0139 - 0.00277) \frac{\text{mol H}_2\text{O}}{\text{mol}} \right] \left( \frac{18.0 \text{ g}}{1 \text{ mol}} \right) = \underline{\underline{71 \text{ g/day}}}$$

Although the problem does not call for it, we could also calculate that  $n_2 = 375 \text{ mol exhaled/day}$ ,  $y_2 = 0.0619$ , and the rate of weight loss by breathing at  $23^\circ\text{C}$  and 50% relative humidity is  
 $n_0(18) = (n_2 y_2 - n_1 y_1)18 = 329 \text{ g/day}.$

- 6.26 a. To increase profits and reduce pollution.  
 b. Assume condensation occurs. A=acetone



For cooling water at 20°C

$$\log_{10} p_A^*(20^\circ\text{C}) = 7.11714 - \frac{1210.595}{20 + 229.664} = 2.26824 \Rightarrow p_A^*(20^\circ\text{C}) = 184.6 \text{ mmHg}$$

Saturation:  $y_1 \cdot P = p_A^*(20^\circ\text{C}) \Rightarrow y_1 = \frac{184.6}{760} = 0.243 > 0.2$ , so no saturation occurs.

For refrigerant at -35°C

$$\log_{10} p_A^*(-35^\circ\text{C}) = 7.11714 - \frac{1210.595}{-35 + 229.664} = 0.89824 \Rightarrow p_A^*(-35^\circ\text{C}) = 7.61 \text{ mmHg}$$

(Note: -35°C is outside the range of validity of the Antoine equation coefficients in Table B.4. An alternative is to look up the vapor pressure of acetone at that temperature in a handbook. The final result is almost identical.)

Saturation:  $y_1 \cdot P = p_A^*(-35^\circ\text{C}) \Rightarrow y_1 = \frac{7.61}{760} = 0.0100$

N<sub>2</sub> mole balance:  $1(0.8) = n_1(1 - 0.01) \Rightarrow n_1 = 0.808 \text{ mol}$

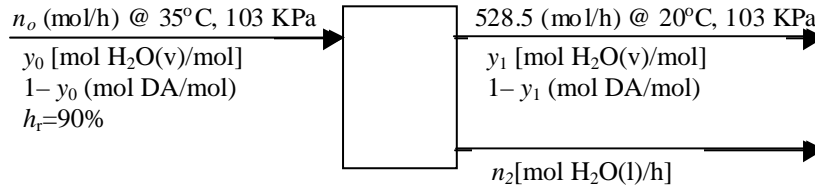
Total mole balance:  $1 = 0.808 + n_2 \Rightarrow n_2 = 0.192 \text{ mol}$

Percentage acetone recovery:  $\frac{0.192}{2} \times 100\% = \underline{\underline{96\%}}$

- c. Costs of acetone, nitrogen, cooling tower, cooling water and refrigerant  
 d. The condenser temperature could never be as low as the initial cooling fluid temperature because heat is transferred between the condenser and the surrounding environment. It will lower the percentage acetone recovery.

6.27

Basis:  $\frac{12500 \text{ L}}{\text{h}} \left| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right| \frac{273 \text{ K}}{293 \text{ K}} \left| \frac{103000 \text{ Pa}}{101325 \text{ Pa}} \right| = 528.5 \text{ mol / h}$



Inlet:  $y_o = \frac{h_r \cdot p_{\text{H}_2\text{O}}^*(35^\circ\text{C})}{P} = \frac{0.90 \times 42.175 \text{ mmHg}}{103000 \text{ Pa}} \left| \frac{101325 \text{ Pa}}{760 \text{ mmHg}} \right| = 0.04913 \text{ mol H}_2\text{O/mol}$

Outlet:  $y_1 = \frac{p_{\text{H}_2\text{O}}^*(20^\circ\text{C})}{P} = \frac{17.535 \text{ mmHg}}{103000 \text{ Pa}} \left| \frac{101325 \text{ Pa}}{760 \text{ mmHg}} \right| = 0.02270 \text{ mol H}_2\text{O / mol}$

Dry air balance:  $(1 - 0.04913)n_o = (1 - 0.02270)(528.5) \Rightarrow n_o = 543.2 \text{ mol / h}$

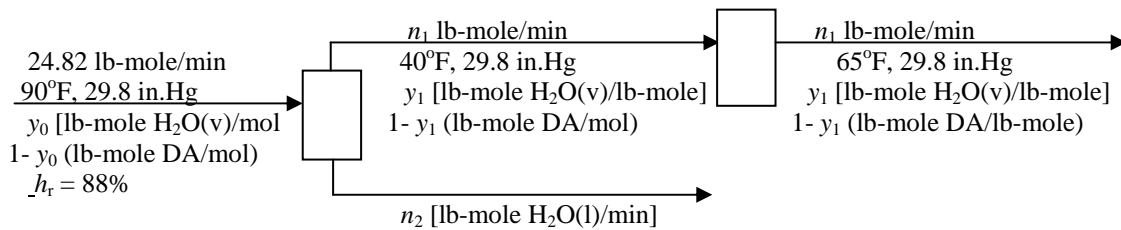
Inlet air:  $\frac{543.2 \text{ mol}}{\text{h}} \left| \frac{22.4 \text{ L(STP)}}{\text{mol}} \right| \frac{308 \text{ K}}{273 \text{ K}} \left| \frac{101325 \text{ Pa}}{103000 \text{ Pa}} \right| = \underline{\underline{13500 \text{ L / h}}}$

Total balance:  $543.2 = 528.5 + n_2 \Rightarrow n_2 = 14.7 \text{ mol / h}$

Condensation rate:  $\frac{14.7 \text{ mol}}{\text{h}} \left| \frac{18.02 \text{ g H}_2\text{O}}{1 \text{ mol H}_2\text{O}} \right| \frac{1 \text{ kg}}{1000 \text{ g}} = \underline{\underline{0.265 \text{ kg / h}}}$

6.28

Basis:  $\frac{10000 \text{ ft}^3}{\text{min}} \left| \frac{1 \text{ lb - mol}}{359 \text{ ft}^3 \text{ (STP)}} \right| \frac{492^\circ\text{R}}{550^\circ\text{R}} \left| \frac{29.8 \text{ in Hg}}{29.92 \text{ in Hg}} \right| = 24.82 \text{ lb - mol / min}$



Inlet:  $y_o = \frac{h_r \cdot p_{\text{H}_2\text{O}}^*(90^\circ\text{F})}{P} = \frac{0.88(36.07 \text{ mmHg})}{29.8 \text{ in Hg}} \left| \frac{1 \text{ in Hg}}{25.4 \text{ mmHg}} \right| = 0.0419 \text{ lb - mol H}_2\text{O / lb - mol}$

Outlet:  $y_1 = \frac{p_{\text{H}_2\text{O}}^*(40^\circ\text{F})}{P} = \frac{6.274 \text{ mmHg}}{29.8 \text{ in Hg}} \left| \frac{1 \text{ in Hg}}{25.4 \text{ mmHg}} \right| = 0.00829 \text{ lb - mol H}_2\text{O / lb - mol}$

Dry air balance:  $24.82(1 - 0.0419) = n_1(1 - 0.00829) \Rightarrow n_1 = 23.98 \text{ lb - mol / min}$

Total balance:  $24.82 = 23.98 + n_2 \Rightarrow n_2 = 0.84 \text{ lb - mole / min}$

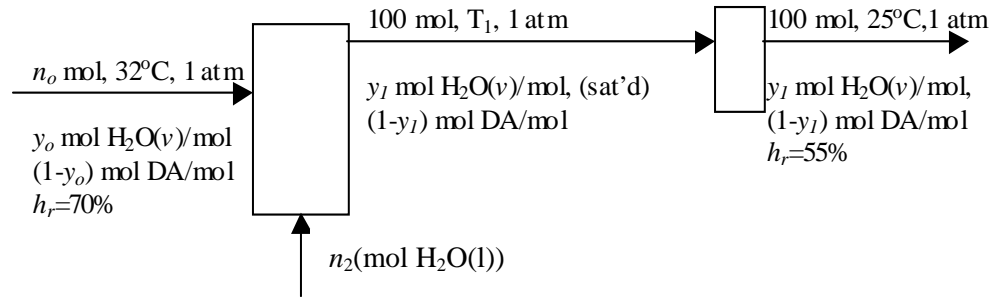


## 6.28 (cont'd)

$$\text{Condensation rate: } \frac{0.84 \text{ lb - mol}}{\text{min}} \left| \frac{18.02 \text{ lb}_m}{\text{lb - mol}} \right| \left| \frac{1 \text{ ft}^3}{62.4 \text{ lb}_m} \right| \left| \frac{7.48 \text{ gal}}{1 \text{ ft}^3} \right| = \underline{\underline{1.81 \text{ gal / min}}}$$

$$\text{Air delivered @ } 65^\circ\text{F: } \frac{23.98 \text{ lb - mol}}{\text{min}} \left| \frac{359 \text{ ft}^3 (\text{STP})}{1 \text{ lb - mol}} \right| \left| \frac{525^\circ \text{R}}{492^\circ \text{R}} \right| \left| \frac{29.92 \text{ in Hg}}{29.8 \text{ in Hg}} \right| = \underline{\underline{9223 \text{ ft}^3 / \text{min}}}$$

## 6.29 Basis: 100 mol product gas



$$\text{Outlet: } y_1 = \frac{h_r \cdot p_{\text{H}_2\text{O}}^*(25^\circ \text{C})}{P} = \frac{0.55(23.756)}{760} = 0.0172 \text{ mol H}_2\text{O} / \text{mol}$$

$$\text{Saturation at } T_1: 0.0172(760) = 13.07 = p_{\text{H}_2\text{O}}^*(T_1) \Rightarrow T_1 = \underline{\underline{15.3^\circ \text{C}}}$$

$$\text{Inlet: } y_o = \frac{h_r \cdot p_{\text{H}_2\text{O}}^*(32^\circ \text{C})}{P} = \frac{0.70(35.663)}{760} = 0.0328 \text{ mol H}_2\text{O} / \text{mol}$$

$$\text{Dry air balance: } n_o(1 - 0.0328) = 100(1 - 0.0172) \Rightarrow n_o = 101.6 \text{ mol}$$

$$\text{Total balance: } 101.6 + n_2 = 100.0 \Rightarrow n_2 = -1.6 \text{ mol (i.e. removed)}$$

$$\text{kg H}_2\text{O removed: } \frac{1.6 \text{ mol}}{1 \text{ mol}} \left| \frac{18.02 \text{ g}}{1 \text{ mol}} \right| \left| \frac{1 \text{ kg}}{1000 \text{ g}} \right| = 0.0288 \text{ kg H}_2\text{O}$$

$$\text{kg dry air: } \frac{100(1 - 0.0172) \text{ mol}}{1 \text{ mol}} \left| \frac{29.0 \text{ g}}{1 \text{ mol}} \right| \left| \frac{1 \text{ kg}}{1000 \text{ g}} \right| = 2.85 \text{ kg dry air}$$

$$\text{Ratio: } \frac{0.0288}{2.85} = \underline{\underline{0.0101 \text{ kg H}_2\text{O removed / kg dry air}}}$$

**6.30 a.** Room air –  $T = 22^\circ\text{C}$ ,  $P = 1\text{ atm}$ ,  $h_r = 40\%$  :

$$y_1 P = 0.40 p^*_{\text{H}_2\text{O}}(22^\circ\text{C}) \Rightarrow y_1 = \frac{(0.40)19.827\text{ mm Hg}}{760\text{ mm Hg}} = 0.01044\text{ mol H}_2\text{O/mol}$$

Second sample –  $T = 50^\circ\text{C}$ ,  $P = 839\text{ mm Hg}$ , saturated:

$$y_2 P = p^*_{\text{H}_2\text{O}}(50^\circ\text{C}) \Rightarrow y_2 = \frac{92.51\text{ mm Hg}}{839\text{ mm Hg}} = 0.1103\text{ mol H}_2\text{O/mol}$$

$$\ln y = bH + \ln a \Leftrightarrow y = ae^{bH}, [y_1 = 0.01044, H_1 = 5], [y_2 = 0.1103, H_2 = 48]$$

$$b = \frac{\ln(y_2/y_1)}{H_2 - H_1} = \frac{\ln(0.1103/0.01044)}{48 - 5} = 0.054827$$

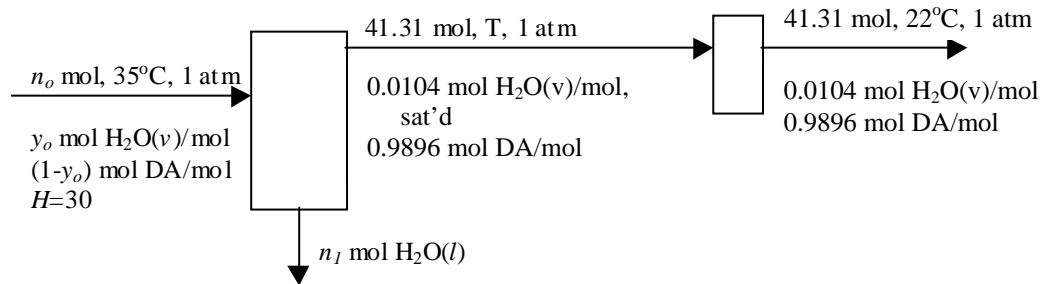
$$\ln a = \ln y_1 - bH_1 = \ln(0.01044) - (0.054827)(5) = -4.8362 \Rightarrow a = \exp(-4.8362) = 7.937 \times 10^{-3}$$

$$\Rightarrow \underline{\underline{y = 7.937 \times 10^{-3} \exp(0.054827H)}}$$

**b.** Basis:

$1\text{ m}^3$ delivered air	$273\text{K}$	$1\text{ k mol}$	$10^3\text{ mol}$
	$(22 + 273)\text{K}$	$22.4\text{m}^3(\text{STP})$	$1\text{ kmol}$

 = 41.31 mol air delivered



Saturation condition prior to reheat stage:

$$y_{\text{H}_2\text{O}} P = p^*_{\text{H}_2\text{O}}(T) \Rightarrow (0.01044)(760\text{ mm Hg}) = 7.93\text{ mm Hg}$$

$$\Rightarrow \underline{\underline{T = 7.8^\circ\text{C}}} \text{ (from Table B.3)}$$

Humidity of outside air:  $H = 30 \xrightarrow{\text{Part (a)}} y_0 = 0.0411\text{ mol H}_2\text{O/mol}$

Overall dry air balance:  $n_0(1 - y_0) = 41.31(0.9896) \Rightarrow n_0 = \frac{(41.31)(0.9896)}{(1 - 0.0411)} = 42.63\text{ mol}$

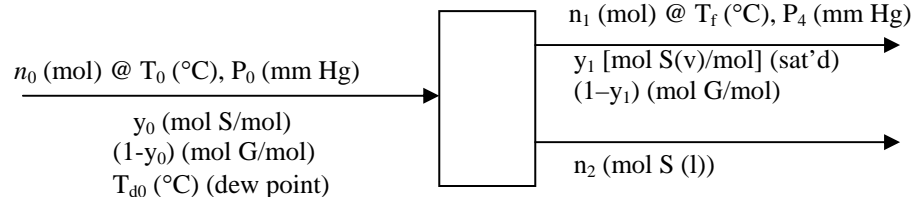
Overall water balance:  $n_0 y_0 = n_1 + (41.31)(0.0104) \Rightarrow n_1 = (42.63)(0.0411) - (41.31)(0.0104)$   
 $= 1.32\text{ mol H}_2\text{O condensed}$

Mass of condensed water = 

$1.32\text{ mol H}_2\text{O}$	$18.02\text{ g H}_2\text{O}$	$1\text{ kg}$
	$1\text{ mol H}_2\text{O}$	$10^3\text{ g}$

  
 $= \underline{\underline{0.024\text{ kg H}_2\text{O condensed/m}^3\text{ air delivered}}}$

**6.31 a.** Basis:  $\dot{n}_0$  mol feed gas. S = solvent, G = solvent-free gas



$$\text{Inlet dew point} = T_0 \Rightarrow y_o P_o = p^*(T_{do}) \Rightarrow y_o = \frac{p^*(T_{do})}{P_o} \quad (1)$$

$$\text{Saturation condition at outlet: } y_1 P_f = p^*(T_f) \Rightarrow y_1 = \frac{p^*(T_f)}{P_f} \quad (2)$$

$$\text{Fractional condensation of S} = f \Rightarrow n_2 = n_0 y_o f \xrightarrow{(1)} n_2 = n_0 f p^*(T_0) / P_o \quad (3)$$

$$\text{Total mole balance: } \dot{n}_0 = n_1 + n_2 \Rightarrow n_1 = \dot{n}_0 - n_2 \xrightarrow{\text{Eq. (3) for } n_1} n_1 = \dot{n}_0 - \frac{\dot{n}_0 f p^*(T_{do})}{P_o} \quad (4)$$

$$\text{S balance: } (n_0)(y_o) = n_1 y_1 + n_2$$

(1) - (4)

$$\begin{aligned} \frac{\dot{n}_0 p^*(T_{do})}{P_o} &= \left[ \dot{n}_0 - \frac{\dot{n}_0 f p^*(T_{do})}{P_o} \right] \left( \frac{p^*(T_f)}{P_f} \right) + \frac{\dot{n}_0 f p^*(T_{do})}{P_o} \\ \Rightarrow \frac{(1-f)p^*(T_{do})}{P_o} &= \left[ 1 - \frac{f p^*(T_{do})}{P_o} \right] \frac{p^*(T_f)}{P_f} \Rightarrow P_f = \frac{p^*(T_f) \left[ 1 - \frac{f p^*(T_{do})}{P_o} \right]}{(1-f) \frac{p^*(T_{do})}{P_o}} \end{aligned}$$

**b.**

Condensation of ethylbenzene from nitrogen											
Antoine constants for ethylbenzene											
A=	6.9665										
B=	1423.5										
C=	213.09										
Run	T0	P0	Td0	f	Tf	p*(Td0)	p*(Tf)	Pf	Orefr	Coamp	Qct
1	50	765	40	0.95	45	21.472	27.60	19139	2675	107027	109702
2	50	765	40	0.95	40	21.472	21.47	14892	4700	83329	88029
3	50	765	40	0.95	35	21.472	16.54	11471	8075	64239	72314
4	50	765	40	0.95	20	21.472	7.07	4902	26300	27582	53882

### 6.31 (cont'd)

- c. When  $T_f$  decreases,  $P_f$  decreases. Decreasing temperature and increasing pressure both to increase the fractional condensation. When you decrease  $T_f$ , less compression is required to achieve a specified fractional condensation.
- d. A lower  $T_f$  requires more refrigeration and therefore a greater refrigeration cost ( $C_{\text{refr}}$ ). However, since less compression is required at the lower temperature,  $C_{\text{comp}}$  is lower at the lower temperature. Similarly, running at a higher  $T_f$  lowers the refrigeration cost but raises the compression cost. The sum of the two costs is a minimum at an intermediate temperature.

6.32 a. Basis:  $120 \text{ m}^3/\text{min}$  feed @  $1000^\circ \text{C}$  ( $1273 \text{ K}$ ),  $35 \text{ atm}$ . Use Kay's rule.

Cmpd.	$T_c (\text{K})$	$P_c (\text{atm})$	$(T_c)_{\text{corr}}$	$(P_c)_{\text{corr}}$	(Apply Newton's corrections for $\text{H}_2$ )
$\text{H}_2$	33.2	12.8	41.3	20.8	
$\text{CO}$	133.0	34.5	—	—	
$\text{CO}_2$	304.2	72.9	—	—	
$\text{CH}_4$	190.7	45.8	—	—	

$$T'_c = \sum y_i T_{ci} = 0.40(41.3) + 0.35(133.0) + 0.20(304.2) + 0.05(190.7) = 133.4 \text{ K}$$

$$P'_c = \sum y_i P_{ci} = 0.40(20.8) + 0.35(34.5) + 0.20(72.9) + 0.05(45.8) = 37.3 \text{ atm}$$

Feed gas to cooler

$$\left. \begin{array}{l} T_r = 1273 \text{ K} / 133.4 \text{ K} = 9.54 \\ P_r = 35.0 \text{ atm} / 37.3 \text{ atm} = 0.94 \end{array} \right\} \text{Generalized compressibility charts (Fig. 5.4-3)} \Rightarrow z = 1.02$$

$$\hat{V} = \frac{1.02}{35 \text{ atm}} \left| \frac{8.314 \text{ N} \cdot \text{m}}{\text{mol} \cdot \text{K}} \right| \frac{1273 \text{ K}}{101325 \text{ N/m}^3} = 3.04 \times 10^{-3} \text{ m}^3/\text{mol}$$

$$\frac{120 \text{ m}^3}{\text{min}} \left| \frac{\text{mol}}{3.04 \times 10^{-3} \text{ m}^3} \right| \frac{1 \text{ kmol}}{10^3 \text{ mol}} = 39.5 \text{ kmol/min}$$

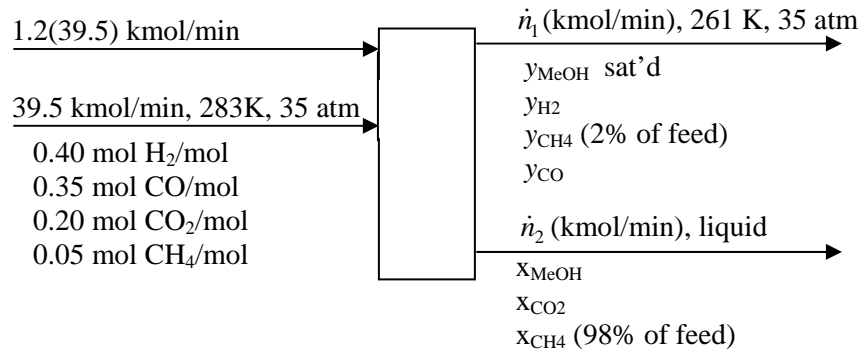
Feed gas to absorber

$$\left. \begin{array}{l} T_r = 283 \text{ K} / 133.4 \text{ K} = 2.12 \\ P_r = 35.0 \text{ atm} / 37.3 \text{ atm} = 0.94 \end{array} \right\} \text{Generalized compressibility charts (Fig. 5.4-3)} \Rightarrow z = 0.98$$

$$\hat{V} = \frac{0.98}{35 \text{ atm}} \left| \frac{8.314 \text{ N} \cdot \text{m}}{\text{mol} \cdot \text{K}} \right| \frac{283 \text{ K}}{101325 \text{ N/m}^3} = 6.50 \times 10^{-4} \text{ m}^3/\text{mol}$$

$$V = \frac{39.5 \text{ kmol}}{\text{min}} \left| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \right| \frac{6.50 \times 10^{-4} \text{ m}^3}{\text{mol}} = 25.7 \frac{\text{m}^3}{\text{min}}$$

6.32 (cont'd)



$$\text{Saturation at Outlet: } y_{\text{MeOH}} = \frac{P^*_{\text{MeOH}}(261\text{K})}{P} = \frac{\left[10^{7.87863-1473.11/(-12+2300)}\right] \text{ mm Hg}}{35 \text{ atm}(760 \text{ mm Hg/atm})}$$

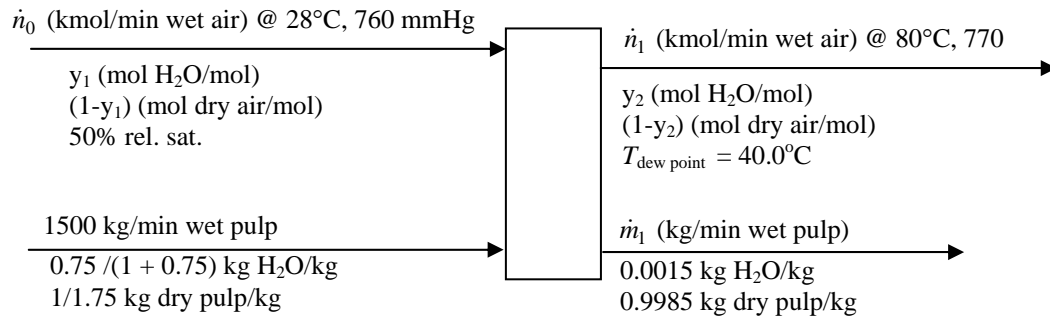
$$= 4.97 \times 10^{-4} \text{ mol MeOH/mol}$$

$$y_{\text{MeOH}} = \frac{n_{\text{MeOH}}}{n_{\text{MeOH}} + \underset{\substack{\uparrow \\ =\text{input}}}{n_{\text{H}_2}} + \underset{\substack{\uparrow \\ =0.02 \text{ of input}}}{n_{\text{CH}_4}} + \underset{\substack{\uparrow \\ =\text{input}}}{n_{\text{CO}}}} = \frac{n_{\text{MeOH}}}{n_{\text{MeOH}} + 39.5(0.40 + 0.02(0.05) + 0.35)}$$

$$\underline{\underline{n_{\text{MeOH}} = 0.0148 \text{ kmol/min MeOH in gas}}}$$

- b. The gas may be used as a fuel.  $\text{CO}_2$  has no fuel value, so that the cost of the added energy required to pump it would be wasted.

6.33



Dry pulp balance:  $1500 \times \frac{1}{1 + 0.75} = \dot{m}_1 (1 - 0.0015) \Rightarrow \dot{m}_1 = 858 \text{ kg / min}$

50% rel. sat'n at inlet:  $y_1 P = 0.50 p_{\text{H}_2\text{O}}^* (28^\circ \text{C}) \Rightarrow y_1 = 0.50(28.349 \text{ mm Hg}) / (760 \text{ mm Hg})$   
 $= 0.0187 \text{ mol H}_2\text{O/mol}$

40°C dew point at outlet:  $y_2 P = p_{\text{H}_2\text{O}}^* (40^\circ \text{C}) \Rightarrow y_2 = (55.324 \text{ mm Hg}) / (770 \text{ mm Hg})$   
 $= 0.0718 \text{ mol H}_2\text{O / mol}$

Mass balance on dry air:

$$\dot{n}_0 (1 - 0.0187) = \dot{n}_1 (1 - 0.0718) \quad (1)$$

Mass balance on water:

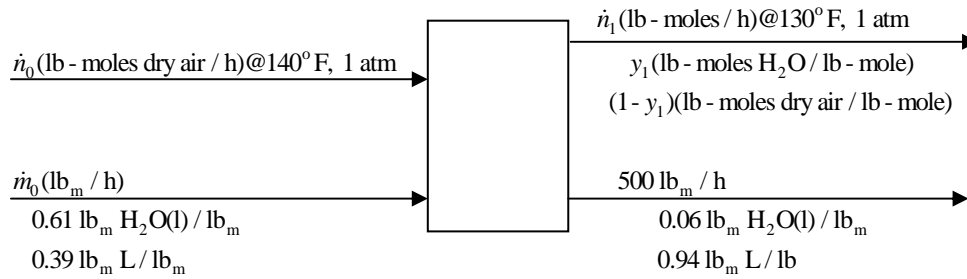
$$\dot{n}_0 (0.0187)(18.0 \text{ kg/kmol}) + 1500(0.75 / 1.75) = \dot{n}_1 (0.0718)(18) + 858(0.0015) \quad (2)$$

Solve (1) and (2)  $\Rightarrow \dot{n}_0 = 622.8 \text{ kmol / min}, \dot{n}_1 = 658.4 \text{ kmol / min}$

Mass of water removed from pulp:  $[1500(0.75/1.75) - 858(.0015)] \text{ kg H}_2\text{O} = \underline{\underline{642 \text{ kg / min}}}$

Air feed rate:  $\dot{V}_0 = \frac{622.8 \text{ kmol}}{\text{min}} \left| \frac{22.4 \text{ m}^3 (\text{STP})}{\text{kmol}} \right| \left| \frac{(273 + 28) \text{ K}}{273 \text{ K}} \right| = \underline{\underline{1.538 \times 10^4 \text{ m}^3 / \text{min}}}$

**6.34** Basis: 500 lb<sub>m</sub>/hr dried leather (L)



Dry leather balance:  $0.39m_0 = (0.94)(500) \Rightarrow m_0 = 1205 \text{ lb}_m \text{ wet leather/hr}$

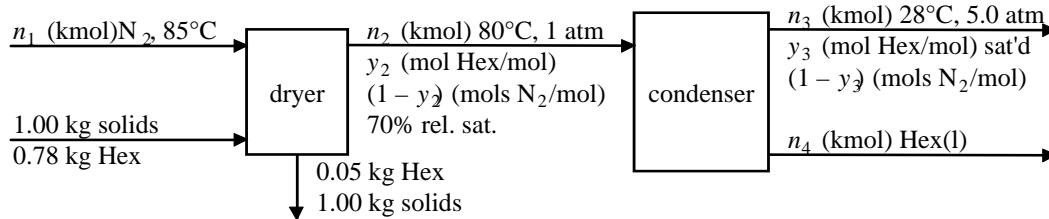
Humidity of outlet air:  $y_1 P = 0.50 p^*_{\text{H}_2\text{O}} (130^\circ \text{F}) \Rightarrow y_1 = \frac{0.50(115 \text{ mm Hg})}{760 \text{ mmHg}} = 0.0756 \frac{\text{mol H}_2\text{O}}{\text{mol}}$

H<sub>2</sub>O balance:  $(0.61)(1205 \text{ lb}_m/\text{hr}) = (0.06)(500 \text{ lb}_m/\text{hr}) + \frac{(0.0756n_1) \text{ lb-moles H}_2\text{O}}{\text{hr}} \left| \frac{18.02 \text{ lb}_m}{1 \text{ lb-mole}} \right.$   
 $\Downarrow$   
 $n_1 = 517.5 \text{ lb-moles/hr}$

Dry air balance:  $n_0 = (1 - 0.0756)(517.5) \text{ lb-moles/hr} = 478.4 \text{ lb-moles/hr}$

$V_{\text{inlet}} = \frac{478.4 \text{ lb-moles}}{\text{hr}} \left| \frac{359 \text{ ft}^3 (\text{STP})}{1 \text{ lb-mole}} \right| \left| \frac{(140 + 460)^\circ \text{R}}{492^\circ \text{R}} \right| = 2.09 \times 10^5 \text{ ft}^3/\text{hr}$

**6.35 a.** Basis: 1 kg dry solids



Mol Hex in gas at 80°C:  $\frac{(0.78 - 0.05) \text{ kg}}{86.17 \text{ kg}} \left| \frac{\text{kmol}}{86.17 \text{ kg}} \right| = 8.47 \times 10^{-3} \text{ kmol Hex}$

70% rel. sat.:  $y_2 = \frac{\overset{\text{Antoine eq.}}{0.70 p^*_{\text{hex}} (80^\circ \text{C})}}{P} = \frac{(0.70) 10^{6.88555 - 1175.817/(80 + 224.867)}}{760} = 0.984 \text{ mol Hex/mol}$

### 6.35 (cont'd)

$$n_2 = \frac{8.47 \times 10^{-3} \text{ kmol Hex}}{0.984 \text{ kmol Hex}} \times 1 \text{ kmol} = 0.0086 \text{ kmol}$$

$$\text{N}_2 \text{ balance on dryer: } n_1 = (1 - 0.984)0.0086 = 1.376 \times 10^{-4} \text{ kmol}$$

$$\text{Saturation at outlet: } y_3 = \frac{p_{\text{hex}}^*(28^\circ\text{C})}{P} = \frac{10^{\frac{6.88555 - 1175.817}{(28+224.867)}}}{5(760)} = 0.0452 \text{ mol Hex/mol}$$

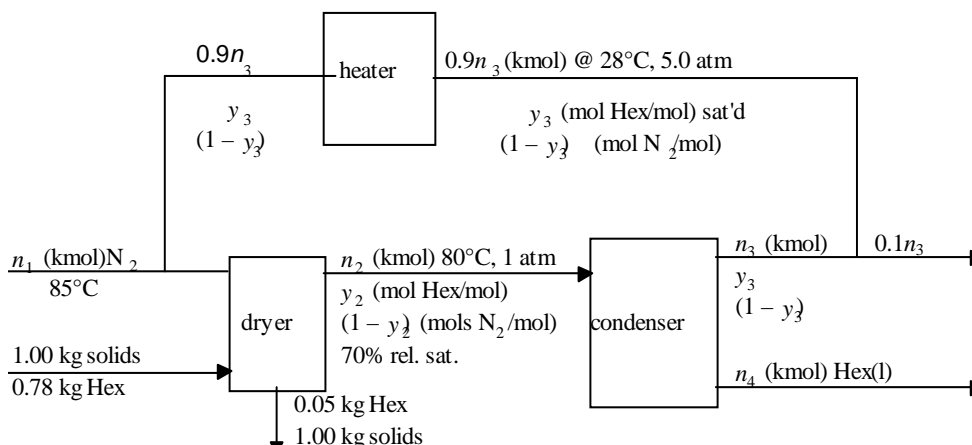
Antoine Eq.  
↓

$$\text{Overall N}_2 \text{ balance: } 1.376 \times 10^{-4} = n_3(1 - 0.0452) \Rightarrow n_3 = 1.44 \times 10^{-4} \text{ kmol}$$

$$\text{Mole balance on condenser: } 0.0086 = 1.44 \times 10^{-4} + n_4 \Rightarrow n_4 = 0.0085 \text{ kmol}$$

$$\text{Fractional hexane recovery: } \frac{0.0085 \text{ kmol cond.}}{0.78 \text{ kg feed}} \times \frac{86.17 \text{ kg}}{\text{kmol}} = \underline{\underline{0.939 \text{ kg cond./kg feed}}}$$

**b. Basis: 1 kg dry solids**



$$\text{Mol Hex in gas at } 80^\circ\text{C: } 8.47 \times 10^{-3} + 0.9n_3(0.0452) = n_2(0.984) \quad (1)$$

$$\text{N}_2 \text{ balance on dryer: } n_1 + 0.9n_3(1 - 0.0452) = n_2(1 - 0.984) \quad (2)$$

$$\text{Overall N}_2 \text{ balance: } n_1 = 0.1n_3(1 - 0.0452) \quad (3)$$

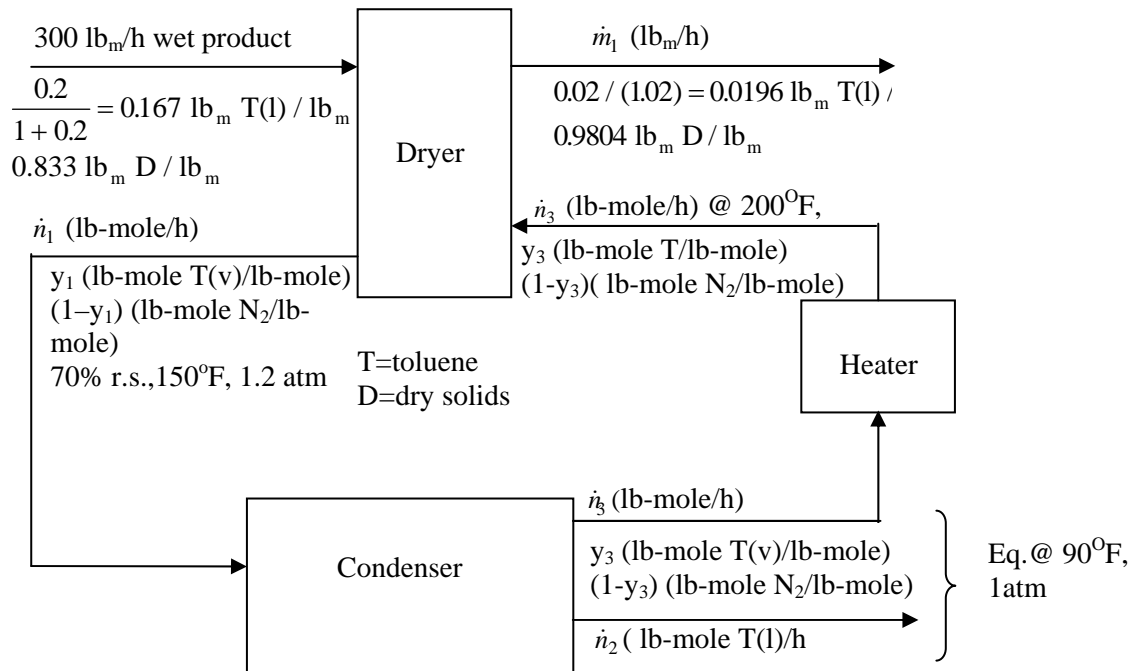
$$\text{Equations (1) to (3)} \Rightarrow \begin{cases} n_1 = 1.38 \times 10^{-5} \text{ kmol} \\ n_2 = 0.00861 \text{ kmol} \\ n_3 = 1.44 \times 10^{-4} \text{ kmol} \end{cases}$$

$$\text{Saved fraction of nitrogen} = \frac{1.376 \times 10^{-4} - 1.38 \times 10^{-5}}{1.376 \times 10^{-4}} \times 100\% = \underline{\underline{90\%}}$$

Introducing the recycle leads to added costs for pumping (compression) and heating.



6.36 b.



Strategy: Overall balance  $\Rightarrow \dot{m}_1$  &  $\dot{n}_2$  ;

Relative saturation  $\Rightarrow y_1$ , Gas and liquid equilibrium  $\Rightarrow y_3$

Balance over the condenser  $\Rightarrow \dot{n}_1$  &  $\dot{n}_3$

$$\left. \begin{array}{l} \text{Toluene Balance: } 300 \times 0.167 = \dot{m}_1 \times 0.0196 + \dot{n}_2 \times 92.13 \\ \text{Dry Solids Balance: } 300 \times 0.833 = \dot{m}_1 \times 0.9804 \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \dot{m}_1 = 255 \text{ lb}_m / \text{h} \\ \dot{n}_2 = 0.488 \text{ lb - mole / h} \end{array} \right.$$

70% relative saturation of dryer outlet gas:

$$p_{C_7H_8}^* (150^\circ \text{F} = 65.56^\circ \text{C}) = 10^{\left( \frac{6.95805 - \frac{1346.773}{65.56 + 219.693}}{1} \right)} = 172.47 \text{ mmHg}$$

$$y_1 P = 0.70 p_{C_7H_8}^* (150^\circ \text{F}) \Rightarrow y_1 = \frac{0.70 p_{C_7H_8}^*}{P} = \frac{(0.70)(172.47)}{1.2 \times 760} = \underline{\underline{0.1324 \text{ lb - mole T(v) / lb - mole}}}$$

Saturation at condenser outlet:

$$p_{C_7H_8}^* (90^\circ \text{F} = 32.22^\circ \text{C}) = 10^{\left( \frac{6.95805 - \frac{1346.773}{32.22 + 219.693}}{1} \right)} = 40.90 \text{ mmHg}$$

$$y_3 = \frac{p_{C_7H_8}^*}{P} = \frac{40.90}{760} = \underline{\underline{0.0538 \text{ mol T(v)/mol}}}$$

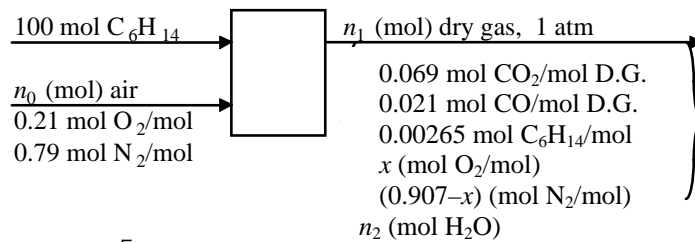
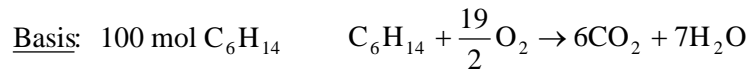
$$\left. \begin{array}{l} \text{Condenser Toluene Balance: } \dot{n}_1 \times 0.1324 = 0.488 + \dot{n}_3 \times 0.0538 \\ \text{Condenser N}_2 \text{ Balance: } \dot{n}_1 \times (1 - 0.1324) = \dot{n}_3 \times (1 - 0.0538) \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \dot{n}_1 = 5.875 \text{ lb - mole / h} \\ \dot{n}_3 = 5.387 \text{ lb - mole / h} \end{array} \right.$$

**6.36 (cont'd)**

$$\begin{aligned} \text{Circulation rate of dry nitrogen} &= 5.875 \times (1 - 0.1324) = \frac{5.097 \text{ lb - mole}}{\text{h}} \left| \frac{\text{lb - mole}}{28.02 \text{ lb}_m} \right. \\ &= \underline{\underline{0.182 \text{ lb}_m / \text{h}}} \end{aligned}$$

$$V_{\text{inlet}} = \frac{5.387 \text{ lb - moles}}{\text{hr}} \left| \frac{359 \text{ ft}^3 (\text{STP})}{1 \text{ lb - mole}} \right| \frac{(200 + 460)^\circ \text{R}}{492^\circ \text{R}} = \underline{\underline{2590 \text{ ft}^3 / \text{h}}}$$

**6.37**



C balance:  $6(100) = n_1 \left[ \frac{0.069}{(\text{CO}_2)} + \frac{0.021}{(\text{CO})} + 6 \frac{0.00265}{(\text{C}_6\text{H}_{14})} \right] \Rightarrow n_1 = 5666 \text{ mol dry gas}$

Conversion:  $\frac{[100 - 0.00265(5666)] \text{ mol reacted}}{100 \text{ mol fed}} \times 100\% = \underline{\underline{85.0\%}}$

H balance:  $14(100) = 2n_2 + 5666(14)(0.00265) \Rightarrow n_2 = 595 \text{ mol H}_2\text{O}$

Dew point:  $y_{\text{H}_2\text{O}} = \frac{595}{595 + 5666} = \frac{p^*(T_{dp})}{760 \text{ mm Hg}} \Rightarrow p^*(T_{dp}) = 72.2 \text{ mm Hg} \xrightarrow{\text{Table B.3}} \underline{\underline{T_{dp} = 45.1^\circ \text{C}}}$

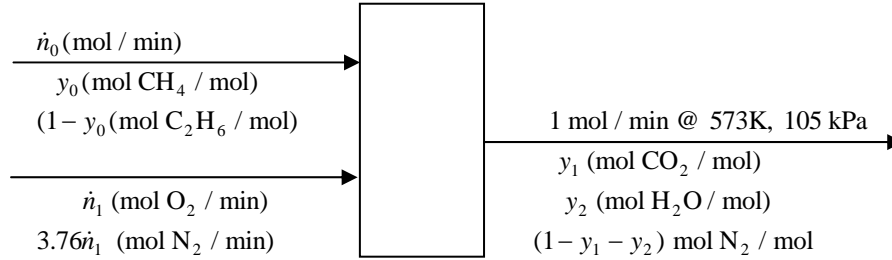
N<sub>2</sub> balance:  $0.79n_0 = 5666(0.907 - x)$   
O balance:  $0.21(n_0)(2) = 5666[(0.069)(2) + 0.021 + 2x] + 595$

Solve simultaneously to obtain  $n_0 = 5888 \text{ mol air}$ ,  $x = 0.086 \text{ mol O}_2/\text{mol}$

Theoretical air:  $\frac{100 \text{ mol C}_2\text{H}_{14}}{2 \text{ mol C}_2\text{H}_{14}} \left| \frac{19 \text{ mol O}_2}{2 \text{ mol C}_2\text{H}_{14}} \right| \frac{1 \text{ mol air}}{0.21 \text{ mol O}_2} = 4524 \text{ mol air}$

Excess air:  $\frac{5888 - 4524}{4524} \times 100\% = \underline{\underline{30.2\% \text{ excess air}}}$

**6.38** Basis: 1 mol outlet gas/min



$$p_{\text{CO}_2} = 80 \text{ mmHg} \Rightarrow y_1 = \frac{80 \text{ mmHg}}{105000 \text{ Pa}} \left| \frac{101325 \text{ Pa}}{760 \text{ mmHg}} \right| = 0.1016 \text{ mol CO}_2 / \text{mol}$$

$$\text{100\% O}_2 \text{ conversion: } 2n_o y_o + \frac{7}{2}n_o(1-y_o) = n_1 \qquad (1)$$

$$\text{C balance: } n_o y_o + 2n_o(1-y_o) = 0.1016 \qquad (2)$$

$$\text{N}_2 \text{ balance: } 3.76n_1 = 1 - y_1 - y_2 \qquad (3)$$

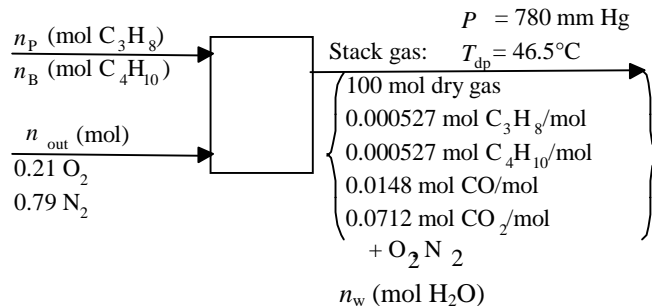
$$\text{H balance: } 4n_o y_o + 6n_o(1-y_o) = 2y_2 \qquad (4)$$

$$\text{Solve equations 1 to 4} \Rightarrow \begin{cases} n_o = 0.0770 \text{ mol} \\ y_o = \underline{\underline{0.6924 \text{ mol CH}_4 / \text{mol}}} \\ n_1 = 0.1912 \text{ mol O}_2 \\ y_2 = 0.1793 \text{ mol H}_2\text{O} / \text{mol} \end{cases}$$

Dew point:

$$p_{\text{H}_2\text{O}}^*(T_{dp}) = \frac{0.1793(105000) \text{ Pa}}{101325 \text{ Pa}} \left| \frac{760 \text{ mmHg}}{101325 \text{ Pa}} \right| = 141.2 \text{ mmHg} \Rightarrow T_{dp} = \underline{\underline{58.8^\circ \text{C}}} \text{ (Table B.3)}$$

**6.39** Basis: 100 mol dry stack gas



### 6.39 (cont'd)

$$\text{Dew point} = 46.5^\circ \text{C} \Rightarrow y_w P = p_w^*(46.5^\circ \text{C}) \Rightarrow y_w = \frac{77.6 \text{ mm Hg}}{780 \text{ mm Hg}} = 0.0995 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

$$\text{But } y_w = \frac{n_w}{100 + n_w} = 0.0995 \Rightarrow n_w = 11.05 \text{ mol H}_2\text{O} \quad (\text{Rounding off strongly affects the result})$$

$$\text{C balance: } 3n_p + 4n_B = (100)[(0.000527)(3) + (0.000527)(4) + 0.0148 + 0.0712]$$

$$\Rightarrow 3n_p + 4n_B = 8.969 \quad (1)$$

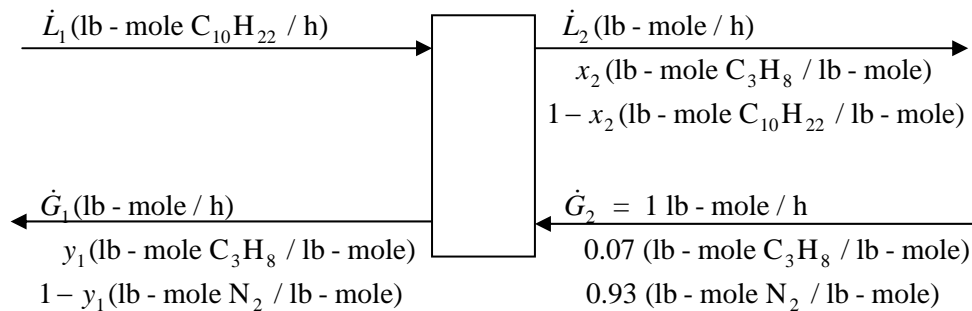
$$\text{H balance: } 8n_p + 10n_B = (100)[(0.000527)(8) + (0.000527)(10)] + (11.05)(2)$$

$$\Rightarrow 8n_p + 10n_B = 23.047 \quad (2)$$

$$\text{Solve (1) \& (2) simultaneously: } \Rightarrow \begin{cases} n_p = 1.25 \text{ mol C}_3\text{H}_8 \\ n_B = 1.30 \text{ mol C}_4\text{H}_{10} \end{cases} \Rightarrow \begin{cases} 49\% \text{ C}_3\text{H}_8 \\ 51\% \text{ C}_4\text{H}_{10} \end{cases}$$

(Answers may vary  $\pm 8\%$  due to loss of precision)

### 6.40 a.



Basis:  $\dot{G}_2 = 1 \text{ lb-mole/h feed gas}$

$$\text{N}_2 \text{ balance: } (1)(0.93) = \dot{G}_1(1 - y_1) \Rightarrow \dot{G}_1(1 - y_1) = 0.93 \quad (1)$$

$$98.5\% \text{ propane absorption} \Rightarrow \dot{G}_1 y_1 = (1 - 0.985)(1)(0.07) \Rightarrow \dot{G}_1 y_1 = 1.05 \times 10^{-3} \quad (2)$$

$$(1) \& (2) \Rightarrow \dot{G}_1 = 0.93105 \text{ lb-mol/h}, y_1 = 1.128 \times 10^{-3} \text{ mol C}_3\text{H}_8/\text{mol}$$

Assume  $\dot{G}_2 - \dot{L}_2$  streams are in equilibrium

From Cox Chart (Figure 6.1-4),  $p^*_{\text{C}_3\text{H}_8}(80^\circ \text{F}) = 160 \text{ lb/in}^2 = 10.89 \text{ atm}$

$$\text{Raoult's law: } x_2 p^*_{\text{C}_3\text{H}_8}(80^\circ \text{F}) = 0.07 p \Rightarrow x_2 = \frac{(0.07)(1.0 \text{ atm})}{10.89 \text{ atm}} = 0.006428 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

$$\begin{aligned} \text{Propane balance: } (0.07)(1) &= \dot{G}_1 y_1 + \dot{L}_2 x_2 \Rightarrow \dot{L}_2 = \frac{0.07 - (0.93105)(1.128 \times 10^{-3})}{0.006428} \\ &= 10.726 \text{ lb-mole/h} \end{aligned}$$

$$\text{Decane balance: } \dot{L}_1 = (1 - x_2)(\dot{L}_2) = (1 - 0.006428)(10.726) = 10.66 \text{ lb-mole/h}$$

$$\Rightarrow \left( \frac{\dot{L}_1}{\dot{G}_2} \right)_{\min} = \underline{\underline{10.7 \text{ mol liquid feed / mol gas feed}}}$$

### 6.40 (cont'd)

- b. The flow rate of propane in the exiting liquid must be the same as in Part (a) [same feed rate and fractional absorption], or

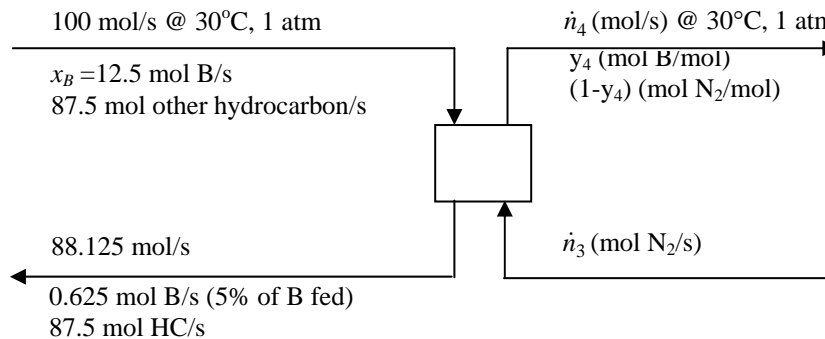
$$\dot{n}_{C_3H_8} = \frac{10.726 \text{ lb - mole}}{\text{h}} \left| \frac{0.006428 \text{ lb - mole } C_3H_8}{\text{lb - mole}} \right| = 0.06895 \text{ lb - mole } C_3H_8 / \text{h}$$

The decane flow rate is  $1.2 \times 10.66 = 12.8 \text{ lb-moles } C_{10}H_{22} / \text{h}$

$$\Rightarrow x_2 = \frac{0.06895 \text{ lb - mole } C_3H_8 / \text{h}}{(0.06895 + 12.8) \text{ lb - moles/h}} = \underline{\underline{0.00536 \text{ lb - mole } C_3H_8 / \text{lb - mole}}}$$

- c. Increasing the liquid/gas feed ratio from the minimum value decreases the size (and hence the cost) of the column, but increases the raw material (decane) and pumping costs. All three costs would have to be determined as a function of the feed ratio.

### 6.41 a. Basis: 100 mol/s liquid feed stream    Let B = n - butane , HC = other hydrocarbons



$$p_B^*(30^\circ \text{C}) \cong 41 \text{ lb / in}^2 = 2120 \text{ mm Hg (from Figure 6.1-4)}$$

$$\text{Raoult's law: } y_4 P = x_B p_B^*(30^\circ \text{C}) \Rightarrow y_4 = \frac{x_B p_B^*(30^\circ \text{C})}{P} = \frac{0.125 \times 2120}{760} = 0.3487$$

$$\text{95\% n-butane stripped: } \dot{n}_4 \cdot (0.3487) = (12.5)(0.95) \Rightarrow \dot{n}_4 = 34.06 \text{ mol / s}$$

$$\text{Total mole balance: } 100 + \dot{n}_3 = 34.06 + 88.125 \Rightarrow \dot{n}_3 = 22.18 \text{ mol/s}$$

$$\Rightarrow \frac{\text{mol gas fed}}{\text{mol liquid fed}} = \frac{22.18 \text{ mol/s}}{100 \text{ mol/s}} = \underline{\underline{0.222 \text{ mol gas fed/mol liquid fed}}}$$

- b. If  $y_4 = 0.8 \times 0.3487 = 0.2790$ , following the same steps as in Part (a),

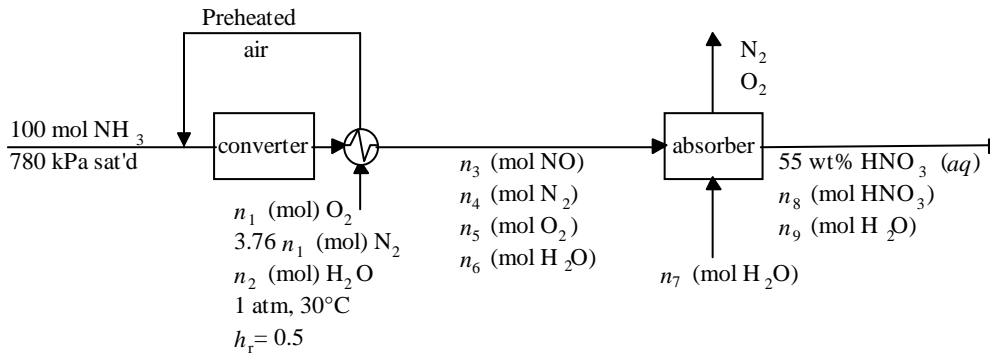
$$\text{95\% n-butane is stripped: } \dot{n}_4 \cdot (0.2790) = (12.5)(0.95) \Rightarrow \dot{n}_4 = 42.56 \text{ mol / s}$$

$$\text{Total mole balance: } 100 + \dot{n}_3 = 42.56 + 88.125 \Rightarrow \dot{n}_3 = 30.68 \text{ mol / s}$$

$$\Rightarrow \frac{\text{mol gas fed}}{\text{mol liquid fed}} = \frac{30.68 \text{ mol/s}}{100 \text{ mol/s}} = \underline{\underline{0.307 \text{ mol gas fed/mol liquid fed}}}$$

- c. When the  $N_2$  feed rate is at the minimum value calculated in (a), the required column length is infinite and hence so is the column cost. As the  $N_2$  feed rate increases for a given liquid feed rate, the column size and cost decrease but the cost of purchasing and compressing (pumping) the  $N_2$  increases. To determine the optimum gas/liquid feed ratio, you would need to know how the column size and cost and the  $N_2$  purchase and compression costs depend on the  $N_2$  feed rate and find the rate at which the cost is a minimum.

**6.42** Basis: 100 mol NH<sub>3</sub>



- a. i)**  $\text{NH}_3$  feed:  $P = P^*(T_{sat}) = 820 \text{ kPa} = 6150 \text{ mm Hg} = 8.09 \text{ atm}$

Antoine:

$$\log_{10}(6150) = 7.55466 - 1002.711 / (T_{sat} + 247.885) \Rightarrow T_{sat} = 18.4^\circ\text{C} = 291.6\text{ K}$$

$$\text{Table B.1} \Rightarrow \left. \begin{array}{l} P_c = 111.3 \text{ atm} \Rightarrow P_r = 8.09 / 111.3 = 0.073 \\ T_c = 405.5 \text{ K} \Rightarrow T_r = 291.6 / 405.5 = 0.72 \end{array} \right\} \Rightarrow z = 0.92 \quad (\text{Fig. 5.3-1})$$

$$V_{\text{NH}_3} = \frac{0.92(100 \text{ mol})}{\text{mol} \cdot \text{K}} \left| \frac{8.314 \text{ Pa}}{\text{mol} \cdot \text{K}} \right| \frac{291.6 \text{ K}}{820 \times 10^3 \text{ Pa}} = \underline{\underline{0.272 \text{ m}^3 \text{ NH}_3}}$$

Air feed:  $\text{NH}_3 + 2\text{O}_2 \rightarrow \text{HNO}_3 + \text{H}_2\text{O}$

$$n_1 = \frac{100 \text{ mol NH}_3}{1 \text{ mol NH}_3} \times \frac{2 \text{ mol O}_2}{4 \text{ mol NH}_3} = 50 \text{ mol O}_2$$

$$\text{Water in Air: } y_{\text{H}_2\text{O}} = \frac{h_r \cdot p^*(30^\circ\text{C})}{p} = \frac{0.500 \times 31.824}{760} = 0.02094$$

$$\Rightarrow 0.02094 = \frac{n_2}{n_2 + \frac{4.76(200)}{(4.76 \text{ mol air/mol O}_2)}} \Rightarrow n_2 = 20.36 \text{ mol H}_2\text{O}$$

$$V_{\text{air}} = \frac{[4.76(200) + 20.36] \text{ mol}}{1 \text{ mol}} \times \frac{22.4 \text{ L (STP)}}{273 \text{ K}} \times \frac{303 \text{ K}}{10^3 \text{ L}} \times \frac{1 \text{ m}^3}{10^3 \text{ L}} = \underline{\underline{24.2 \text{ m}^3 \text{ air}}}$$

- ii) Reactions:  $4\text{NH}_3 + 5\text{O}_2 \rightarrow 4\text{NO} + 6\text{H}_2\text{O}$  ,  $4\text{NH}_3 + 3\text{O}_2 \rightarrow 2\text{N}_2 + 6\text{H}_2\text{O}$

Balances on converter

$$\underline{\text{NO:}} \quad n_3 = \frac{97 \text{ mol NH}_3}{4 \text{ mol NH}_3} \times \frac{4 \text{ mol NO}}{4 \text{ mol NH}_3} = 97 \text{ mol NO}$$

**6.42 (cont'd)**

$$\begin{aligned}
 \underline{\text{N}_2}: n_4 &= 3.76(2.00) \text{ mol} + \frac{3 \text{ mol NH}_3}{4 \text{ mol NH}_3} \left| \frac{2 \text{ mol N}_2}{4 \text{ mol NH}_3} \right| = 753.5 \text{ mol N}_2 \\
 \underline{\text{O}_2}: n_5 &= 200 \text{ mol} - \frac{97 \text{ mol NH}_3}{4 \text{ mol NH}_3} \left| \frac{5 \text{ mol O}_2}{4 \text{ mol NH}_3} \right| \\
 &\quad - \frac{3 \text{ mol NH}_3}{4 \text{ mol NH}_3} \left| \frac{3 \text{ mol O}_2}{4 \text{ mol NH}_3} \right| = 76.5 \text{ mol O}_2 \\
 \underline{\text{H}_2\text{O}}: n_6 &= 20.36 \text{ mol} + \frac{100 \text{ mol NH}_3}{4 \text{ mol NH}_3} \left| \frac{6 \text{ mol H}_2\text{O}}{4 \text{ mol NH}_3} \right| = 170.4 \text{ mol H}_2\text{O} \\
 \Rightarrow n_{\text{total}} &= (97 + 753.5 + 76.5 + 170.4) \text{ mol} \\
 &= \underline{\underline{1097 \text{ mol converter effluent}}} \\
 &\quad \underline{\underline{8.8\% \text{ NO}, 68.7\% \text{ N}_2, 7.0\% \text{ O}_2, 15.5\% \text{ H}_2\text{O}}}
 \end{aligned}$$

iii) Reaction:  $4\text{NO} + 3\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{HNO}_3$

$$\begin{aligned}
 \underline{\text{HNO}_3 \text{ bal. in absorber}}: n_8 &= \frac{97 \text{ mol NO react}}{4 \text{ mol NO}} \left| \frac{4 \text{ mol HNO}_3}{4 \text{ mol NO}} \right| = 97 \text{ mol HNO}_3 \\
 \underline{\text{H}_2\text{O in product}}: n_9 &= \frac{97 \text{ mol HNO}_3}{55 \text{ g HNO}_3} \left| \frac{63.02 \text{ g HNO}_3}{\text{mol}} \right| \left| \frac{45 \text{ g H}_2\text{O}}{18.02 \text{ g H}_2\text{O}} \right| \left| \frac{1 \text{ mol H}_2\text{O}}{18.02 \text{ g H}_2\text{O}} \right| \\
 &= 277.56 \text{ mol H}_2\text{O} \\
 \underline{\text{H balance on absorber}}: (170.4)(2) + 2n_7 &= 97 + (277.6)(2) (\text{mol H}) \\
 \Rightarrow n_7 &= 155.7 \text{ mol H}_2\text{O added} \\
 V_{\text{H}_2\text{O}} &= \frac{155.7 \text{ mol H}_2\text{O}}{1 \text{ mol}} \left| \frac{18.02 \text{ g H}_2\text{O}}{1 \text{ g}} \right| \left| \frac{1 \text{ cm}^3}{10^6 \text{ cm}^3} \right| = \underline{\underline{2.81 \times 10^{-3} \text{ m}^3 \text{ H}_2\text{O}(l)}}
 \end{aligned}$$

**b.**

$$\begin{aligned}
 \underline{M_{\text{acid}} \text{ in old basis}} &= \frac{97 \text{ mol HNO}_3}{\text{mol}} \left| \frac{63.02 \text{ g HNO}_3}{\text{mol}} \right| + \frac{277.6 \text{ mol H}_2\text{O}}{\text{mol}} \left| \frac{18.02 \text{ g H}_2\text{O}}{\text{mol}} \right| \\
 &= 11115 \text{ g} = 11.115 \text{ kg}
 \end{aligned}$$

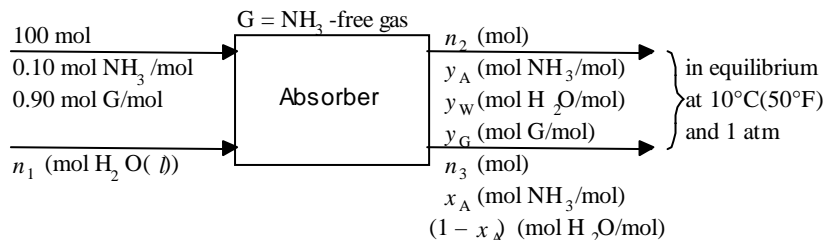
$$\underline{\text{Scale factor}} = \frac{(1000 \text{ metric tons})(1000 \text{ kg/metric ton})}{11.115 \text{ kg}} = 8.997 \times 10^4$$

$$V_{\text{NH}_3} = (8.997 \times 10^4) (0.272 \text{ m}^3 \text{ NH}_3) = \underline{\underline{2.45 \times 10^4 \text{ m}^3 \text{ NH}_3}}$$

$$V_{\text{air}} = (8.997 \times 10^4) (24.2 \text{ m}^3 \text{ air}) = \underline{\underline{2.18 \times 10^6 \text{ m}^3 \text{ air}}}$$

$$V_{\text{H}_2\text{O}} = (8.997 \times 10^4) (2.81 \times 10^{-3} \text{ m}^3 \text{ H}_2\text{O}) = \underline{\underline{253 \text{ m}^3 \text{ H}_2\text{O}(l)}}$$

**6.43 a.** Basis: 100 mol feed gas



Composition of liquid effluent . Basis: 100 g solution

Perry, Table 2.32, p. 2-99:  $T = 10^\circ\text{C} (50^\circ\text{F})$ ,  $\rho = 0.9534 \text{ g/mL} \Rightarrow 0.120 \text{ g NH}_3/\text{g solution}$

$$\Rightarrow \frac{12.0 \text{ g NH}_3}{(17.0 \text{ g / 1 mol})} = 0.706 \text{ mol NH}_3, \quad \frac{88.0 \text{ g H}_2\text{O}}{(18.0 \text{ g / 1 mol})} = 4.89 \text{ mol H}_2\text{O}$$

$$\Rightarrow 12.6 \text{ mole\% NH}_3(\text{aq}), 87.4 \text{ mole\% H}_2\text{O(l)}$$

Composition of gas effluent

$$T = 50^\circ\text{F}, x_A = 0.126 \xrightarrow{\text{Perry}} \left. \begin{array}{l} p_{\text{NH}_3} = 1.21 \text{ psia (Table 2 - 23)} \\ p_{\text{H}_2\text{O}} = 0.155 \text{ psia (Table 2 - 21)} \\ p_{\text{total}} = 14.7 \text{ psia} \end{array} \right\}$$

$$y_A = 1.21 / 14.7 = 0.0823 \text{ mol NH}_3/\text{mol}$$

$$\Rightarrow y_W = 0.155 / 14.7 = 0.0105 \text{ mol H}_2\text{O/mol}$$

$$y_G = 1 - y_A - y_W = 0.907 \text{ mol G/mol}$$

$$\text{G balance: } (100)(0.90) = n_2 y_G \Rightarrow n_2 = (100)(0.90)/(0.907) = 99.2 \text{ mol}$$

$$\text{NH}_3 \text{ absorbed} = (100)(0.10)_{\text{in}} - (99.2)(0.0823)_{\text{out}} = 1.84 \text{ mol NH}_3$$

$$\% \text{ absorption} = \frac{1.84 \text{ mol absorbed}}{(100)(0.10) \text{ mol fed}} \times 100\% = \underline{\underline{18.4\%}}$$

- b.** If the slip stream or densitometer temperature were higher than the temperature in the contactor, dissolved ammonia would come out of solution and the calculated solution composition would be in error.

**6.44 a.**

15% oleum: Basis - 100kg

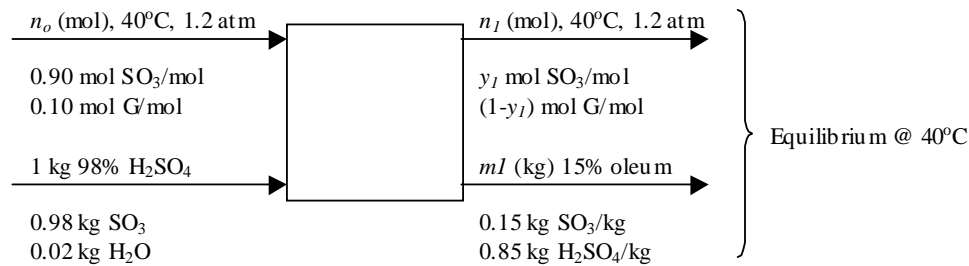
$$15 \text{ kg SO}_3 + \frac{85 \text{ kg H}_2\text{SO}_4}{98.08 \text{ kg H}_2\text{SO}_4} \left| \frac{1 \text{ kmol H}_2\text{SO}_4}{1 \text{ kmol H}_2\text{SO}_4} \right| \left| \frac{1 \text{ kmol SO}_3}{1 \text{ kmol SO}_3} \right| \frac{80.07 \text{ kg SO}_3}{1 \text{ kmol SO}_3} = 84.4 \text{ kg}$$

$$\Rightarrow 84.4\% \text{ SO}_3$$



### 6.44 (cont'd)

b. Basis 1 kg liquid feed



$$\text{i) } y_1 = \frac{p_{\text{SO}_3}(40^\circ\text{C}, 84.4\%)}{P} = \frac{1.15}{760} = 1.51 \times 10^{-3} \text{ mol SO}_3/\text{mol}$$

$$\text{ii) H balance: } \frac{0.98 \text{ kg H}_2\text{SO}_4}{98.08 \text{ kg H}_2\text{SO}_4} + \frac{0.02 \text{ kg H}_2\text{O}}{18.02 \text{ kg H}_2\text{O}} = \frac{0.85 m_1 \text{ H}_2\text{SO}_4}{98.08 \text{ kg H}_2\text{SO}_4} + \frac{2.02 \text{ kg H}}{18.02 \text{ kg H}_2\text{O}} \Rightarrow m_1 = 1.28 \text{ kg}$$

But since the feed solution has a mass of 1 kg,

$$\text{SO}_3 \text{ absorbed} = (1.28 - 1.0) \text{ kg} = \frac{0.28 \text{ kg SO}_3}{10^3 \text{ g}} \times \frac{1 \text{ mol}}{80.07 \text{ g}} = 3.50 \text{ mol}$$

$$\Rightarrow 3.5 \text{ mol} = n_0 - n_1$$

$$\text{G balance: } 0.10n_0 = (1 - 1.51 \times 10^{-3})n_1$$

$$n_0 = 3.89 \text{ mol}$$

$$n_1 = 0.39 \text{ mol}$$

$$V = \frac{3.89 \text{ mol}}{1 \text{ kg liquid feed}} \times \frac{22.4 \text{ L (STP)}}{\text{mol}} \times \frac{313 \text{ K}}{273 \text{ K}} \times \frac{1 \text{ atm}}{1.2 \text{ atm}} \times \frac{1 \text{ m}^3}{10^3 \text{ L}} = 8.33 \times 10^{-2} \text{ m}^3/\text{kg liquid feed}$$

6.45 a. Raoult's law can be used for water and Henry's law for nitrogen.

b. Raoult's law can be used for each component of the mixture, but Henry's law is not valid here.

c. Raoult's law can be used for water, and Henry's law can be used for CO<sub>2</sub>.

$$6.46 \quad p_B^*(100^\circ\text{C}) = 10^{**} \left( 6.89272 - 1203.531/(100 + 219.888) \right) = 1350.1 \text{ mm Hg}$$

$$p_T^*(100^\circ\text{C}) = 10^{**} \left( 6.95805 - 1346.773/(100 + 219.693) \right) = 556.3 \text{ mm Hg}$$

$$\text{Raoult's Law: } y_B P = x_B p_B^* \Rightarrow y_B = \frac{0.40(1350.1)}{10(760)} = 0.0711 \text{ mol Benzene/mol}$$

$$y_T = \frac{0.60(556.3)}{10(760)} = 0.0439 \text{ mol Toluene/mol}$$

$$y_{\text{N}_2} = 1 - 0.0711 - 0.0439 = 0.885 \text{ mol N}_2/\text{mol}$$

**6.47** N<sub>2</sub> - Henry's law: Perry's Chemical Engineers' Handbook, Page. 2 - 127, Table 2 - 138

$$\Rightarrow H_{N_2}(80^\circ\text{C}) = 12.6 \times 10^4 \text{ atm/mole fraction}$$

$$\Rightarrow p_{N_2} = x_{N_2} H_{N_2} = (0.003)(12.6 \times 10^4) = 378 \text{ atm}$$

$$\text{H}_2\text{O} - \text{Raoult's law: } p_{\text{H}_2\text{O}}^*(80^\circ\text{C}) = \frac{355.1 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \frac{1 \text{ atm}}{760 \text{ mm Hg}} \right| = 0.467 \text{ atm}$$

$$\Rightarrow p_{\text{H}_2\text{O}} = (x_{\text{H}_2\text{O}})(p_{\text{H}_2\text{O}}^*) = (0.997)(0.467) = 0.466 \text{ atm}$$

$$\text{Total pressure: } P = p_{N_2} + p_{\text{H}_2\text{O}} = 378 + 0.466 = \underline{\underline{378.5 \text{ atm}}}$$

$$\text{Mole fractions: } y_{\text{H}_2\text{O}} = p_{\text{H}_2\text{O}}/P = 0.466/378.5 = \underline{\underline{1.23 \times 10^{-3} \text{ mol H}_2\text{O/mol gas}}}$$

$$y_{N_2} = 1 - y_{\text{H}_2\text{O}} = \underline{\underline{0.999 \text{ mol N}_2/\text{mol gas}}}$$

**6.48** H<sub>2</sub>O - Raoult's law:  $p_{\text{H}_2\text{O}}^*(70^\circ\text{C}) = \frac{233.7 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \frac{1 \text{ atm}}{760 \text{ mm Hg}} \right| = 0.3075 \text{ atm}$

$$\Rightarrow p_{\text{H}_2\text{O}} = x_{\text{H}_2\text{O}} p_{\text{H}_2\text{O}}^* = (1 - x_m)(0.3075)$$

$$\text{Methane - Henry's law: } p_m = x_m \cdot H_m$$

$$\text{Total pressure: } P = p_m + p_{\text{H}_2\text{O}} = x_m \cdot 6.66 \times 10^4 + (1 - x_m)(0.3075) = 10$$

$$\Rightarrow x_m = \underline{\underline{1.46 \times 10^{-4} \text{ mol CH}_4 / \text{mol}}}$$

**6.49 a.**

$$\text{Moles of water: } n_{\text{H}_2\text{O}} = \frac{1000 \text{ cm}^3}{\text{cm}^3} \left| \frac{1 \text{ g}}{\text{cm}^3} \right| \left| \frac{\text{mol}}{18.02 \text{ g}} \right| = 55.49 \text{ mol}$$

Moles of nitrogen:

$$n_{N_2} = \frac{(1 - 0.334) \times 14.1 \text{ cm}^3 (\text{STP})}{22.4 \text{ L (STP)}} \left| \frac{1 \text{ mol}}{22.4 \text{ L (STP)}} \right| \left| \frac{1 \text{ L}}{1000 \text{ cm}^3} \right| = 4.192 \times 10^{-4} \text{ mol}$$

Moles of oxygen:

$$n_{O_2} = \frac{(0.334) \cdot 14.1 \text{ cm}^3 (\text{STP})}{22.4 \text{ L (STP)}} \left| \frac{\text{mol}}{22.4 \text{ L (STP)}} \right| \left| \frac{\text{L}}{1000 \text{ cm}^3} \right| = 2.102 \times 10^{-4} \text{ mol}$$

Mole fractions of dissolved gases:

$$x_{N_2} = \frac{n_{N_2}}{n_{\text{H}_2\text{O}} + n_{N_2} + n_{O_2}} = \frac{4.192 \times 10^{-4}}{55.49 + 4.192 \times 10^{-4} + 2.102 \times 10^{-4}} = 7.554 \times 10^{-6} \frac{\text{mol N}_2}{\text{mol}}$$

$$x_{O_2} = \frac{n_{O_2}}{n_{\text{H}_2\text{O}} + n_{N_2} + n_{O_2}} = \frac{2.102 \times 10^{-4}}{55.49 + 4.192 \times 10^{-4} + 2.102 \times 10^{-4}} = 3.788 \times 10^{-6} \text{ mol O}_2 / \text{mol}$$

**6.49 (cont'd)**

Henry's law

$$\text{Nitrogen: } H_{N_2} = \frac{p_{N_2}}{x_{N_2}} = \frac{0.79 \cdot 1}{7.554 \times 10^{-6}} = \underline{\underline{1.046 \times 10^5 \text{ atm / mole fraction}}}$$

$$\text{Oxygen: } H_{O_2} = \frac{p_{O_2}}{x_{O_2}} = \frac{0.21 \cdot 1}{3.788 \times 10^{-6}} = \underline{\underline{5.544 \times 10^4 \text{ atm / mole fraction}}}$$

**b.** Mass of oxygen dissolved in 1 liter of blood:

$$m_{O_2} = \frac{2.102 \times 10^{-4} \text{ mol}}{1} \left| \frac{32.0 \text{ g}}{\text{mol}} \right| = 6.726 \times 10^{-3} \text{ g}$$

$$\text{Mass flow rate of blood: } \dot{m}_{\text{blood}} = \frac{0.4 \text{ g } O_2}{\text{min}} \left| \frac{1 \text{ L blood}}{6.72 \times 10^{-3} \text{ g } O_2} \right| = \underline{\underline{59 \text{ L blood / min}}}$$

**c.** Assumptions:

- (1) The solubility of oxygen in blood is the same as it is in pure water (in fact, it is much greater)
- (2) The temperature of blood is 36.9°C.

**6.50 a.** Basis: 1 cm<sup>3</sup> H<sub>2</sub>O(l)

$$\xrightarrow{(SG)_{H_2O}=1.0} \frac{1 \text{ g } H_2O}{1} \left| \frac{1 \text{ mol}}{18.0 \text{ g}} \right| = 0.0555 \text{ mol } H_2O$$

$$\xrightarrow{(SC)_{CO_2}=0.0901} \frac{0.0901 \text{ cm}^3 \text{ (STP)} CO_2}{1} \left| \frac{1 \text{ mol}}{22,400 \text{ cm}^3 \text{ (STP)}} \right| = 4.022 \times 10^{-6} \text{ mol } CO_2$$

$$p_{CO_2} = 1 \text{ atm} \Rightarrow x_{CO_2} = \frac{(4.022 \times 10^{-6}) \text{ mol } CO_2}{(0.0555 + 4.022 \times 10^{-6}) \text{ mol}} = 7.246 \times 10^{-5} \text{ mol } CO_2 / \text{mol}$$

$$p_{CO_2} = x_{CO_2} H_{CO_2} \Rightarrow H_{CO_2} (20^\circ \text{C}) = \frac{1 \text{ atm}}{7.246 \times 10^{-5}} = \underline{\underline{13800 \text{ atm/mole fraction}}}$$

**b.** For simplicity, assume  $n_{\text{total}} \approx n_{H_2O}$  (mol)

$$x_{CO_2} = p_{CO_2} / H = (3.5 \text{ atm}) / (13800 \text{ atm/mole fraction}) = 2.536 \times 10^{-4} \text{ mol } CO_2 / \text{mol}$$

$$n_{CO_2} = \frac{12 \text{ oz}}{33.8 \text{ oz}} \left| \frac{1 \text{ L}}{1} \right| \left| \frac{10^3 \text{ g } H_2O}{1 \text{ L}} \right| \left| \frac{1 \text{ mol } H_2O}{18.0 \text{ g } H_2O} \right| \left| \frac{2.536 \times 10^{-4} \text{ mol } CO_2}{1 \text{ mol } H_2O} \right| \left| \frac{44.0 \text{ g } CO_2}{1 \text{ mol } CO_2} \right|$$

$$= \underline{\underline{0.220 \text{ g } CO_2}}$$

$$\text{c. } V = \frac{0.220 \text{ g } CO_2}{44.0 \text{ g } CO_2} \left| \frac{1 \text{ mol } CO_2}{1 \text{ mol}} \right| \left| \frac{22.4 \text{ L (STP)}}{1 \text{ mol}} \right| \left| \frac{(273 + 37) \text{ K}}{273 \text{ K}} \right| = 0.127 \text{ L} = \underline{\underline{127 \text{ cm}^3}}$$

- 6.51 a.** – SO<sub>2</sub> is hazardous and should not be released directly into the atmosphere, especially if the analyzer is inside.
- From Henry's law, the partial pressure of SO<sub>2</sub> increases with the mole fraction of SO<sub>2</sub> in the liquid, which increases with time. If the water were never replaced, the gas leaving the bubbler would contain 1000 ppm SO<sub>2</sub> (nothing would be absorbed), and the mole fraction of SO<sub>2</sub> in the liquid would have the value corresponding to 1000 ppm SO<sub>2</sub> in the gas phase.

**b.** Calculate  $x(\text{mol SO}_2/\text{mol})$  in terms of  $r(\text{g SO}_2/100 \text{ g H}_2\text{O})$

Basis:  $100 \text{ g H}_2\text{O}(1 \text{ mol}/18.02 \text{ g}) = 5.55 \text{ mol H}_2\text{O}$

$$r(\text{g SO}_2)(1 \text{ mol}/64.07 \text{ g}) = 0.01561r(\text{mol SO}_2)$$

$$\Rightarrow x_{\text{SO}_2} = \frac{0.01561r}{5.55 + 0.01561r} \left( \frac{\text{mol SO}_2}{\text{mol}} \right)$$

From this relation and the given data,  $p_{\text{SO}_2} = 0 \text{ mmHg} \Leftrightarrow x_{\text{SO}_2} = 0 \text{ mol SO}_2/\text{mol}$

42	$1.4 \times 10^{-3}$
85	$2.8 \times 10^{-3}$
129	$4.2 \times 10^{-3}$
176	$5.6 \times 10^{-3}$

A plot of  $p_{\text{SO}_2}$  vs.  $x_{\text{SO}_2}$  is a straight line. Fitting the line using the method of least squares

(Appendix A.1) yields  $(p_{\text{SO}_2} = H_{\text{SO}_2} x_{\text{SO}_2})$ ,  $H_{\text{SO}_2} = 3.136 \times 10^4 \frac{\text{mm Hg}}{\text{mole fraction}}$

**c.**  $100 \text{ ppm SO}_2 \Rightarrow y_{\text{SO}_2} = \frac{100 \text{ mol SO}_2}{10^6 \text{ mols gas}} = 1.00 \times 10^{-4} \frac{\text{mol SO}_2}{\text{mol}}$

$$\Rightarrow p_{\text{SO}_2} = y_{\text{SO}_2} P = (1.0 \times 10^{-4})(760 \text{ mm Hg}) = 0.0760 \text{ mm Hg}$$

$$\begin{aligned} \text{Henry's law } \Rightarrow x_{\text{SO}_2} &= \frac{p_{\text{SO}_2}}{H_{\text{SO}_2}} = \frac{0.0760 \text{ mm Hg}}{3.136 \times 10^4 \text{ mm Hg/mole fraction}} \\ &= 2.40 \times 10^{-6} \text{ mol SO}_2/\text{mol} \end{aligned}$$

Since  $x_{\text{SO}_2}$  is so low, we may assume for simplicity that  $V_{\text{final}} \approx V_{\text{initial}} = 140 \text{ L}$ , and

$$n_{\text{final}} \approx n_{\text{initial}} = \frac{140 \text{ L}}{1 \text{ L}} \left| \frac{10^3 \text{ g H}_2\text{O}(l)}{18 \text{ g}} \right| \frac{1 \text{ mol}}{18 \text{ g}} = 7.78 \times 10^3 \text{ moles}$$

$$\begin{aligned} \Rightarrow n_{\text{SO}_2} &= \frac{7.78 \times 10^3 \text{ mol solution}}{1 \text{ mol solution}} \left| \frac{2.40 \times 10^{-6} \text{ mol SO}_2}{1 \text{ mol solution}} \right| = 0.0187 \text{ mol SO}_2 \text{ dissolved} \\ \frac{0.0187 \text{ mol SO}_2 \text{ dissolved}}{140 \text{ L}} &= 1.34 \times 10^{-4} \text{ mol SO}_2/\text{L} \end{aligned}$$

$$y_{\text{H}_2\text{O}} = \frac{x_{\text{H}_2\text{O}}^* P_{\text{H}_2\text{O}}^*(30^\circ \text{C})}{P} = \frac{(1)(31.824 \text{ mm Hg})}{760 \text{ mm Hg}} = 0.419 \frac{\text{mol H}_2\text{O}(v)}{\text{mol}}$$

Raoult's law for water:

$$y_{\text{air}} = 1 - y_{\text{SO}_2} - y_{\text{H}_2\text{O}} = 0.958 \frac{\text{mol dry air}}{\text{mol}}$$

- d.** Agitate/recirculate the scrubbing solution, change it more frequently. Add a base to the solution to react with the absorbed SO<sub>2</sub>.

**6.52** Raoult's law + Antoine equation (S = styrene, T = toluene):

$$y_S P = x_S p_S^* \Rightarrow x_S = \frac{0.650(150 \text{ mm Hg})}{10^{7.06623 - 1507.434/(T+214.985)}}$$

$$y_T P = x_T p_T^* \Rightarrow x_T = \frac{0.350(150 \text{ mm Hg})}{10^{6.95334 - 1343.943/(T+219.377)}}$$

$$1 = x_S + x_T = \frac{0.65(150)}{10^{7.06623 - 1507.434/(T+214.985)}} + \frac{0.35(150)}{10^{6.95334 - 1343.943/(T+219.377)}}$$

$$\Rightarrow T = \underline{\underline{86.0^\circ\text{C}}} \text{ (Determine using E-Z Solve or a spreadsheet)}$$

$$x_S = \frac{0.65(150)}{10^{7.06623 - 1507.434/(86.0+214.985)}} = \underline{\underline{0.853 \text{ mol styrene/mol}}}$$

$$x_T = 1 - x_S = 1 - 0.853 = \underline{\underline{0.147 \text{ mol toluene/mol}}}$$

**6.53**  $p_B^*(85^\circ\text{C}) = 10^{6.89272 - 1205.531/(85+219.888)} = 881.6 \text{ mm Hg}$

$$p_T^*(85^\circ\text{C}) = 10^{6.95805 - 1346.773/(85+219.693)} = 345.1 \text{ mm Hg}$$

Raoult's Law:  $y_B P = x_B p_B^* \Rightarrow y_B = \frac{0.35(881.6)}{10(760)} = \underline{\underline{0.0406 \text{ mol Benzene/mol}}}$

$$y_T = \frac{0.65(345.1)}{10(760)} = \underline{\underline{0.0295 \text{ mol Toluene/mol}}}$$

$$y_{N_2} = 1 - 0.0406 - 0.0295 = \underline{\underline{0.930 \text{ mol } N_2/\text{mol}}}$$

**6.54 a.** From the Cox chart, at  $77^\circ\text{F}$ ,  $p_p^* = 140 \text{ psig}$ ,  $p_{nB}^* = 35 \text{ psig}$ ,  $p_{iB}^* = 51 \text{ psig}$

$$\text{Total pressure } P = x_p \cdot p_p^* + x_{nB} \cdot p_{nB}^* + x_{iB} \cdot p_{iB}^*$$

$$= 0.50(140) + 0.30(35) + 0.20(51) = \underline{\underline{91 \text{ psia} \Rightarrow 76 \text{ psig}}}$$

$P < 200 \text{ psig}$ , so the container is technically safe.

**b.** From the Cox chart, at  $140^\circ\text{F}$ ,  $p_p^* = 300 \text{ psig}$ ,  $p_{nB}^* = 90 \text{ psig}$ ,  $p_{iB}^* = 120 \text{ psig}$

$$\text{Total pressure } P = 0.50(300) + 0.30(90) + 0.20(120) \cong 200 \text{ psig}$$

The temperature in a room will never reach  $140^\circ\text{F}$  unless a fire breaks out, so the container is adequate.

**6.55 a.** Antoine:  $p_{np}^*(120^\circ\text{C}) = 10^{6.84471 - 1060.793/(120+231.541)} = 6717 \text{ mm Hg}$

$$p_{ip}^*(120^\circ\text{C}) = 10^{6.73457 - 992.019/(120+231.541)} = 7883 \text{ mm Hg}$$

(Note: We are using the Antoine equation at  $120^\circ\text{C}$ , well above the validity ranges in Table B.4 for *n*-pentane and isopentane, so that all calculated vapor pressures must be considered rough estimates. To get more accuracy, we would need to find a vapor pressure correlation valid at higher temperatures.)

When the first bubble of vapor forms,

**6.55 (cont'd)**

$$x_{np} = \frac{0.500 \text{ mol } n\text{-C}_5\text{H}_{12}(\text{l})}{\text{mol}} \quad x_{ip} = \frac{0.500 \text{ mol } i\text{-C}_5\text{H}_{12}(\text{l})}{\text{mol}}$$

$$\text{Total pressure: } P = x_{np} \cdot p_{np}^* + x_{ip} \cdot p_{ip}^* = 0.50(6717) + 0.50(7883) = \underline{7300 \text{ mm Hg}}$$

$$y_{np} = \frac{x_{np} \cdot p_{np}^*}{P} = \frac{0.500(6717)}{7300} = \underline{0.46 \text{ mol } n\text{-C}_5\text{H}_{12}(\text{v})/\text{mol}}$$

$$y_{ip} = 1 - y_{np} = 1 - 0.46 = \underline{0.54 \text{ mol } i\text{-C}_5\text{H}_{12}(\text{v})/\text{mol}}$$

When the last drop of liquid evaporates,

$$y_{np} = \frac{0.500 \text{ mol } n\text{-C}_5\text{H}_{12}(\text{v})}{\text{mol}} \quad y_{ip} = \frac{0.500 \text{ mol } i\text{-C}_5\text{H}_{12}(\text{v})}{\text{mol}}$$

$$x_{np} + x_{ip} = \frac{y_{np}P}{p_{np}^*(120^\circ\text{C})} + \frac{y_{ip}P}{p_{ip}^*(120^\circ\text{C})} = \frac{0.500P}{6725} + \frac{0.500P}{7960} = 1 \Rightarrow \underline{P = 7291 \text{ mm Hg}}$$

$$x_{np} = \frac{0.5 \cdot 7250 \text{ mm Hg}}{6717 \text{ mm Hg}} = \underline{0.54 \text{ mol } n\text{-C}_5\text{H}_{12}(\text{l})/\text{mol}}$$

$$x_{ip} = 1 - x_{np} = 1 - 0.54 = \underline{0.46 \text{ mol } i\text{-C}_5\text{H}_{12}(\text{l})/\text{mol}}$$

**b.** When the first drop of liquid forms,

$$y_{np} = \frac{0.500 \text{ mol } n\text{-C}_5\text{H}_{12}(\text{v})}{\text{mol}} \quad y_{ip} = \frac{0.500 \text{ mol } i\text{-C}_5\text{H}_{12}(\text{v})}{\text{mol}}$$

$$P = (1200 + 760) = 1960 \text{ mm Hg}$$

$$x_{np} + x_{ip} = \frac{0.500P}{p_{np}^*(T_{dp})} + \frac{0.500P}{p_{ip}^*(T_{dp})} = \frac{980}{10^{6.84471-1060.793/(T_{dp}+231.541)}} + \frac{980}{10^{6.73457-992.019/(T_{dp}+231.541)}} = 1$$

$$\Rightarrow \underline{T_{dp} = 63.1^\circ\text{C}}$$

$$p_{np}^* = 10^{6.84471-1060.793/(63.1+231.541)} = 1758 \text{ mm Hg}$$

$$p_{ip}^* = 10^{6.73457-992.019/(63.1+231.541)} = 2215 \text{ mm Hg}$$

$$x_{np} = \frac{0.5 \cdot 1960 \text{ mm Hg}}{p_{np}^*(63.1^\circ\text{C})} = \underline{0.56 \text{ mol } n\text{-C}_5\text{H}_{12}/\text{mol}}$$

$$x_{ip} = 1 - x_{np} = 1 - 0.56 = \underline{0.44 \text{ mol } i\text{-C}_5\text{H}_{12}/\text{mol}}$$

When the last bubble of vapor condenses,

$$x_{np} = \frac{0.500 \text{ mol } n\text{-C}_5\text{H}_{12}(\text{l})}{\text{mol}} \quad x_{ip} = \frac{0.500 \text{ mol } i\text{-C}_5\text{H}_{12}(\text{l})}{\text{mol}}$$

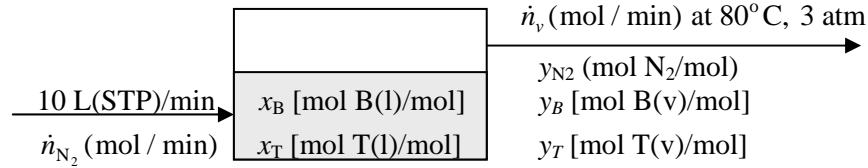
$$\text{Total pressure: } P = x_{np} \cdot p_{np}^* + x_{ip} \cdot p_{ip}^*$$

$$\Rightarrow 1960 = (0.5)10^{6.84471-1060.793/(T+231.541)} + (0.5)10^{6.73457-992.019/(T_{bp}+231.541)} \Rightarrow \underline{T = 62.6^\circ\text{C}}$$

$$y_{np} = \frac{x_{np} \cdot p_{np}^*(62.6^\circ\text{C})}{P} = \frac{0.5(1734)}{1960} = \underline{0.44 \text{ mol } n\text{-C}_5\text{H}_{12}(\text{v})/\text{mol}}$$

$$y_{ip} = 1 - y_{np} = 1 - 0.44 = \underline{0.56 \text{ mol } i\text{-C}_5\text{H}_{12}(\text{v})/\text{mol}}$$

6.56 B = benzene, T = toluene



$$\dot{n}_{N_2} = \frac{10.0 \text{ L(STP)} / \text{min}}{22.4 \text{ L(STP)} / \text{mol}} = 0.4464 \text{ mol } N_2 / \text{min}$$

Antoine:  $p_B^*(80^\circ\text{C}) = 10^{6.89272-1203.531/(80+219.888)} = 757.6 \text{ mm Hg}$

$$p_T^*(80^\circ\text{C}) = 10^{6.95805-1346.773/(80+219.693)} = 291.2 \text{ mm Hg}$$

a. Initially,  $x_B = 0.500$ ,  $x_T = 0.500$ .

$N_2$  balance:  $0.4464 \text{ mol } N_2 / \text{min} = \dot{n}_v(1 - 0.166 - 0.0639) \Rightarrow \dot{n}_v = 0.5797 \text{ mol / min}$

$$\Rightarrow \dot{n}_{B0} = \left( 0.5797 \frac{\text{mol}}{\text{min}} \right) \left( 0.166 \frac{\text{mol B}}{\text{mol}} \right) = \underline{\underline{0.0962 \frac{\text{mol B(v)}}{\text{min}}}}$$

$$\dot{n}_{T0} = \left( 0.5797 \frac{\text{mol}}{\text{min}} \right) \left( 0.0639 \frac{\text{mol B}}{\text{mol}} \right) = \underline{\underline{0.0370 \frac{\text{mol T(v)}}{\text{min}}}}$$

- b. Since benzene is evaporating more rapidly than toluene,  $x_B$  decreases with time and  $x_T (= 1-x_B)$  increases.
- c. Since  $x_B$  decreases,  $y_B (= x_B p_B^*/P)$  also decreases. Since  $x_T$  increases,  $y_T (= x_T p_T^*/P)$  also increases.

6.57 a.  $P = x_{hex} p_{hex}^*(T_{bp}) + x_{hep} p_{hep}^*(T_{bp})$ ,  $y_i = \frac{x_i p_i^*(T_{bp})}{P}$ , Antoine equation for  $p_i^*$

$$760 \text{ mm Hg} = 0.500 \left[ 10^{6.88555-1175.817/(T_{bp}+224.867)} \right] + 0.500 \left[ 10^{6.90253-1267.828/(T_{bp}+216.823)} \right]$$

E-Z Solve or Goal Seek  $\Rightarrow \underline{\underline{T_{bp} = 80.5^\circ\text{C}}} \Rightarrow \underline{\underline{y_{hex} = 0.713, y_{hep} = 0.287}}$

b.  $x_i = \frac{y_i P}{p_i^*(T_{dp})} \Rightarrow \sum_i x_i = P \sum_i \frac{y_i}{p_i^*(T_{dp})} = 1$

$$760 \text{ mmHg} \left[ \frac{0.30}{10^{6.88555-1175.817/(T_{dp}+224.867)}} + \frac{0.30}{10^{6.90253-1267.828/(T_{dp}+216.823)}} \right] = 1$$

E-Z Solve or Goal Seek  $\Rightarrow \underline{\underline{T_{dp} = 71.1^\circ\text{C}}} \Rightarrow \underline{\underline{x_{hex} = 0.279, x_{hep} = 0.721}}$

6.58 a.  $f(T) = P - \sum_{i=1}^N x_i p_i^*(T) = 0 \Rightarrow T$ , where  $p_i^*(T) = 10^{\left(A_i - \frac{B_i}{T+C_i}\right)}$

$$y_i (i=1,2,\dots,N) = \frac{x_i p_i^*(T)}{P}$$

b.

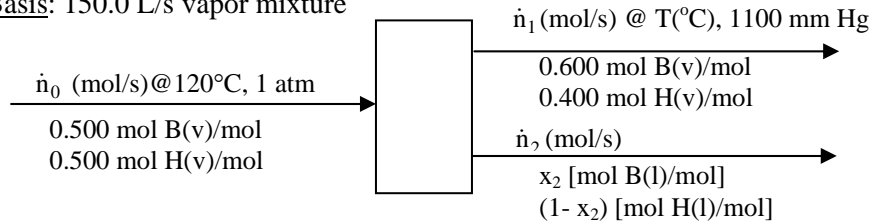
Calculation of Bubble Points							
	A	B	C				
Benzene	6.89272	1203.531	219.888				
Ethylbenzene	6.95650	1423.543	213.091				
Toluene	6.95805	1346.773	219.693				
P(mmHg)=	760						
$x_B$	$x_{EB}$	$x_T$	$T_{bp}(^{\circ}\text{C})$	$p_B$	$p_{EB}$	$p_T$	$f(T)$
0.226	0.443	0.331	<b>108.09</b>	378.0	148.2	233.9	-0.086
0.443	0.226	0.331	<b>96.47</b>	543.1	51.6	165.2	0.11
0.226	0.226	0.548	<b>104.48</b>	344.0	67.3	348.6	0.07

$$\left. \begin{array}{l} \text{When } x_B = 1 (\text{pure benzene}), T_{bp} = (T_{bp})_{C_6H_6} = 80.1^{\circ}\text{C} \\ \text{When } x_{EB} = 1 (\text{pure ethylbenzene}), T_{bp} = (T_{bp})_{C_8H_{10}} = 136.2^{\circ}\text{C} \\ \text{When } x_T = 1 (\text{pure toluene}), T_{bp} = (T_{bp})_{C_7H_8} = 110.6^{\circ}\text{C} \end{array} \right\} \Rightarrow T_{bp,EB} > T_{bp,T} > T_{bp,B}$$

Mixture 1 contains more ethylbenzene (higher boiling point) and less benzene (lower bp) than Mixture 2, and so  $(T_{bp})_1 > (T_{bp})_2$ . Mixture 3 contains more toluene (lower bp) and less ethylbenzene (higher bp) than Mixture 1, and so  $(T_{bp})_3 < (T_{bp})_1$ . Mixture 3 contains more toluene (higher bp) and less benzene (lower bp) than Mixture 2, and so  $(T_{bp})_3 > (T_{bp})_2$ .



6.59 a. Basis: 150.0 L/s vapor mixture



Gibbs phase rule:  $F=2+c-\pi=2+2-2=2$

Since the composition of the vapor and the pressure are given, the information is enough.

Equations needed: Mole balances on butane and hexane, Antoine equation and Raoult's law for butane and hexane

b. Molar flow rate of feed:  $\dot{n}_0 = \frac{150.0 \text{ L}}{\text{s}} \times \frac{273 \text{ K}}{393 \text{ K}} \times \frac{\text{mol}}{22.4 \text{ L (STP)}} = 4.652 \text{ mol/s}$

Raoult's law for butane:  $0.600(1100) = x_2 \cdot 10^{6.82485 - 943.453/(T+239.711)}$  (1)

Raoult's law for hexane:  $0.400(1100) = (1-x_2) \cdot 10^{6.88555 - 1175.817/(T+224.867)}$  (2)

Mole balance on butane:  $4.652(0.5) = \dot{n}_1 \cdot 0.6 + \dot{n}_2 \cdot x_2$  (3)

Mole balance on hexane:  $4.652(0.5) = \dot{n}_1 \cdot 0.4 + \dot{n}_2 \cdot (1-x_2)$  (4)

c. From (1) and (2),  $1 = \frac{1100(0.6)}{10^{6.82485 - \frac{943.453}{T+239.711}}} + \frac{1100(0.4)}{10^{6.88555 - \frac{1175.817}{T+224.867}}}$

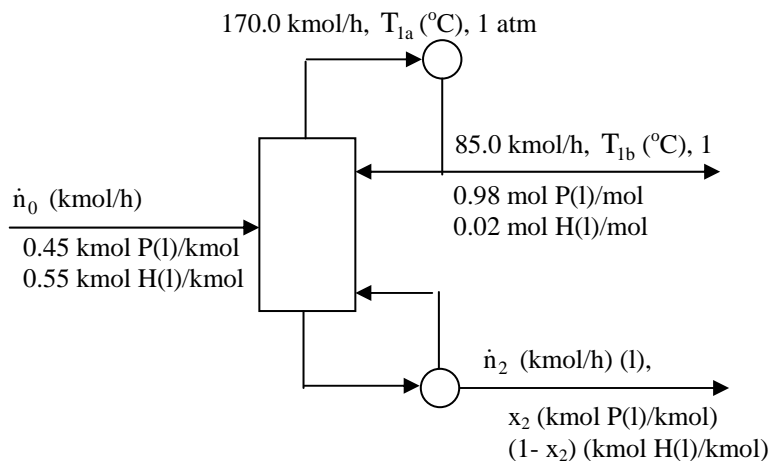
$\Rightarrow T = \underline{57.0^\circ\text{C}}$

$x_2 = \frac{1100(0.6)}{10^{6.82485 - 943.453/(57.0+239.711)}} = \underline{0.149 \text{ mol butane/mol}}$

Solving (3) and (4) simultaneously  $\Rightarrow \dot{n}_1 = \underline{3.62 \text{ mol C}_4\text{H}_{10}/\text{s}}$ ;  $\dot{n}_2 = \underline{1.03 \text{ mol C}_6\text{H}_{14}/\text{s}}$

- d. Assumptions: (1) Antoine equation is accurate for the calculation of vapor pressure;  
(2) Raoult's law is accurate;  
(3) Ideal gas law is valid.

6.60 P = *n*-pentane, H = *n*-hexane



## 6.60 (cont'd)

a. Molar flow rate of feed:  $\dot{n}_0(0.45)(0.95) = 85(0.98) \Rightarrow \dot{n}_0 = \underline{\underline{195 \text{ kmol / h}}}$

Total mole balance :  $195 = 85.0 + \dot{n}_2 \Rightarrow \dot{n}_2 = \underline{\underline{110 \text{ kmol / h}}}$

Pentane balance:  $195(0.45) = 85.0(0.98) + 110 \cdot x_2 \Rightarrow x_2 = \underline{\underline{0.0405 \text{ mol P / mol}}}$

b. Dew point of column overhead vapor effluent:

Eq. 6.4-7, Antoine equation

$$\Rightarrow \frac{0.98(760)}{10^{6.84471-1060.793/(T_{1a}+231.541)}} + \frac{0.02(760)}{10^{6.88555-1175.817/(T_{1a}+224.687)}} = 1 \Rightarrow \underline{\underline{T_{1a} = 37.3^\circ \text{C}}}$$

Flow rate of column overhead vapor effluent. Assuming ideal gas behavior,

$$\dot{V}_{\text{vapor}} = \frac{170 \text{ kmol}}{\text{h}} \left| \frac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}} \right| \frac{(273.2 + 37.3) \text{ K}}{1 \text{ atm}} = \underline{\underline{4330 \text{ m}^3 / \text{h}}}$$

Flow rate of liquid distillate product.

Table B.1  $\Rightarrow \rho_P = 0.621 \text{ g / mL}$ ,  $\rho_H = 0.659 \text{ g / mL}$

$$\begin{aligned} \dot{V}_{\text{distillate}} &= \frac{0.98(85) \text{ kmol P}}{\text{h}} \left| \frac{72.15 \text{ kg P}}{\text{kmol P}} \right| \frac{\text{L}}{0.621 \text{ kg P}} \\ &+ \frac{0.02(85) \text{ kmol H}}{\text{h}} \left| \frac{86.17 \text{ kg H}}{\text{kmol H}} \right| \frac{\text{L}}{0.659 \text{ kg H}} = \underline{\underline{9.9 \times 10^3 \text{ L / h}}} \end{aligned}$$

c. Reboiler temperature.

$$0.04 \cdot 10^{6.84471-1060.793/(T_2+231.541)} + 0.96 \cdot 10^{6.88555-1175.817/(T_2+224.867)} = 760 \Rightarrow T_2 = \underline{\underline{66.6^\circ \text{C}}}$$

Boilup composition.

$$y_2 = \frac{x_2 P_P^*(66.6^\circ \text{C})}{P} = \frac{0.04 \cdot 10^{6.84471-1060.793/(66.6+231.541)}}{760} = \underline{\underline{0.102 \text{ mol P(v)/mol}}}$$

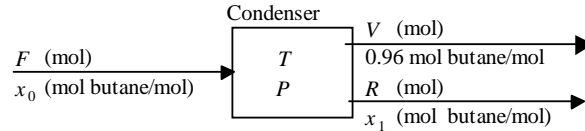
$$\Rightarrow (1 - y_2) = \underline{\underline{0.898 \text{ mol H(v) / mol}}}$$

d. Minimum pipe diameter

$$\begin{aligned} \dot{V} \left( \frac{\text{m}^3}{\text{s}} \right) &= u_{\text{max}} \left( \frac{\text{m}}{\text{s}} \right) \times \frac{\pi D_{\text{min}}^2}{4} (\text{m}^2) \\ \Rightarrow D_{\text{min}} &= \sqrt{\frac{4 \dot{V}_{\text{vapor}}}{\pi \cdot u_{\text{max}}}} = \sqrt{\frac{4}{\pi} \left| \frac{4330 \text{ m}^3 / \text{h}}{10 \text{ m / s}} \right| \frac{1 \text{ h}}{3600 \text{ s}}} = \underline{\underline{0.39 \text{ m (39 cm)}}} \end{aligned}$$

Assumptions: Ideal gas behavior, validity of Raoult's law and the Antoine equation, constant temperature and pressure in the pipe connecting the column and the condenser, column operates at steady state.

6.61 a.



Partial condenser:  $40^\circ\text{C}$  is the dew point of a 96%  $\text{C}_4\text{H}_{10}$  – 4%  $\text{C}_5\text{H}_{12}$  vapor mixture at

$$P = P_{\min}$$

Total condenser:  $40^\circ\text{C}$  is the bubble point of a 96%  $\text{C}_4\text{H}_{10}$  - 4%  $\text{C}_5\text{H}_{12}$  liquid mixture at

$$P = P_{\min}$$

Dew Point:  $1 = \sum x_i = \sum \frac{y_i P}{p_i^*(40^\circ\text{C})} \Rightarrow P_{\min} = \frac{1}{\sum y_i / p_i^*(40^\circ\text{C})}$

(Raoult's Law)

$$\begin{aligned} &\downarrow \text{Antoine Eq. for } p_i^*(\text{C}_4\text{H}_{10}) = 10^{\left( \frac{6.82485 - 943.453}{40 + 239.711} \right)} = 2830.70 \text{ mmHg} \\ &\downarrow \text{Antoine Eq. for } p_i^*(\text{C}_5\text{H}_{12}) = 10^{\left( \frac{6.84471 - 1060.793}{40 + 231.541} \right)} = 867.22 \text{ mmHg} \end{aligned}$$

$$\Rightarrow P_{\min} = \frac{1}{0.96/2830.70 + 0.04/867.22} = \underline{\underline{2595.63 \text{ mm Hg (partial condenser)}}}$$

Bubble Point:  $P = \sum y_i P = \sum x_i p_i^*(40^\circ\text{C})$

$$P = 0.96(2830.70) + 0.04(867.22) = \underline{\underline{2752.16 \text{ mm Hg (total condenser)}}}$$

b.  $\dot{V} = 75 \text{ kmol/h}$ ,  $\dot{R}/\dot{V} = 1.5 \Rightarrow \dot{R} = 75 \times 1.5 \text{ kmol/h} = \underline{\underline{112.5 \text{ kmol/h}}}$

Feed and product stream compositions are identical:  $y = \underline{\underline{0.96 \text{ kmol butane/kmol}}}$

Total balance:  $\dot{F} = 75 + 112.5 = \underline{\underline{187.5 \text{ kmol/h}}}$

c. Total balance as in b.  $\dot{R} = 112.5 \text{ kmol/h}$   $\dot{F} = 187.5 \text{ kmol/h}$

$$\begin{aligned} &\left. \begin{array}{l} \text{Equilibrium: } 0.96P = x_1(2830.70) \\ \text{(Raoult's law) } 0.04P = (1 - x_1)(867.22) \end{array} \right\} \begin{array}{l} P = 2596 \text{ mm Hg} \\ x_1 = 0.8803 \text{ mol butane/mol} \end{array} \end{aligned}$$

Butane balance:  $187.5x_0 = 112.5(0.8803) + 0.96(75) \Rightarrow x_0 = \underline{\underline{0.9122 \text{ mol butane/mol reflux}}}$

6.62 a. Raoult's law:  $\frac{y_i}{x_i} = \frac{p_i^*}{P} \Rightarrow \alpha_{AB} = \frac{y_A/x_A}{y_B/x_B} = \frac{p_A^*/P}{p_B^*/P} = \frac{p_A^*}{p_B^*} = \underline{\underline{\alpha_{AB}}}$

b.  $p_S^*(85^\circ\text{C}) = 10^{\left( \frac{7.06623 - 1507.434}{85 + 214.985} \right)} = 109.95 \text{ mm Hg}$

$$p_{EB}^*(85^\circ\text{C}) = 10^{\left( \frac{6.95650 - 1423.543}{85 + 213.091} \right)} = 151.69 \text{ mm Hg}$$

$$p_B^*(85^\circ\text{C}) = 10^{\left( \frac{6.89272 - 1203.531}{85 + 219.888} \right)} = 881.59 \text{ mm Hg}$$

**6.62 (cont'd)**

$$\alpha_{S,EB} = \frac{p_S^*}{p_{EB}^*} = \frac{109.95}{151.69} = 0.725, \quad \alpha_{B,EB} = \frac{p_B^*}{p_{EB}^*} = \frac{881.59}{151.69} = 5.812$$

Styrene – ethylbenzene is the more difficult pair to separate by distillation

because  $\alpha_{S,EB}$  is closer to 1 than is  $\alpha_{B,EB}$ .

$$\text{c. } \alpha_{ij} = \frac{y_i/x_i}{y_j/x_j} \xRightarrow{\substack{y_j=1-y_i \\ x_j=1-x_i}} \alpha_{ij} = \frac{y_i/x_i}{(1-y_i)/(1-x_i)} \Rightarrow y_i = \frac{\alpha_{ij}x_i}{1+(\alpha_{ij}-1)x_i}$$

$$\text{d. } \alpha_{B,EB} = 5.810 \Rightarrow y_B = \frac{x_B \alpha_{B,EB}}{1+(\alpha_{B,EB}-1)x_B} = \frac{5.81x_B}{1+4.81x_B}, \quad P = x_B p_B^* + (1-x_B)p_{EB}^*$$

$x_B$	0.0	0.2	0.4	0.6	0.8	1.0	mol B(l)/mol
$y_B$	0.0	0.592	0.795	0.897	0.959	1.0	mol B(v)/mol
$P$	152	298	444	5900	736	882	mmHg

**6.63 a.** Since benzene is more volatile, *the fraction of benzene will increase moving up the column.* For ideal stages, the temperature of each stage corresponds to the bubble point temperature of the liquid. Since the fraction of benzene (the more volatile species) increases moving up the column, *the temperature will decrease moving up the column.*

**b.** Stage 1:  $\dot{n}_l = 150 \text{ mol/h}$ ,  $\dot{n}_v = 200 \text{ mol/h}$ ;  $x_1 = 0.55 \text{ mol B/mol} \Rightarrow 0.45 \text{ mol S/mol}$ ;  
 $y_0 = 0.65 \text{ mol B/mol} \Rightarrow 0.35 \text{ mol S/mol}$

Bubble point  $T$ :  $P = \sum x_i p_i^*(T)$

$$P_1 = (0.400 \times 760) \text{ mmHg} = (0.55)10^{6.89272-1203.531/(T+219.888)} + (0.45)10^{7.06623-1507.434/(T+214.985)}$$

$$\xrightarrow{\text{E-Z Solve}} T_1 = 67.6^\circ \text{C}$$

$$\Rightarrow y_1 = \frac{x_1 p_B^*(T)}{P} = \frac{0.55(508)}{0.400 \times 760} = 0.920 \text{ mol B/mol} \Rightarrow 0.080 \text{ mol S/mol}$$

$$\text{B balance: } y_0 \dot{n}_v + x_2 \dot{n}_l = y_1 \dot{n}_v + x_1 \dot{n}_l \Rightarrow x_2 = 0.910 \text{ mol B/mol} \Rightarrow 0.090 \text{ mol S/mol}$$

Stage 2:

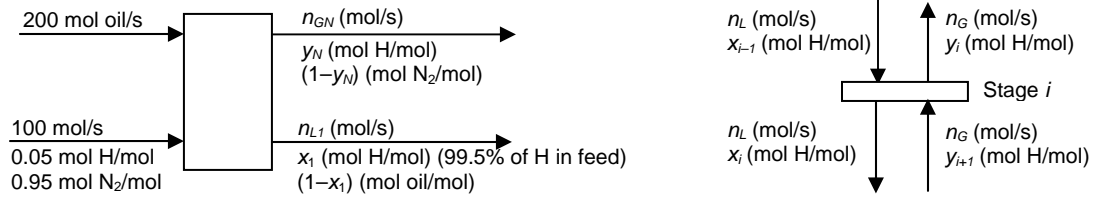
$$(0.400 \times 760) \text{ mmHg} = 0.910 p_B^*(T_2) + 0.090 p_S^*(T_2) \xrightarrow{\text{E-Z Solve}} T_2 = 55.3^\circ \text{C}$$

$$y_2 = \frac{0.910(331.0)}{760 \times 0.400} = 0.991 \text{ mol B/mol} \Rightarrow 0.009 \text{ mol S/mol}$$

$$\text{B balance: } y_1 \dot{n}_v + x_3 \dot{n}_l = y_2 \dot{n}_v + x_2 \dot{n}_l \Rightarrow x_3 \approx 1 \text{ mol B/mol} \Rightarrow \approx 0 \text{ mol S/mol}$$

**c.** In this process, the styrene content is less than 5% in two stages. In general, the calculation of part b would be repeated until  $(1-y_n)$  is less than the specified fraction.

**6.64** Basis: 100 mol/s gas feed. H=hexane.



a. 
$$\left. \begin{array}{l} \text{N}_2 \text{ balance: } 0.95(100) = (1 - y_N) \dot{n}_{GN} \\ 99.5\% \text{ absorption: } 0.05(100)(0.005) = y_N \dot{n}_{GN} \end{array} \right\} \Rightarrow \begin{array}{l} \dot{n}_{GN} = 95.025 \text{ mol/s} \\ y_N = 2.63 \times 10^{-4} \text{ mol H(v)/mol} \end{array}$$

Mole Balance:  $100 + 200 = 95.025 + \dot{n}_{L1} \Rightarrow \dot{n}_{L1} = 205 \text{ mol/s}$

Hexane Balance:  $0.05(100) = 2.63 \times 10^{-4} (95.025) + x_1 (204.99) \Rightarrow x_1 = 0.0243 \text{ mol H(l)/mol}$

$\dot{n}_L = \frac{1}{2} (200 + 205) \Rightarrow \dot{n}_L = 202.48 \text{ mol/s}$ ,  $\dot{n}_G = \frac{1}{2} (100 + 95.025) \Rightarrow \dot{n}_G = 97.52 \text{ mol/s}$

b. 
$$y_1 = x_1 p_H^*(50^\circ\text{C}) / P = 0.0243(403.73) / 760 = 0.0129 \text{ mol H(v)/mol}$$

H balance on 1<sup>st</sup> Stage:  $y_0 \dot{n}_v + x_2 \dot{n}_l = y_1 \dot{n}_v + x_1 \dot{n}_l \Rightarrow x_2 = 0.00643 \text{ mol H(l)/mol}$

c. The given formulas follow from Raoult's law and a hexane balance on Stage  $i$ .

d.

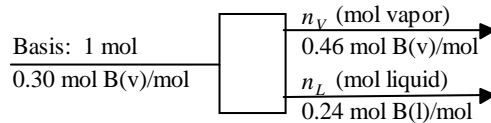
Hexane Absorption								
P=	760	PR=	1					
y0=	0.05	x1=	0.0243	yN=	2.63E-04			
nGN=	95.025	nL1=	204.98	nG=	97.52	nL=	202.48	
A=	6.88555	B=	1175.817	C=	224.867			
T	p*(T)		T	p*(T)		T	p*(T)	
30	187.1		50	405.3059		70	790.5546	
i	x(i)	y(i)	i	x(i)	y(i)	i	x(i)	y(i)
0		5.00E-02	0		5.00E-02	0		5.00E-02
1	2.43E-02	5.98E-03	1	2.43E-02	1.30E-02	1	2.43E-02	2.53E-02
2	3.10E-03	7.63E-04	2	6.46E-03	3.45E-03	2	1.24E-02	1.29E-02
3	5.86E-04	1.44E-04	3	1.88E-03	1.00E-03	3	6.43E-03	6.69E-03
			4	7.01E-04	3.74E-04	4	3.44E-03	3.58E-03
			5	3.99E-04	2.13E-04	5	1.94E-03	2.02E-03
						...	...	...
						21	4.38E-04	4.56E-04

**6.64 (cont'd)**

- e. If the column is long enough, the liquid flowing down eventually approaches equilibrium with the entering gas. At 70°C, the mole fraction of hexane in the exiting liquid in equilibrium with the mole fraction in the entering gas is  $4.56 \times 10^{-4}$  mol H/mol, which is insufficient to bring the total hexane absorption to the desired level. To reach that level at 70°C, either the liquid feed rate must be increased or the pressure must be raised to a value for which the final mole fraction of hexane in the vapor is  $2.63 \times 10^{-4}$  or less. The solution is  $\underline{P_{\min} = 1037 \text{ mm Hg}}$ .

**6.65 a.** Intersection of vapor curve with  $y_B = 0.30$  at  $\underline{T = 104^\circ\text{C} \Rightarrow 13\% \text{ B(l)}, 87\% \text{ T(l)}}$

b.  $\underline{T = 100^\circ\text{C} \Rightarrow x_B = 0.24 \text{ mol B/mol (liquid)}, y_B = 0.46 \text{ mol B/mol (vapor)}}$



Balances

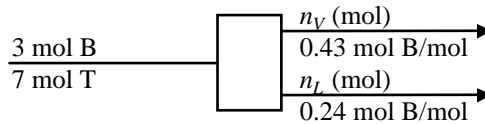
$$\left. \begin{array}{l} \text{Total moles: } 1 = n_V + n_L \\ \text{B: } 0.30 = 0.46n_V + 0.24n_L \end{array} \right\} \Rightarrow \begin{array}{l} n_L = 0.727 \text{ mol} \\ n_V = 0.273 \text{ mol} \end{array} \Rightarrow \frac{n_V}{n_L} = 0.375 \frac{\text{mol vapor}}{\text{mol liquid}}$$

c. Intersection of liquid curve with  $x_B = 0.3$  at  $\underline{T = 98^\circ\text{C} \Rightarrow 50\% \text{ B(v)}, 50\% \text{ T(v)}}$

**6.66 a.**  $\underline{P = 798 \text{ mm Hg}, y_B = 0.50 \text{ mol B(v)/mol}}$

b.  $\underline{P = 690 \text{ mm Hg}, x_B = 0.15 \text{ mol B(l)/mol}}$

c.  $\underline{P = 750 \text{ mm Hg}, y_B = 0.43 \text{ mol B(v)/mol}, x_B = 0.24 \text{ mol B(l)/mol}}$



$$\left. \begin{array}{l} \text{Mole bal.: } 10 = n_V + n_L \\ \text{B bal.: } 3 = 0.43n_V + 0.24n_L \end{array} \right\} \Rightarrow \begin{array}{l} n_V = 3.16 \text{ mol} \\ n_L = 6.84 \text{ mol} \end{array} \Rightarrow \frac{n_V}{n_L} = 0.46 \frac{\text{mol vapor}}{\text{mol liquid}}$$

Answers may vary due to difficulty of reading chart.

d. i)  $P = 1000 \text{ mm Hg} \Rightarrow$  all liquid. Assume volume additivity of mixture components.

$$V = \frac{3 \text{ mol B}}{\text{mol B}} \left| \frac{78.11 \text{ g B}}{0.879 \text{ g B}} \right| \frac{10^{-3} \text{ L}}{1} + \frac{7 \text{ mol T}}{\text{mol T}} \left| \frac{92.13 \text{ g T}}{0.866 \text{ g T}} \right| \frac{10^{-3} \text{ L}}{1} = \underline{1.0 \text{ L}}$$

ii) 750 mmHg. Assume liquid volume negligible

**6.66 (cont'd)**

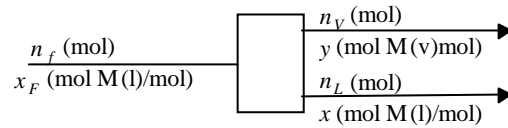
$$V = \frac{3.16 \text{ mol vapor}}{\text{mol} \cdot \text{K}} \left| \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \right| \left| \frac{373 \text{ K}}{750 \text{ mm Hg}} \right| \left| \frac{760 \text{ mm Hg}}{1 \text{ atm}} \right| - 0.6 \text{ L} = \underline{\underline{97.4 \text{ L}}}$$

(Liquid volume is about 0.6 L)

iii) 600 mm Hg

$$v = \frac{10 \text{ mol vapor}}{\text{mol} \cdot \text{K}} \left| \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \right| \left| \frac{373 \text{ K}}{600 \text{ mm Hg}} \right| \left| \frac{760 \text{ mm Hg}}{1 \text{ atm}} \right| = \underline{\underline{388 \text{ L}}}$$

**6.67 a.** M = methanol

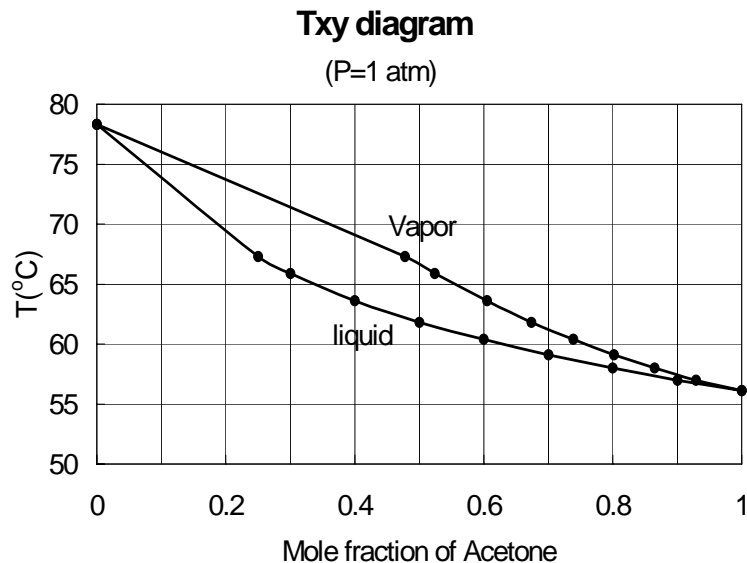


$$\left. \begin{array}{l} \text{Mole balance: } n_f = n_v + n_L \\ \text{MeOH balance: } x_F n_f = y n_v + x n_L \end{array} \right\} \Rightarrow x_F n_v + x_F n_L = y n_v + x n_L \Rightarrow f = \frac{n_v}{n_L} = \frac{x_F - x}{y - x}$$

$$x_F = 0.4, x = 0.23, y = 0.62 \Rightarrow f = \frac{0.4 - 0.23}{0.62 - 0.23} = \underline{\underline{0.436}}$$

**b.**  $\underline{\underline{T_{\min} = 75^\circ \text{C}}}$ ,  $\underline{\underline{f = 0}}$ ,  $\underline{\underline{T_{\max} = 87^\circ \text{C}}}$ ,  $\underline{\underline{f = 1}}$

**6.68 a.**



**b.**  $\underline{\underline{x_A = 0.47}}$ ;  $\underline{\underline{y_A = 0.66}}$

**6.68 (cont'd)**

c. (i)  $x_A = 0.34$ ;  $y_A = 0.55$

(ii) 
$$\left. \begin{array}{l} \text{Mole bal.: } 1 = n_V + n_L \\ \text{A bal.: } 0.50 = 0.55n_V + 0.34n_L \end{array} \right\} \Rightarrow n_V = 0.762 \text{ mol vapor, } n_L = 0.238 \text{ mol liquid}$$
  

$$\Rightarrow \underline{\underline{76.2 \text{ mole\% vapor}}}$$

(iii)  $\rho_{A(l)} = 0.791 \text{ g/cm}^3$ ,  $\rho_{E(l)} = 0.789 \text{ g/cm}^3 \Rightarrow \rho_l \approx 0.790 \text{ g/cm}^3$

(To be more precise, we could convert the given mole fractions to mass fractions and calculate the weighted average density of the mixture, but since the pure component densities are almost identical there is little point in doing all that.)

$M_A = 58.08 \text{ g/mol}$ ,  $M_E = 46.07 \text{ g/mol}$

$\Rightarrow M_l = (0.34)(58.08) + (1 - 0.34)(46.07) = 50.15 \text{ g/mol}$

Basis: 1 mol liquid  $\Rightarrow (0.762 \text{ mol vapor} / 0.238 \text{ mol liquid}) = 3.2 \text{ mol vapor}$

Liquid volume:  $V_l = \frac{(1 \text{ mol})(50.15 \text{ g/mol})}{(0.790 \text{ g/cm}^3)} = 63.48 \text{ cm}^3$

Vapor volume:

$$V_v = \frac{3.2 \text{ mol}}{\text{mol}} \left| \frac{22400 \text{ cm}^3 \text{ (STP)}}{\text{mol}} \right| \left| \frac{(65 + 273)\text{K}}{273\text{K}} \right| = 88,747 \text{ cm}^3$$

Volume percent of vapor =  $\frac{88,747}{88,747 + 63.48} \times 100\% = \underline{\underline{99.9 \text{ volume\% vapor}}}$

d. For a basis of 1 mol fed, guess  $T$ , calculate  $n_V$  as above; if  $n_V \neq 0.20$ , pick new  $T$ .

$T$	$x_A$	$y_A$	$f_V$
65 °C	0.34	0.55	0.333
<b>64.5 °C</b>	<b>0.36</b>	<b>0.56</b>	0.200

e. Raoult's law:  $y_i P = x_i p_i^* \Rightarrow P = x_A p_A^* + x_E p_E^*$

$760 = 0.5 \times 10^{7.11714 - 1210.595/(T_{bp} + 229.664)} + 0.5 \times 10^{8.11220 - 1592.864/(T_{bp} + 226.184)} \Rightarrow \underline{\underline{T_{bp} = 66.16^\circ \text{C}}}$

$y = \frac{x p_A^*}{P} = \frac{0.5 \times 10^{7.11714 - 1210.595/(66.25 + 229.664)}}{760} = \underline{\underline{0.696 \text{ mol acetone/mol}}}$

The actual  $T_{bp} = 61.8^\circ \text{C} \Rightarrow \frac{\Delta T_{bp}}{T_{bp}(\text{real})} = \frac{66.25 - 61.8}{61.8} \times 100\% = \underline{\underline{7.20\% \text{ error in } T_{bp}}}$

$y_A = 0.674 \Rightarrow \frac{\Delta y_A}{y_A(\text{real})} = \frac{0.696 - 0.674}{0.674} \times 100\% = \underline{\underline{3.3\% \text{ error in } y_A}}$

Acetone and ethanol are not structurally similar compounds (as are, for example, pentane and hexane or benzene and toluene). There is consequently no reason to expect Raoult's law to be valid for acetone mole fractions that are not very close to 1.

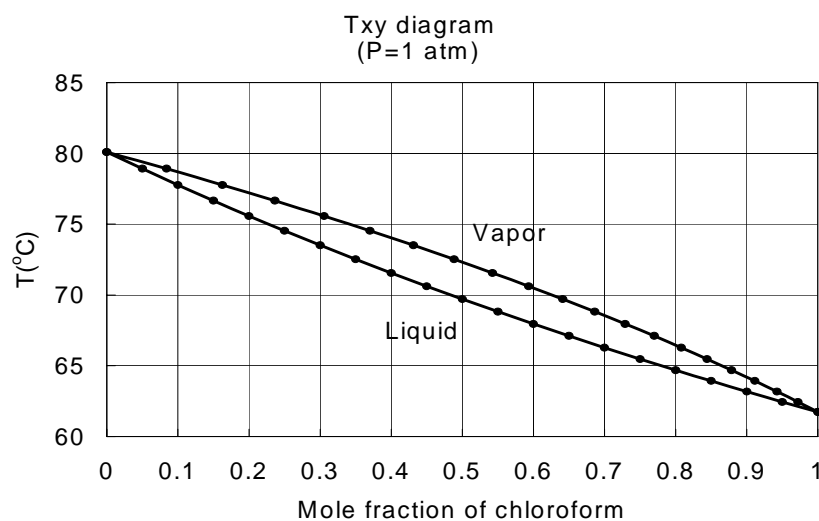


**6.69 a.** B = benzene, C = chloroform. At 1 atm,  $(T_{bp})_B = 80.1^\circ\text{C}$ ,  $(T_{bp})_C = 61.0^\circ\text{C}$

The  $T_{xy}$  diagram should look like Fig. 6.4-1, with the curves converging at  $80.1^\circ\text{C}$  when  $x_C = 0$  and at  $61.0^\circ\text{C}$  when  $x_C = 1$ . (See solution to part c.)

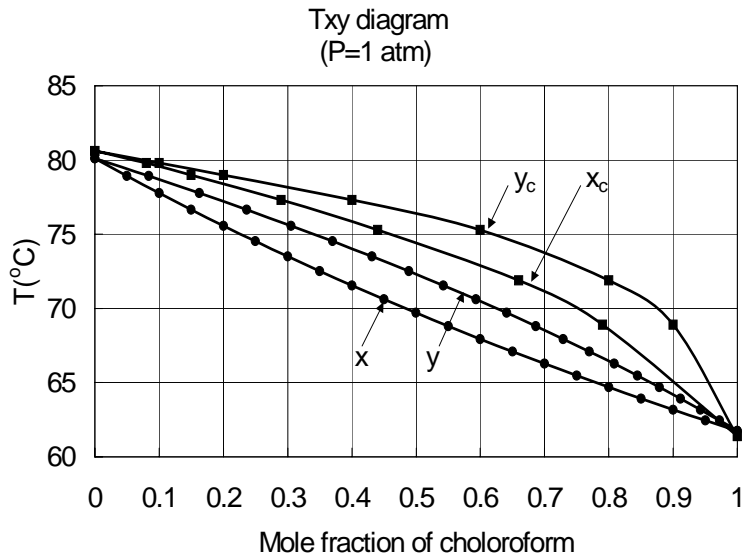
**b.**

Txy Diagram for an Ideal Binary Solution					
	A	B	C		
<b>Chloroform</b>	6.90328	1163.03	227.4		
<b>Benzene</b>	6.89272	1203.531	219.888		
<b>P(mmHg)=</b>	760				
<b>x</b>	<b>T</b>	<b>y</b>	<b>p1</b>	<b>p2</b>	<b>p1+p2</b>
0	80.10	0	0	760	760
0.05	78.92	0.084	63.90	696.13	760.03
0.1	77.77	0.163	123.65	636.28	759.93
0.15	76.66	0.236	179.63	580.34	759.97
0.2	75.58	0.305	232.10	527.86	759.96
0.25	74.53	0.370	281.34	478.59	759.93
0.3	73.51	0.431	327.61	432.30	759.91
0.35	72.52	0.488	371.15	388.79	759.94
0.4	71.56	0.542	412.18	347.85	760.03
0.45	70.62	0.593	450.78	309.20	759.99
0.5	69.71	0.641	487.27	272.79	760.07
0.55	68.82	0.686	521.68	238.38	760.06
0.6	67.95	0.729	554.15	205.83	759.98
0.65	67.11	0.770	585.00	175.10	760.10
0.7	66.28	0.808	614.02	145.94	759.96
0.75	65.48	0.844	641.70	118.36	760.06
0.8	64.69	0.879	667.76	92.17	759.93
0.85	63.93	0.911	692.72	67.35	760.07
0.9	63.18	0.942	716.27	43.75	760.03
0.95	62.45	0.972	738.72	21.33	760.05
1	61.73	1	760	0	760



6.69 (cont'd)

d.



$$\begin{aligned} \text{Raoult's law: } T_{bp} = 71^\circ\text{C}, y = 0.58 \Rightarrow \frac{\Delta T}{T_{\text{actual}}} &= \frac{71 - 75.3}{75.3} \times 100\% = \underline{\underline{-5.7\% \text{ error in } T_{bp}}} \\ \frac{\Delta y}{y_{\text{actual}}} &= \frac{0.58 - 0.60}{0.60} \times 100\% = \underline{\underline{-3.33\% \text{ error in } y}} \end{aligned}$$

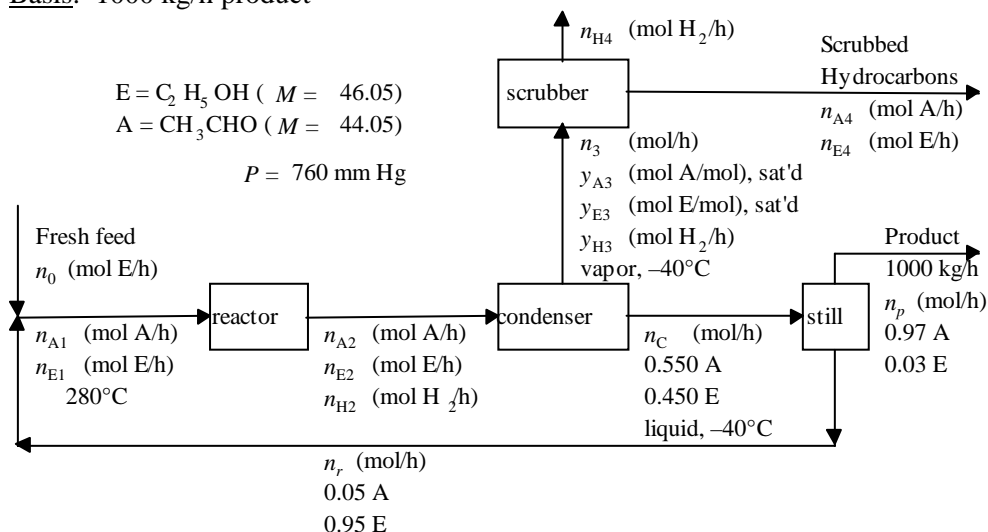
Benzene and chloroform are not structurally similar compounds (as are, for example, pentane and hexane or benzene and toluene). There is consequently no reason to expect Raoult's law to be valid for chloroform mole fractions that are not very close to 1.

$$\begin{aligned} \text{6.70 } P \approx 1 \text{ atm} = 760 \text{ mm Hg} &= x_m p_m^*(T_{bp}) + (1 - x_m) p_P^*(T_{bp}) \\ 760 &= 0.40 \times 10^{7.87863 - 1473.11/(T_{bp} + 230)} + 0.60 \times 10^{7.74416 - 1437.686/(T_{bp} + 198.463)} \xrightarrow{\text{E-Z Solve}} \underline{\underline{T = 79.9^\circ\text{C}}} \end{aligned}$$

We assume (1) the validity of Antoine's equation and Raoult's law, (ii) that pressure head and surface tension effects on the boiling point are negligible.

The liquid temperature will rise until it reaches 79.9 °C, where boiling will commence. The escaping vapor will be richer in methanol and thus the liquid composition will become richer in propanol. The increasing fraction of the less volatile component in the residual liquid will cause the boiling temperature to rise.

**6.71** Basis: 1000 kg/h product



Strategy

- Calculate molar flow rate of product ( $\dot{n}_p$ ) from mass flow rate and composition
- Calculate  $y_{A3}$  and  $y_{E3}$  from Raoult's law:  $y_{H3} = 1 - y_{A3} - y_{E3}$ . Balances about the still involve fewest unknowns ( $\dot{n}_c$  and  $\dot{n}_r$ )
- Total mole balance about still  
A balance about still  $\Rightarrow \dot{n}_c, \dot{n}_r$
- A, E and  $H_2$  balances about scrubber  $\Rightarrow \dot{n}_{A4}, \dot{n}_{E4}$ , and  $\dot{n}_{H4}$  in terms of  $\dot{n}_3$ .  
Overall atomic balances on C, H, and O now involve only 2 unknowns ( $\dot{n}_0, \dot{n}_3$ )
- Overall C balance  
Overall H balance  $\Rightarrow \dot{n}_0, \dot{n}_3$
- A balance about fresh feed-recycle mixing point  $\Rightarrow \dot{n}_{A1}$
- E balance about fresh feed-recycle mixing point  $\Rightarrow \dot{n}_{E1}$
- A, E,  $H_2$  balances about condenser  $\dot{n}_{A2}, \dot{n}_{E2}, \dot{n}_{H2}$
- All desired quantities may now be calculated from known molar flow rates.

**a.** Molar flow rate of product

$$\bar{M} = 0.97 M_A + 0.03 M_E = (0.97)(44.05) + (0.03)(46.05) = 44.11 \text{ g/mol}$$

$$\dot{n}_p = \frac{1000 \text{ kg}}{\text{h}} \left| \frac{1 \text{ kmol}}{44.11 \text{ kg}} \right| = 22.67 \text{ kmol/h}$$

$$\text{Table B.4 (Antoine)} \Rightarrow p_A^*(-40^\circ\text{C}) = 44.8 \text{ mm Hg}$$

$$p_E^*(-40^\circ\text{C}) = 0.360 \text{ mm Hg}$$

Note: The calculations that follow can at best be considered rough estimates, since we are using the Antoine correlations of Table B.4 far outside their temperature ranges of validity.

$$\text{Raoult's law} \Rightarrow y_{A3} = \frac{0.550 p_A^*(-40^\circ\text{C})}{P} = \frac{0.550(44.8)}{760} = 0.03242 \text{ kmol A/kmol}$$

**6.71 (cont'd)**

$$y_{E3} = \frac{0.450 p_E^* (-40^\circ \text{C})}{P} = \frac{0.450(0.360)}{760} = 2.13 \times 10^{-4} \text{ kmol E/kmol}$$

$$y_{H3} = 1 - y_{A3} - y_{E3} = 0.9674 \text{ kmol H}_2/\text{kmol}$$

$$\left. \begin{array}{l} \text{Mole balance about still: } \dot{n}_c = \dot{n}_p + \dot{n}_r \Rightarrow \dot{n}_c = 22.67 + \dot{n}_r \\ \text{A balance about still: } 0.550\dot{n}_c = 0.97(22.67) + 0.05\dot{n}_r \end{array} \right\} \Rightarrow \begin{array}{l} \dot{n}_r = 29.5 \text{ kmol / h recycle} \\ \dot{n}_c = 52.1 \text{ kmol / h} \end{array}$$

$$\text{A balance about scrubber: } \dot{n}_{A4} = \dot{n}_3 y_{A3} = 0.03242\dot{n}_3 \quad (1)$$

$$\text{E balance about scrubber: } \dot{n}_{E4} = \dot{n}_3 y_{E3} = 2.13 \times 10^{-4} \dot{n}_3 \quad (2)$$

$$\text{H}_2 \text{ balance about scrubber: } \dot{n}_{H4} = \dot{n}_3 y_{H3} = 0.9764\dot{n}_3 \quad (3)$$

Overall C balance:

$$\begin{array}{c|c} \dot{n}_0 \text{ (mol E)} & 2 \text{ mol C} \\ \hline \text{h} & 1 \text{ mol E} \end{array} = (\dot{n}_{A4})(2) + (\dot{n}_{E4})(2) + (0.97\dot{n}_p)(2) + (0.03\dot{n}_p)(2)$$

$$\Rightarrow \dot{n}_0 = \dot{n}_{A4} + \dot{n}_{E4} + 22.67 \quad (4)$$

Overall H balance:

$$6\dot{n}_0 = 2\dot{n}_{H4} + 4\dot{n}_{A4} + 6\dot{n}_{E4} + \dot{n}_p [(0.97)(4) + (0.03)(6)] \quad (5)$$

Solve (1)–(5) simultaneously (E-Z Solve):

$$\underline{\dot{n}_0 = 23.4 \text{ kmol E/h (fresh feed), } \dot{n}_{H4} = 22.7 \text{ kmol H}_2/\text{h (in off-gas)}}$$

$$\dot{n}_3 = 23.3 \text{ kmol/h, } \dot{n}_{A4} = 0.755 \text{ kmol A/h, } \dot{n}_{E4} = 0.00496 \text{ kmol E/h}$$

$$\text{A balance about feed mixing point: } \dot{n}_{A1} = 0.05\dot{n}_r = 1.475 \text{ kmol A/h}$$

$$\text{E balance about feed mixing point: } \dot{n}_{E1} = \dot{n}_0 + 0.95\dot{n}_r = 51.5 \text{ kmol E/h}$$

$$\text{E balance about condenser: } \dot{n}_{E2} = \dot{n}_3 y_{E3} + 0.450\dot{n}_c = 23.5 \text{ kmol E/h}$$

Ideal gas equation of state :

$$V_{\text{reactor feed}} = \frac{(1.47 + 51.5) \text{ kmol}}{\text{h}} \left| \frac{22.4 \text{ m}^3 (\text{STP})}{1 \text{ kmol}} \right| \left| \frac{(273+280) \text{ K}}{273 \text{ K}} \right| = \underline{\underline{2.40 \times 10^3 \text{ m}^3/\text{h}}}$$

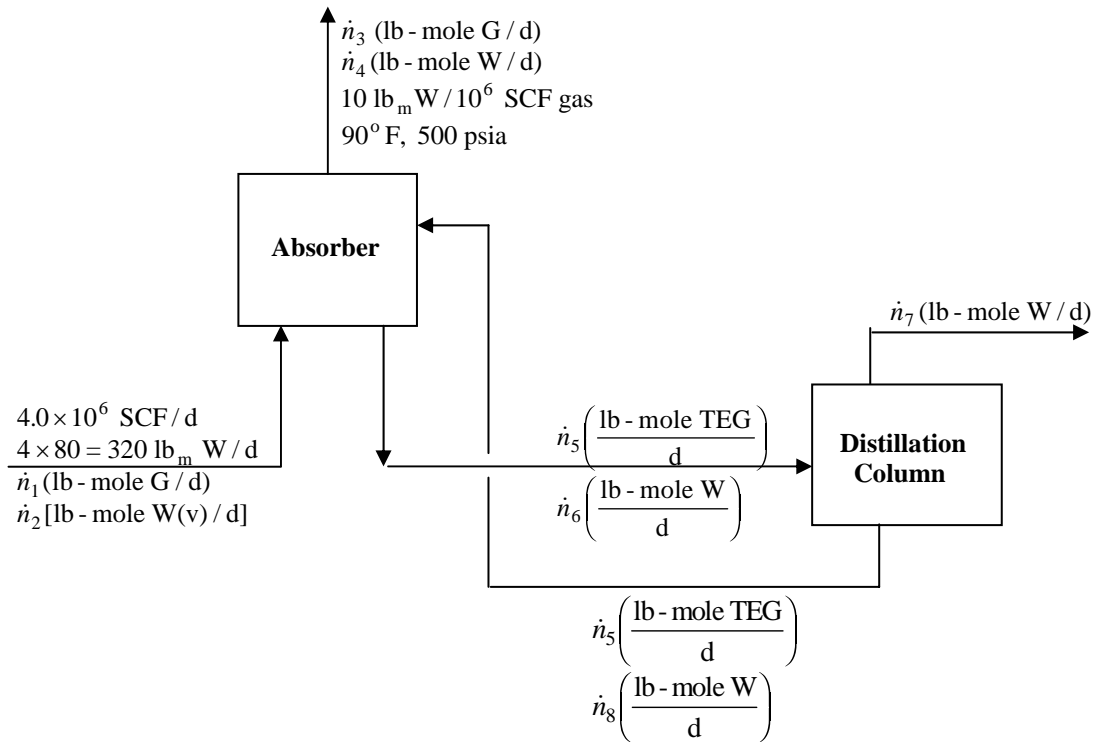
$$\text{b. Overall conversion} = \frac{\dot{n}_0 - 0.03\dot{n}_p}{\dot{n}_0} \times 100\% = \frac{23.4 - (0.03)(22.67)}{23.4} \times 100\% = \underline{\underline{97\%}}$$

$$\text{Single-pass conversion} = \frac{\dot{n}_{E1} - \dot{n}_{E2}}{\dot{n}_{E1}} \times 100\% = \frac{51.5 - 23.5}{51.5} \times 100\% = \underline{\underline{54\%}}$$

$$\text{Feed rate of A to scrubber: } \underline{\underline{\dot{n}_{A4} = 0.76 \text{ kmol A/h}}}$$

$$\text{Feed rate of E to scrubber: } \underline{\underline{\dot{n}_{E4} = 0.0050 \text{ kmol E/h}}}$$

6.72 a. G = dry natural gas, W = water



Overall system D.F. analysis:    5 unknowns ( $\dot{n}_1, \dot{n}_2, \dot{n}_3, \dot{n}_4, \dot{n}_7$ )  
 – 2 feed specifications (total flow rate, flow rate of water)  
 – 1 water content of dried gas  
 – 2 balances (W, G)  
0 D.F.

Water feed rate:  $\dot{n}_2 = \frac{320 \text{ lb}_m \text{ W}}{\text{d}} \left| \frac{1 \text{ lb - mole}}{18.0 \text{ lb}_m} \right| = 17.78 \text{ lb - moles W / d}$

Dry gas feed rate:

$$\dot{n}_1 = \frac{4.0 \times 10^6 \text{ SCF}}{\text{d}} \left| \frac{1 \text{ lb - mole}}{359 \text{ SCF}} \right| - 17.78 \frac{\text{lb - moles W}}{\text{d}} = 1.112 \times 10^4 \text{ lb - moles G / d}$$

Overall G balance:  $\dot{n}_1 = \dot{n}_3 \Rightarrow \dot{n}_3 = 1.112 \times 10^4 \text{ lb - moles G / d}$

Flow rate of water in dried gas:

$$\dot{n}_4 = \frac{(\dot{n}_3 + \dot{n}_4) \text{ lb - moles}}{\text{d}} \left| \frac{359 \text{ SCF gas}}{\text{lb - mole}} \right| \left| \frac{10 \text{ lb}_m \text{ W}}{10^6 \text{ SCF}} \right| \left| \frac{1 \text{ lb - mole W}}{18.0 \text{ lb}_m} \right|$$

$$\xrightarrow{\dot{n}_3 = 1.112 \times 10^4} \dot{n}_4 = 2.218 \text{ lb - mole W(l) / d}$$

Overall W balance:

$$\dot{n}_7 = \frac{(17.78 - 2.218) \text{ lb - moles W}}{\text{d}} \left| \frac{18.0 \text{ lb}_m}{1 \text{ lb - mole}} \right| = 280 \frac{\text{lb}_m \text{ W}}{\text{d}} \times \left( \frac{1 \text{ ft}^3}{62.4 \text{ lb}_m} \right) = 4.5 \frac{\text{ft}^3 \text{ W}}{\text{d}}$$

### 6.72 (cont'd)

- b. Mole fraction of water in dried gas =

$$y_w = \frac{\dot{n}_4}{\dot{n}_3 + \dot{n}_4} = \frac{2.218 \text{ lb - moles W / d}}{(2.218 + 1.112 \times 10^4) \text{ lb - moles / d}} = 1.99 \times 10^{-4} \frac{\text{lb - moles W(v)}}{\text{lb - mole}}$$

Henry's law:  $y_w P = H_w x_w \Rightarrow$

$$(x_w)_{\max} = \frac{(1.99 \times 10^{-4})(500 \text{ psia})(1 \text{ atm} / 14.7 \text{ psia})}{0.398 \text{ atm / mole fraction}} = 0.0170 \frac{\text{lb - mole dissolved W}}{\text{lb - mole solution}}$$

- c. Solvent/solute mole ratio

$$\frac{\dot{n}_5}{\dot{n}_2 - \dot{n}_4} = \frac{37 \text{ lb}_m \text{ TEG}}{\text{lb}_m \text{ W}} \bigg| \frac{1 \text{ lb - mole TEG}}{150.2 \text{ lb}_m \text{ TEG}} \bigg| \frac{18.0 \text{ lb}_m \text{ W}}{1 \text{ lb}_m \text{ W}} = 4.434 \frac{\text{lb - mole TEG}}{\text{lb - mole W absorbed}}$$

$$\Rightarrow \dot{n}_5 = 4.434(17.78 - 2.22) = 69.0 \text{ lb - moles TEG / d}$$

$$(x_w)_{\text{in}} = 0.80(0.0170) = 0.0136 \frac{\text{lb-mole W}}{\text{lb-mole}} = \frac{\dot{n}_8}{\dot{n}_5 + \dot{n}_8} \xrightarrow{\dot{n}_5 = 69.0} \dot{n}_8 = 0.951 \text{ lb-mole W/d}$$

Solvent stream entering absorber

$$\dot{m} = \frac{0.951 \text{ lb - moles W}}{\text{d}} \bigg| \frac{18.0 \text{ lb}_m}{\text{lb - mole}} + \frac{69.0 \text{ lb - moles TEG}}{\text{d}} \bigg| \frac{150.2 \text{ lb}_m}{\text{lb - mole}}$$

$$= \underline{\underline{1.04 \times 10^4 \text{ lb}_m / \text{d}}}$$

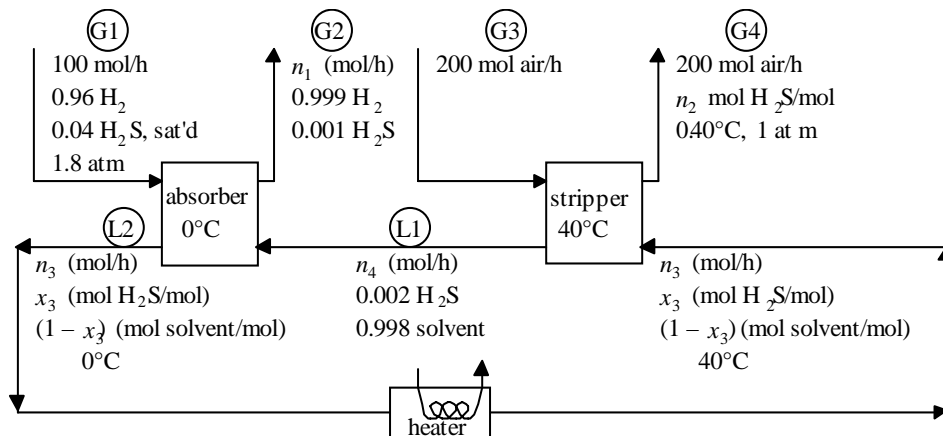
W balance on absorber

$$\dot{n}_6 = (17.78 + 0.95 - 2.22) \text{ lb-moles W/d} = 16.51 \text{ lb-moles W/d}$$

$$\Rightarrow (x_w)_{\text{out}} = \frac{16.51 \text{ lb-moles W/d}}{(16.51 + 69.9) \text{ lb-moles/d}} = \underline{\underline{0.19 \text{ lb-mole W/lb-mole}}}$$

- d. The distillation column recovers the solvent for subsequent re-use in the absorber.

### 6.73 Basis: Given feed rates



### 6.73 (cont'd)

Equilibrium condition: At G1,  $p_{\text{H}_2\text{S}} = (0.04)(1.8 \text{ atm}) = 0.072 \text{ atm}$

$$\Rightarrow x_3 = \frac{p_{\text{H}_2\text{S}}}{H_{\text{H}_2\text{S}}} = \frac{0.072 \text{ atm}}{27 \text{ atm/mol fraction}} = 2.67 \times 10^{-3} \text{ mole H}_2\text{S/mole}$$

Strategy: Overall  $\text{H}_2$  and  $\text{H}_2\text{S}$  balances  $\Rightarrow \dot{n}_1, \dot{n}_2$

$\dot{n}_2 + \text{air flow rate} \Rightarrow \text{volumetric flow rate at G4}$

$\text{H}_2\text{S}$  and solvent balances around absorber  $\Rightarrow \dot{n}_3, \dot{n}_4$

$0.998\dot{n}_4 = \text{solvent flow rate}$

Overall  $\text{H}_2$  balance:  $(100)(0.96) = 0.999\dot{n}_1 \Rightarrow \dot{n}_1 = 96.1 \text{ mol/h}$

Overall  $\text{H}_2\text{S}$  balance:  $(100)(0.04) = 0.001\dot{n}_1 + \dot{n}_2 \xrightarrow{\dot{n}_1=96.1} \dot{n}_2 = 3.90 \text{ mol H}_2\text{S/h}$

Volumetric flow rate at stripper outlet

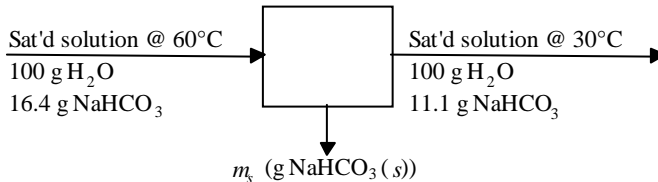
$$\dot{V}_{\text{G4}} = \frac{(200 + 3.90) \text{ mol}}{\text{h}} \left| \frac{22.4 \text{ liters(STP)}}{1 \text{ mol}} \right| \left| \frac{(273 + 40) \text{ K}}{273 \text{ K}} \right| = \underline{\underline{5240 \text{ L/hr}}}$$

$\text{H}_2\text{S}$  and solvent balances around absorber:

$$\left. \begin{aligned} (100)(0.04) + 0.002\dot{n}_4 &= 0.001\dot{n}_1 + \dot{n}_3 x_3 \Rightarrow \dot{n}_4 = 1.335\dot{n}_3 - 1952 \\ 0.998\dot{n}_4 &= \dot{n}_3(1 - 2.67 \times 10^{-3}) \end{aligned} \right\} \Rightarrow \dot{n}_3 \approx \dot{n}_4 = 5830 \text{ mol/h}$$

Solvent flow rate  $= 0.998\dot{n}_4 = \underline{\underline{5820 \text{ mol solvent/h}}}$

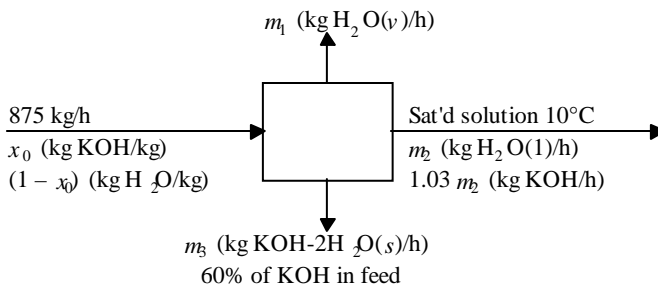
### 6.74 Basis: 100 g $\text{H}_2\text{O}$



$\text{NaHCO}_3$  balance  $\Rightarrow 16.4 = 11.1 + m_s \Rightarrow m_s = 5.3 \text{ g NaHCO}_3(\text{s})$

$$\underline{\underline{\% \text{ crystallization}}} = \frac{5.3 \text{ g crystallized}}{16.4 \text{ g fed}} \times 100\% = \underline{\underline{32.3\%}}$$

### 6.75 Basis: 875 kg/h feed solution



**6.75 (cont'd)**

Analysis of feed:  $2\text{KOH} + \text{H}_2\text{SO}_4 \rightarrow \text{K}_2\text{SO}_4 + 2\text{H}_2\text{O}$

$$x_0 = \frac{22.4 \text{ mL H}_2\text{SO}_4(\text{l})}{5 \text{ g feed soln}} \left| \frac{1 \text{ L}}{10^3 \text{ mL}} \right| \frac{0.85 \text{ mol H}_2\text{SO}_4}{\text{L}} \left| \frac{2 \text{ mol KOH}}{1 \text{ mol H}_2\text{SO}_4} \right| \frac{56.11 \text{ g KOH}}{1 \text{ mol KOH}} = 0.427 \text{ g KOH/g feed}$$

60% recovery:  $875(0.427)(0.60) = 224.2 \text{ kg KOH/h}$

$$m_3 = \frac{224.2 \text{ kg KOH}}{\text{h}} \left| \frac{92.15 \text{ kg KOH} \cdot 2\text{H}_2\text{O}}{56.11 \text{ kg KOH}} \right| = 368.2 \text{ kg KOH} \cdot 2\text{H}_2\text{O/h} \text{ (143.8 kg H}_2\text{O/h)}$$

KOH balance:  $0.427(875) = 224.2 + 1.03m_2 \Rightarrow m_2 = 145.1 \text{ kg/h}$

Total mass balance:  $875 = 368.2 + 2.03(145.1) + m_1 \Rightarrow m_1 = 212 \text{ kg H}_2\text{O/h evaporated}$

**6.76 a.**

$$C_A = \frac{\text{g A dissolved}}{\text{mL solution}} \quad \begin{array}{c|c|c|c} R & 0 & 30 & 45 \\ \hline C_A & 0 & 0.200 & 0.300 \end{array}$$

Plot  $C_A$  vs.  $R \Rightarrow C_A = R / 150$

**b. Mass of solution:**  $\frac{500 \text{ mol}}{\text{ml}} \left| \frac{1.10 \text{ g}}{\text{ml}} \right| = 550 \text{ g (160 g A, 390 g S)}$

The initial solution is saturated at  $10.2^\circ\text{C}$ .

Solubility @  $10.2^\circ\text{C}$   $= \frac{160 \text{ g A}}{390 \text{ g S}} = 0.410 \text{ g A/g S} = 41.0 \text{ g A/100 g S @ } 10.2^\circ\text{C}$

At  $0^\circ\text{C}$ ,  $R = 17.5 \Rightarrow C_A = \frac{17.5/150 \text{ g A}}{\text{mL soln}} \left| \frac{1 \text{ mL soln}}{1.10 \text{ g soln}} \right| = 0.106 \text{ g A/g soln}$

Thus 1 g of solution saturated at  $0^\circ\text{C}$  contains 0.106 g A & 0.894 g S.

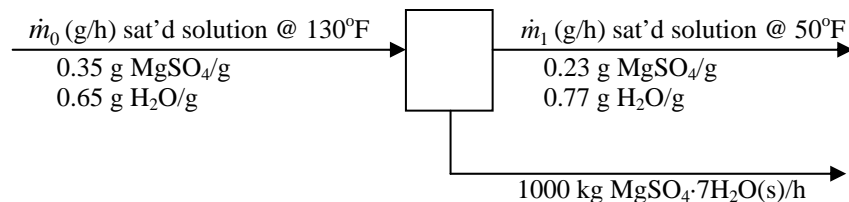
Solubility @  $0^\circ\text{C}$   $\frac{0.106 \text{ g A}}{0.894 \text{ g S}} = 0.118 \text{ g A/g S} = 11.8 \text{ g A/100 g S @ } 0^\circ\text{C}$

Mass of solid A:  $160 \text{ g A} - \frac{390 \text{ g S}}{\text{100 g S}} \left| \frac{11.8 \text{ g A}}{\text{100 g S}} \right| = 114 \text{ g A(s)}$

**c.**  $\frac{\text{g A initial}}{(160 - 114) \text{ g A}} - \frac{\text{g A remaining in soln}}{0.5 \times 390 \text{ g S}} \left| \frac{11.8 \text{ g A}}{100 \text{ g S}} \right| = 23.0 \text{ g A(s)}$

**6.77 a.** Table 6.5-1 shows that at  $50^\circ\text{F}$  ( $10.0^\circ\text{C}$ ), the salt that crystallizes is  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ , which contains 48.8 wt%  $\text{MgSO}_4$ .

**b. Basis:** 1000 kg crystals/h.





**6.77 (cont'd)**

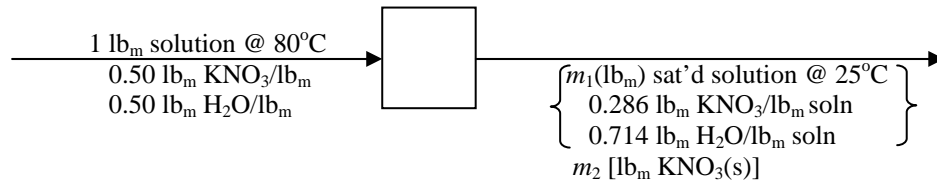
$$\left. \begin{array}{l} \text{Mass balance: } \dot{m}_0 = \dot{m}_1 + 1000 \text{ kg / h} \\ \text{MgSO}_4 \text{ balance: } 0.35\dot{m}_0 = 0.23\dot{m}_1 + 0.488(1000) \text{ kg MgSO}_4 / \text{h} \end{array} \right\} \Rightarrow \frac{\dot{m}_0 = 2150 \text{ kg feed / h}}{\dot{m}_1 = 1150 \text{ kg soln / h}}$$

$$\text{The crystals would yield } 0.488 \times 1000 \text{ kg / h} = 488 \frac{\text{kg anhydrous MgSO}_4}{\text{h}}$$

**6.78** Basis: 1 lb<sub>m</sub> feed solution.

Figure 6.5-1  $\Rightarrow$  a saturated KNO<sub>3</sub> solution at 25°C contains 40 g KNO<sub>3</sub>/100 g H<sub>2</sub>O

$$\Rightarrow x_{\text{KNO}_3} = \frac{40 \text{ g KNO}_3}{(40 + 100) \text{ g solution}} = 0.286 \text{ g KNO}_3 / \text{g} = 0.286 \text{ lb}_m \text{ KNO}_3 / \text{lb}_m x$$



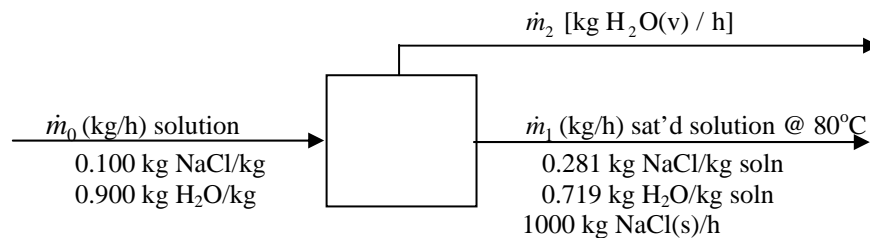
$$\left. \begin{array}{l} \text{Mass balance: } 1 \text{ lb}_m = m_1 + m_2 \\ \text{KNO}_3 \text{ balance: } 0.50 \text{ lb}_m \text{ KNO}_3 = 0.286m_1 + m_2 \end{array} \right\} \Rightarrow \frac{m_1 = 0.700 \text{ lb}_m \text{ solution / lb}_m \text{ feed}}{m_2 = 0.300 \text{ lb}_m \text{ crystals / lb}_m \text{ feed}}$$

$$\text{Solid / liquid mass ratio} = \frac{0.300 \text{ lb}_m \text{ crystals / lb}_m \text{ feed}}{0.700 \text{ lb}_m \text{ solution / lb}_m \text{ feed}} = 0.429 \text{ lb}_m \text{ crystals / lb}_m \text{ solution}$$

**6.79 a.** Basis: 1000 kg NaCl(s)/h.

Figure 6.5-1  $\Rightarrow$  a saturated NaCl solution at 80°C contains 39 g NaCl/100 g H<sub>2</sub>O

$$\Rightarrow x_{\text{NaCl}} = \frac{39 \text{ g NaCl}}{(39 + 100) \text{ g solution}} = 0.281 \text{ g NaCl / g} = 0.281 \text{ kg NaCl / kg}$$



$$\left. \begin{array}{l} \text{Mass balance: } \dot{m}_0 = \dot{m}_1 + \dot{m}_2 \\ \text{NaCl balance: } 0.100 \text{ kg NaCl} = 0.281\dot{m}_1 + \dot{m}_2 \end{array} \right\} \Rightarrow \frac{\dot{m}_1 = 0.700 \text{ lb}_m \text{ solution / lb}_m \text{ feed}}{\dot{m}_2 = 0.300 \text{ lb}_m \text{ crystals / lb}_m \text{ feed}}$$

$$\text{Solid / liquid mass ratio} = \frac{0.300 \text{ lb}_m \text{ crystals / lb}_m \text{ feed}}{0.700 \text{ lb}_m \text{ solution / lb}_m \text{ feed}} = 0.429 \text{ lb}_m \text{ crystals / lb}_m \text{ solution}$$

The minimum feed rate would be that for which all of the water in the feed evaporates to produce solid NaCl at the specified rate. In this case

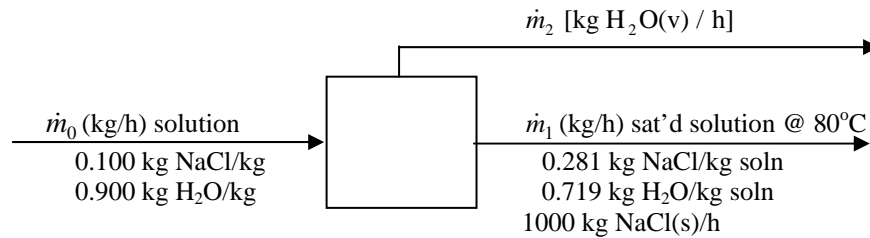
### 6.79 (cont'd)

$$0.100(\dot{m}_0)_{\min} = 1000 \text{ kg NaCl} / \text{h} \Rightarrow (\dot{m}_0)_{\min} = \underline{\underline{10,000 \text{ kg} / \text{min}}}$$

$$\text{Evaporation rate: } \underline{\underline{\dot{m}_2 = 9000 \text{ kg H}_2\text{O} / \text{h}}}$$

$$\text{Exit solution flow rate: } \underline{\underline{\dot{m}_1 = 0}}$$

b.



$$\underline{\underline{40\% \text{ solids content in slurry}}} \Rightarrow 1000 \frac{\text{kg NaCl}}{\text{h}} = 0.400(\dot{m}_1)_{\max} \Rightarrow (\dot{m}_1)_{\max} = \underline{\underline{2500 \frac{\text{kg}}{\text{h}}}}$$

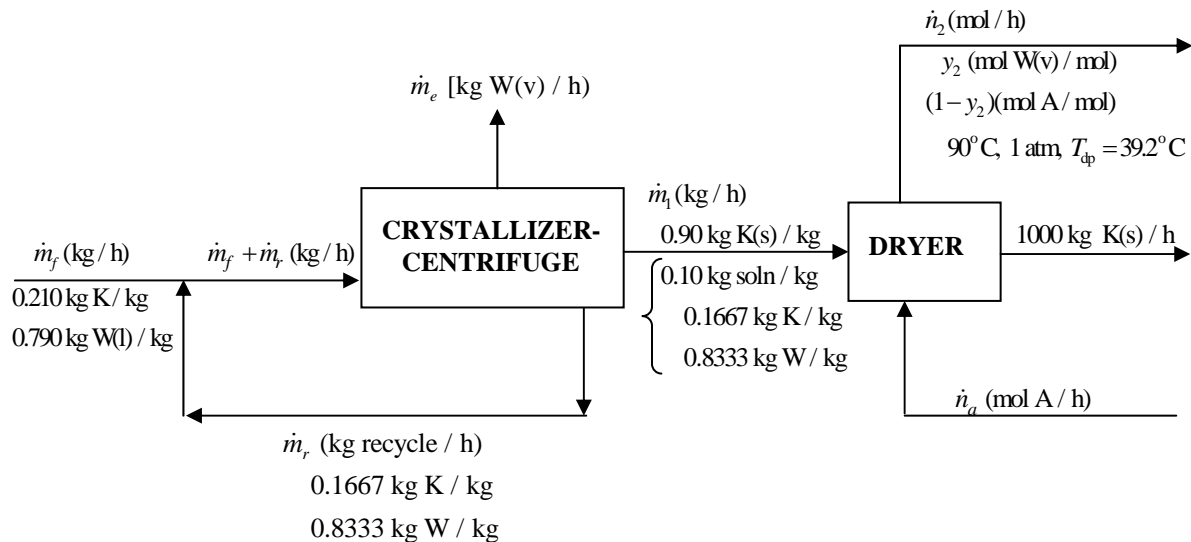
$$\underline{\underline{\text{NaCl balance: } 0.100\dot{m}_0 = 0.281(2500) \Rightarrow \dot{m}_0 = 7025 \text{ kg} / \text{h}}}$$

$$\underline{\underline{\text{Mass balance: } \dot{m}_0 = 2500 + \dot{m}_2 \Rightarrow \dot{m}_2 = 4525 \text{ kg H}_2\text{O evaporate} / \text{h}}}$$

**6.80 Basis:** 1000 kg  $\text{K}_2\text{Cr}_2\text{O}_7(\text{s})/\text{h}$ . Let K =  $\text{K}_2\text{Cr}_2\text{O}_7$ , A = dry air, S = solution, W = water.

Composition of saturated solution:

$$\frac{0.20 \text{ kg K}}{\text{kg W}} \Rightarrow \frac{0.20 \text{ kg K}}{(1 + 0.20) \text{ kg soln}} = 0.1667 \text{ kg K/kg soln}$$



$$\underline{\underline{\text{Dryer outlet gas: } y_2 P = p_w^*(39.2^\circ\text{C}) \Rightarrow y_2 = \frac{53.01 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.0698 \text{ mol W/mol}}}$$

$$\underline{\underline{\text{Overall K balance: } 0.210\dot{m}_f = 1000 \text{ kg K/h} \Rightarrow \dot{m}_f = \underline{\underline{4760 \text{ kg/h feed solution}}}}}$$

**6.80 (cont'd)**

K balance on dryer:  $0.90\dot{m}_1 + (0.1667)(0.10\dot{m}_1) = 1000 \text{ kg/h} \Rightarrow \dot{m}_1 = 1090 \text{ kg/h}$

Mass balance around crystallizer-centrifuge

$$\dot{m}_f + \dot{m}_r = \dot{m}_e + \dot{m}_1 + \dot{m}_r \Rightarrow \dot{m}_e = 4760 - 1090 = \underline{\underline{3670 \text{ kg/h water evaporated}}}$$

$$\begin{array}{l} \text{95\% solution recycled} \Rightarrow \dot{m}_r = \frac{(0.10 \times 1090) \text{ kg/h not recycled}}{\quad \quad \quad} \left| \begin{array}{l} 95 \text{ kg recycled} \\ 5 \text{ kg not recycled} \end{array} \right. \\ \quad \quad \quad = \underline{\underline{2070 \text{ kg/h recycled}}} \end{array}$$

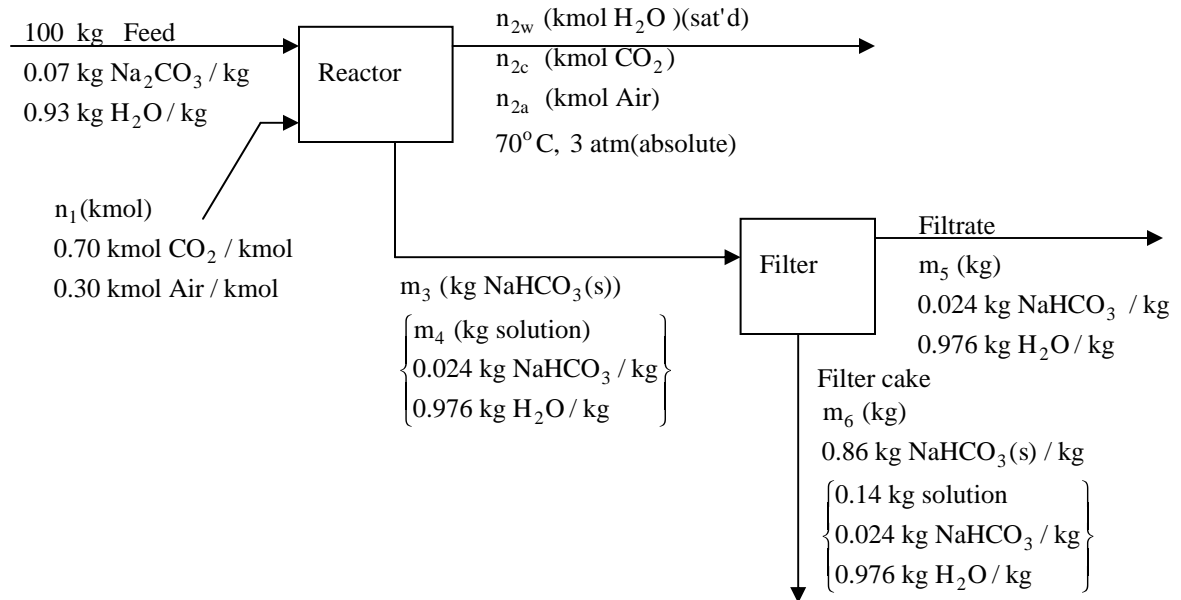
Water balance on dryer

$$\frac{(0.8333)(0.10)(1090) \text{ kg W/h}}{18.01 \times 10^{-3} \text{ kg/mol}} = 0.0698\dot{n}_2 \Rightarrow \dot{n}_2 = 7.225 \times 10^4 \text{ mol/h}$$

Dry air balance on dryer

$$\dot{n}_a = \frac{(1 - 0.0698)7.225 \times 10^4 \text{ mol}}{\text{h}} \left| \frac{22.4 \text{ L(STP)}}{1 \text{ mol}} \right. = \underline{\underline{1.51 \times 10^6 \text{ L(STP)/h}}}$$

**6.81. Basis :** 100 kg liquid feed. Assume  $P_{\text{atm}}=1$  atm



Degree of freedom analysis:

Reactor

6 unknowns ( $n_1, n_2, y_{2w}, y_{2c}, m_3, m_4$ )  
 -4 atomic species balances (Na, C, O, H)  
 -1 air balance  
-1 (Raoult's law for water)  
 0 DF

Filter

2 unknowns  
-2 balances  
 0 DF

Na balance on reactor

$$\begin{array}{c|c|c|c|c} 100 \text{ kg} & 0.07 \text{ kg Na}_2\text{CO}_3 & 46 \text{ kg Na} & = & (m_3 + 0.024m_4) \text{ kg NaHCO}_3 \\ & \text{kg} & 106 \text{ kg Na}_2\text{CO}_3 & & 23 \text{ kg Na} \\ & & & & 84 \text{ kg NaHCO}_3 \end{array}$$

$$\Rightarrow 3.038 = 0.2738(m_3 + 0.024m_4) \quad (1)$$

Air balance:  $0.300n_1 = n_{2a} \quad (2)$

C balance on reactor :

$$\begin{array}{c|c|c|c|c|c} n_1 \text{ (kmol)} & 0.700 \text{ kmol CO}_2 & 12 \text{ kg C} & + & 100 \text{ kg} & 0.07 \text{ kg Na}_2\text{CO}_3 \\ & \text{kmol} & 1 \text{ kmol CO}_2 & & & \text{kg} \\ & & & & & 106 \text{ kg Na}_2\text{CO}_3 \end{array}$$

$$= (n_{2c})(12) + (m_3 + 0.024m_4)\left(\frac{12}{84}\right) \Rightarrow 8.40n_1 + 0.7924 = 12n_{2c} + 0.1429(m_3 + 0.024m_4) \quad (3)$$

H balance :

$$(100)(0.93)\left(\frac{2}{18}\right) = (n_{2w})(2) + (m_3 + 0.024m_4)\left(\frac{1}{84}\right) + 0.976m_4\left(\frac{2}{18}\right)$$

$$\Rightarrow 10.33 = 2n_{2w} + 0.01190(m_3 + 0.024m_4) + 0.1084m_4 \quad (4)$$

**6.81(cont'd)**

O balance (not counting O in the air):

$$\begin{aligned}
 n_1(0.700)(932) + 100(0.07)\left(\frac{48}{106}\right) + 100(0.93)\left(\frac{16}{18}\right) \\
 = (n_{2w})(16) + n_{2c}(32) + (m_3 + 0.024m_4)\left(\frac{48}{84}\right) + 0.976m_4\left(\frac{16}{18}\right) \\
 \Rightarrow 22.4n_1 + 85.84 = 16n_{2w} + 32n_{2c} + 0.5714(m_3 + 0.024m_4) + 0.8676m_4 \quad (5)
 \end{aligned}$$

Raoult's Law :

$$\begin{aligned}
 y_w P = p_w^*(70^\circ \text{C}) \Rightarrow \frac{n_{2w}}{n_{2w} + n_{2c} + n_{2a}} = \frac{233.7 \text{ mm Hg}}{(3 * 760) \text{ mm Hg}} \\
 \Rightarrow n_{2w} = 0.1025(n_{2w} + n_{2c} + n_{2a}) \quad (6)
 \end{aligned}$$

Solve (1)-(6) simultaneously with E-Z solve (need a good set of starting values to converge).

$$\begin{aligned}
 n_1 = 0.8086 \text{ kmol}, \quad n_{2a} = 0.2426 \text{ kmol air}, \quad n_{2c} = 0.500 \text{ kmol CO}_2, \\
 n_{2w} = 0.0848 \text{ kmol H}_2\text{O(v)}, \quad m_3 = 8.874 \text{ kg NaHCO}_3(\text{s}), \quad m_4 = 92.50 \text{ kg solution}
 \end{aligned}$$

NaHCO<sub>3</sub> balance on filter:

$$\begin{aligned}
 m_3 + 0.024m_4 &= 0.024m_5 + m_6[0.86 + (0.14)(0.024)] \\
 \xrightarrow[m_4=92.50]{m_3=8.874} 11.09 &= 0.024m_5 + 0.8634m_6 \quad (7)
 \end{aligned}$$

$$\text{Mass Balance on filter: } 8.874 + 92.50 = 101.4 = m_5 + m_6 \quad (8)$$

$$\begin{aligned}
 \text{Solve (7) \& (8)} \Rightarrow \begin{matrix} m_5 = 91.09 \text{ kg filtrate} \\ m_6 = 10.31 \text{ kg filter cake} \end{matrix} \Rightarrow (0.86)(10.31) = 8.867 \text{ kg NaHCO}_3(\text{s})
 \end{aligned}$$

$$\text{Scale factor} = \frac{500 \text{ kg / h}}{8.867 \text{ kg}} = 56.39 \text{ h}^{-1}$$

**(a)** Gas stream leaving reactor

$$\begin{aligned}
 \left. \begin{aligned} \dot{n}_{2w} &= (0.0848)(56.39) = 4.78 \text{ kmol H}_2\text{O(v) / h} \\ \dot{n}_{2c} &= (0.500)(56.39) = 28.2 \text{ kmol O}_2 \text{ / h} \\ \dot{n}_{2a} &= (0.2426)(56.39) = 13.7 \text{ kmol air / h} \end{aligned} \right\} \Rightarrow \begin{cases} 46.7 \text{ kmol / h} \\ 0.102 \text{ kmol H}_2\text{O(v) / kmol} \\ 0.604 \text{ kmol CO}_2 \text{ / kmol} \\ 0.293 \text{ kmol Air / kmol} \end{cases}
 \end{aligned}$$

$$\dot{V}_2 = \frac{\dot{n}_2 RT}{P} = \frac{(46.7 \text{ kmol / h})(0.08206 \frac{\text{m}^3 \text{atm}}{\text{kmol} \cdot \text{K}})(343 \text{ K})}{3 \text{ atm}} = \underline{\underline{438 \text{ m}^3 \text{ / h}}}$$

$$\text{(b) Gas feed rate: } \dot{V}_1 = \frac{56.39 \times 0.8086 \text{ kmol}}{\text{h}} \bigg| \frac{22.4 \text{ m}^3(\text{STP})}{\text{kmol}} \bigg| \frac{1 \text{ h}}{60 \text{ min}} = \underline{\underline{17.0 \text{ SCMM}}}$$

**6.81(cont'd)**

(c) Liquid feed:  $(100)(56.39) = \underline{\underline{5640 \text{ kg/h}}}$

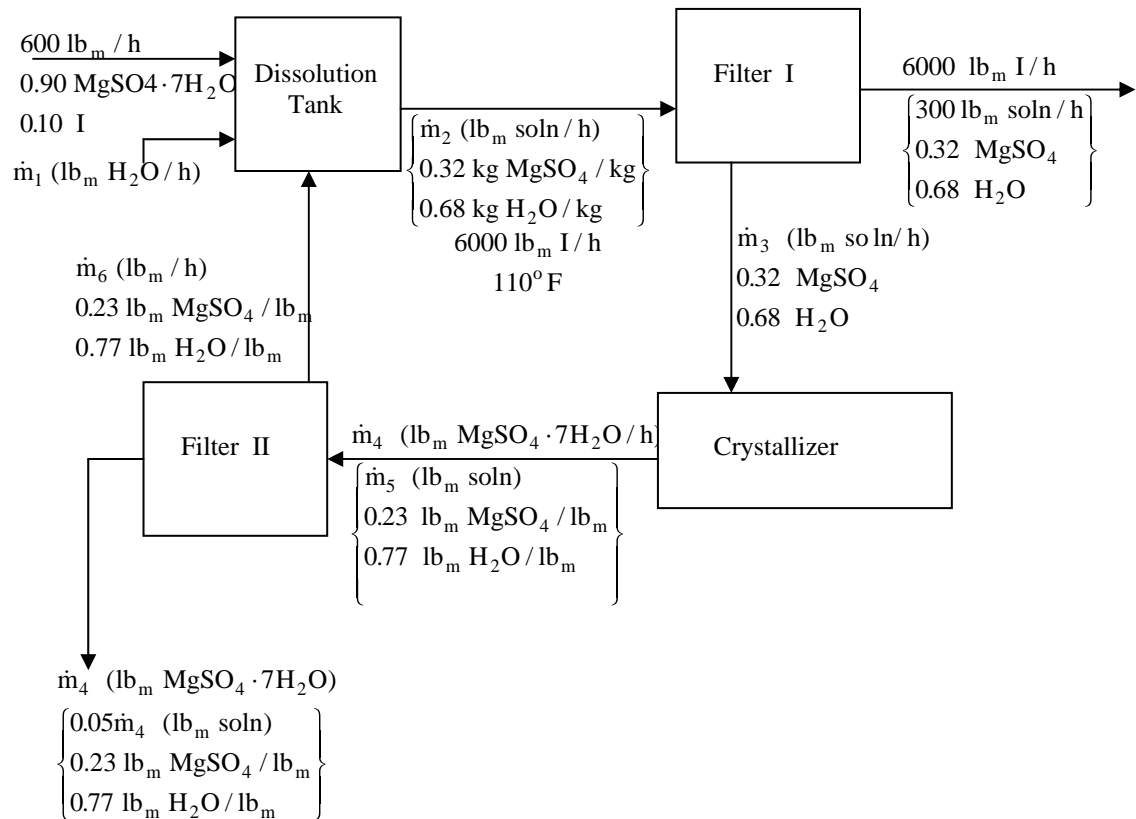
To calculate  $\dot{V}$ , we would need to know the density of a 7 wt% aqueous  $\text{Na}_2\text{CO}_3$  solution.

(d) If T dropped in the filter, more solid  $\text{NaHCO}_3$  would be recovered and the residual solution would contain less than 2.4%  $\text{NaHCO}_3$ .

(e)

Benefit: Higher pressure  $\Rightarrow$  greater  $p_{\text{CO}_2}$   $\xRightarrow{\text{Henry's law}}$  higher concentration of  $\text{CO}_2$  in solution  
 $\Rightarrow$  higher rate of reaction  $\Rightarrow$  smaller reactor needed to get the same conversion  $\Rightarrow$  lower cost  
Penalty: Higher pressure  $\Rightarrow$  greater cost of compressing the gas (purchase cost of compressor, power consumption)

**6.82**



a. Heating the solution dissolves all  $\text{MgSO}_4$ ; filtering removes I, and cooling recrystallizes  $\text{MgSO}_4$  enabling subsequent recovery.

(b) Strategy: Do D.F analysis.

6.82(cont'd)

$$\left. \begin{array}{l} \text{Overall mass balance} \\ \text{Overall MgSO}_4 \text{ balance} \end{array} \right\} \Rightarrow \dot{m}_1, \dot{m}_4 \quad \left. \begin{array}{l} \text{Diss. tank overall mass balance} \\ \text{Diss. tank MgSO}_4 \text{ balance} \end{array} \right\} \Rightarrow \dot{m}_2, \dot{m}_6$$

$$(MW)_{\text{MgSO}_4} = (24.31 + 32.06 + 64.00) = 120.37, (MW)_{\text{MgSO}_4 \cdot 7\text{H}_2\text{O}} = (120.37 + 7 \cdot 18.01) = 246.44$$

Overall  $\text{MgSO}_4$  balance:

$$\begin{array}{c|c|c} 60,000 \text{ lb}_m & 0.90 \text{ lb}_m \text{ MgSO}_4 \cdot 7\text{H}_2\text{O} & 120.37 \text{ lb}_m \text{ MgSO}_4 \\ \hline \text{h} & \text{lb}_m & 246.44 \text{ lb}_m \text{ MgSO}_4 \cdot 7\text{H}_2\text{O} \end{array}$$

$$= (300 \text{ lb}_m / \text{h})(0.32 \text{ lb}_m \text{ MgSO}_4 / \text{lb}_m) + \dot{m}_4 (120.37 / 246.44) + 0.05\dot{m}_4 (0.23)$$

$$\Rightarrow \dot{m}_4 = 5.257 \times 10^4 \text{ lb}_m \text{ crystals} / \text{h}$$

$$\dot{m}_4 = 5.257 \times 10^4 \text{ lb}_m / \text{h}$$

Overall mass balance:  $60,000 + \dot{m}_1 = 6300 + 1.05\dot{m}_4 \Rightarrow \dot{m}_1 = 1494 \text{ lb}_m \text{ H}_2\text{O} / \text{h}$

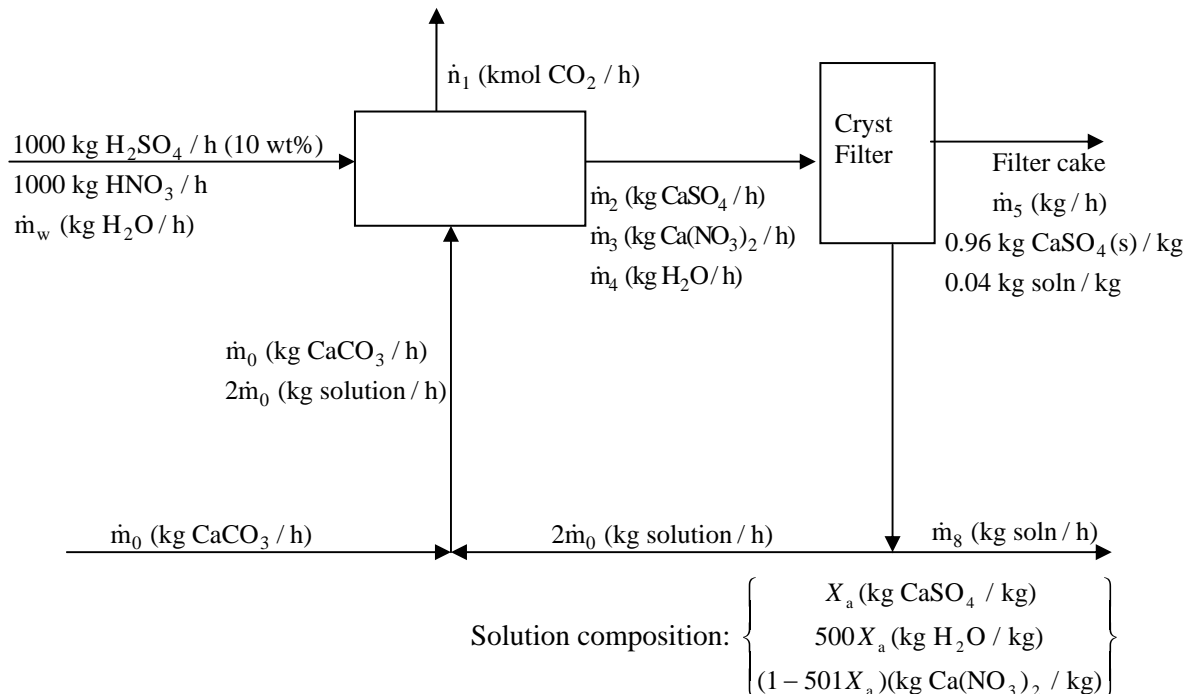
c.

$$\left. \begin{array}{l} \text{Diss. tank overall mass balance: } 60,000 + \dot{m}_1 + \dot{m}_6 = \dot{m}_2 + 6000 \\ \text{Diss. tank MgSO}_4 \text{ balance: } 54,000(120.37 / 246.44) + 0.23\dot{m}_6 = 0.32\dot{m}_2 \end{array} \right\}$$

$$\Rightarrow \begin{array}{l} \dot{m}_2 = 1.512 \times 10^5 \text{ lb}_m / \text{h} \\ \dot{m}_6 = 9.575 \times 10^4 \text{ lb}_m / \text{h} \text{ recycle} \end{array}$$

$$\text{Recycle/fresh feed ratio} = \frac{9.575 \times 10^4 \text{ lb}_m / \text{h}}{1494 \text{ lb}_m / \text{h}} = 64 \text{ lb}_m \text{ recycle} / \text{lb}_m \text{ fresh feed}$$

6.83 a.



### 6.83 (cont'd)

b. Acid is corrosive to pipes and other equipment in waste water treatment plant.

c. Acid feed:  $\frac{1000 \text{ kg H}_2\text{SO}_4 / \text{h}}{(2000 + \dot{m}_w) \text{ kg / h}} = 0.10 \Rightarrow \dot{m}_w = 8000 \text{ kg H}_2\text{O / h}$

Overall S balance:

$$\begin{array}{c|c|c|c|c} 1000 \text{ kg H}_2\text{SO}_4 & 32 \text{ kg S} & \dot{m}_5 \text{ (kg / h)} & (0.96 + 0.04X_a) \text{ (kg CaSO}_4\text{)} & 32 \text{ kg S} \\ \hline \text{h} & 98 \text{ kg H}_2\text{SO}_4 & & \text{kg} & 136 \text{ kg CaSO}_4 \\ + & \dot{m}_8 \text{ (kg / h)} & X_a \text{ (kg CaSO}_4\text{)} & 32 \text{ kg S} & \\ \hline & & \text{kg} & 136 \text{ kg CaSO}_4 & \end{array}$$

$$\Rightarrow 326.5 = 0.2353\dot{m}_5(0.96 + 0.04X_a) + 0.2353\dot{m}_8X_a \quad (1)$$

Overall N balance:

$$\begin{array}{c|c|c|c|c} 1000 \text{ kg HNO}_3 & 14 \text{ kg N} & 0.04\dot{m}_5 \text{ (kg / h)} & (1 - 501X_a) \text{ (kg Ca(NO}_3\text{)}_2\text{)} & 28 \text{ kg N} \\ \hline \text{h} & 63 \text{ kg HNO}_3 & & \text{kg} & 164 \text{ kg Ca(NO}_3\text{)}_2 \\ + & \dot{m}_8 \text{ (kg / h)} & (1 - 501X_a) \text{ (kg Ca(NO}_3\text{)}_2\text{)} & 28 \text{ kg N} & \\ \hline & & \text{kg} & 164 \text{ kg Ca(NO}_3\text{)}_2 & \end{array}$$

$$\Rightarrow 222.2 = 0.00683\dot{m}_5(1 - 501X_a) + 0.171\dot{m}_8(1 - 501X_a) \quad (2)$$

Overall Ca balance:

$$\begin{array}{c|c|c|c|c} \dot{m}_0 \text{ (kg / h)} & 40 \text{ kg Ca} & \dot{m}_5 \text{ (kg / h)} & (0.96 + 0.04X_a) \text{ (kg CaSO}_4\text{)} & 40 \text{ kg Ca} \\ \hline & 100 \text{ kg CaCO}_3 & & \text{kg} & 136 \text{ kg CaSO}_4 \\ + & (1 - 501X_a) \text{ (kg Ca(NO}_3\text{)}_2\text{)} & 0.04\dot{m}_5 \text{ (kg / h)} & 40 \text{ kg Ca} & \\ \hline & \text{kg} & & 164 \text{ kg Ca(NO}_3\text{)}_2 & \\ + & \dot{m}_8 \text{ (kg / h)} & X_a \text{ (kg CaSO}_4\text{)} & 40 \text{ kg Ca} & \\ \hline & & \text{kg} & 136 \text{ kg CaSO}_4 & \\ + & \dot{m}_8 \text{ (kg / h)} & (1 - 501X_a) \text{ (kg Ca(NO}_3\text{)}_2\text{)} & 40 \text{ kg Ca} & \\ \hline & & \text{kg} & 164 \text{ kg Ca(NO}_3\text{)}_2 & \end{array}$$

$$\begin{aligned} \Rightarrow 0.40\dot{m}_0 &= 0.294\dot{m}_5(0.96 + 0.04X_a) + 0.00976\dot{m}_5(1 - 501X_a) \\ &+ 0.294\dot{m}_8X_a + 0.244\dot{m}_8(1 - 501X_a) \end{aligned} \quad (3)$$

Overall C balance :

$$\begin{array}{c|c|c|c|c} \dot{m}_0 \text{ (kg / h)} & 12 \text{ kg C} & \dot{n}_1 \text{ (kmol CO}_2\text{ / h)} & 1 \text{ kmol C} & 12 \text{ kg C} \\ \hline & 100 \text{ kg CaCO}_3 & & 1 \text{ kmol CO}_2 & 1 \text{ kmol C} \end{array}$$

$$\Rightarrow 0.01\dot{m}_0 = \dot{n}_1 \quad (4)$$



### 6.83 (cont'd)

Overall H balance :

$$\begin{array}{c}
 \frac{1000 \text{ (kg H}_2\text{SO}_4\text{)}}{\text{h}} \left| \frac{2 \text{ kg H}}{98 \text{ kg H}_2\text{SO}_4} + \frac{1000 \text{ kg HNO}_3}{\text{h}} \right| \frac{1 \text{ kg H}}{63 \text{ kg HNO}_3} + \frac{\dot{m}_w \text{ (kg / h)}}{\text{h}} \left| \frac{2 \text{ kg H}}{18 \text{ kg H}_2\text{O}} \right. \\
 = \frac{0.04\dot{m}_5 \text{ (kg / h)}}{\text{kg}} \left| \frac{500X_a \text{ (kg H}_2\text{O)}}{\text{kg}} \right| \frac{2 \text{ kg H}}{18 \text{ kg H}_2\text{O}} + \frac{\dot{m}_8 \text{ (kg / h)}}{\text{kg}} \left| \frac{500X_a \text{ (kg H}_2\text{O)}}{\text{kg}} \right| \frac{2 \text{ kg H}}{18 \text{ kg H}_2\text{O}} \\
 \Rightarrow 925.17 = 2.22\dot{m}_5 X_a + 55.56\dot{m}_8 X_a \quad (5)
 \end{array}$$

Solve eqns. (1)-(5) simultaneously, using E-Z Solve.

$$\begin{array}{l}
 \dot{m}_0 = \underline{\underline{1812.5 \text{ kg CaCO}_3\text{(s)} / \text{h}}}, \quad \dot{m}_5 = \underline{\underline{1428.1 \text{ kg} / \text{h}}}, \quad \dot{m}_8 = \underline{\underline{9584.9 \text{ kg soln} / \text{h}}}, \\
 \dot{n}_1 = 18.1 \text{ kmol CO}_2 / \text{h(v)}, \quad X_a = 0.00173 \text{ kg CaSO}_4 / \text{kg}
 \end{array}$$

$$\underline{\underline{\text{Recycle stream}}} = 2 * \dot{m}_0 = \underline{\underline{3625 \text{ kg soln} / \text{h}}}$$

$$\left\{ \begin{array}{l} 0.00173(\text{kg CaSO}_4 / \text{kg}) \\ 500 * 0.00173(\text{kg H}_2\text{O} / \text{kg}) \\ (1 - 501 * 0.00173)(\text{kg Ca(NO}_3)_2 / \text{kg}) \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \underline{\underline{0.173\% \text{ CaSO}_4}} \\ \underline{\underline{86.5\% \text{ H}_2\text{O}}} \\ \underline{\underline{13.3\% \text{ Ca(NO}_3)_2}} \end{array} \right\}$$

**d.** From Table B.1, for CO<sub>2</sub>:

$$\begin{array}{l}
 T_c = 304.2 \text{ K}, \quad P_c = 72.9 \text{ atm} \\
 \Rightarrow T_r = \frac{T}{T_c} = \frac{(40 + 273.2) \text{ K}}{304.2} = 1.03, \quad P_r = \frac{30 \text{ atm}}{72.9 \text{ atm}} = 0.411
 \end{array}$$

From generalized compressibility chart (Fig. 5.4-2):

$$z = 0.86 \Rightarrow \hat{V} = \frac{zRT}{P} = \frac{0.86}{\text{mol} \cdot \text{K}} \left| \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \right| \frac{313.2 \text{ K}}{30 \text{ atm}} = 0.737 \frac{\text{L}}{\text{mol CO}_2}$$

Volumetric flow rate of CO<sub>2</sub>:

$$\dot{V} = \dot{n}_1 * \hat{V} = \frac{18.1 \text{ kmol CO}_2}{\text{h}} \left| \frac{0.737 \text{ L}}{\text{mol CO}_2} \right| \frac{1000 \text{ mol}}{1 \text{ kmol}} = \underline{\underline{1.33 \times 10^4 \text{ L} / \text{h}}}$$

**e.** Solution saturated with Ca(NO<sub>3</sub>)<sub>2</sub>:

$$\Rightarrow \frac{1 - 501X_a \text{ (kg Ca(NO}_3)_2 / \text{kg)}}{500X_a \text{ (kg H}_2\text{O} / \text{kg)}} = 1.526 \Rightarrow X_a = 0.00079 \text{ kg CaSO}_4 / \text{kg}$$

Let  $\dot{m}_1$  (kg HNO<sub>3</sub>/h) = feed rate of nitric acid corresponding to saturation without crystallization.

### 6.83 (cont'd)

Overall S balance:

$$\begin{array}{r|l|l|l|l}
 1000 \text{ kg H}_2\text{SO}_4 & 32 \text{ kg S} & \dot{m}_5 \text{ (kg / h)} & (0.96 + (0.04)(0.00079)) \text{ (kg CaSO}_4\text{)} & 32 \text{ kg S} \\
 \text{h} & 98 \text{ kg H}_2\text{SO}_4 & & \text{kg} & 136 \text{ kg CaSO}_4 \\
 \hline
 & + \dot{m}_8 \text{ (kg / h)} & 0.00079 \text{ (kg CaSO}_4\text{)} & 32 \text{ kg S} & \\
 & & \text{kg} & 136 \text{ kg CaSO}_4 & \\
 \hline
 \Rightarrow 326.5 = 0.226\dot{m}_5 + 0.000186\dot{m}_8 & & & & (1')
 \end{array}$$

Overall N balance:

$$\begin{array}{r|l|l|l|l}
 \dot{m}_1 \text{ (kg HNO}_3\text{)} & 14 \text{ kg N} & 0.04\dot{m}_5 \text{ (kg / h)} & (1 - (501)(0.00079)) \text{ (kg Ca(NO}_3\text{)}_2\text{)} & 28 \text{ kg N} \\
 \text{h} & 63 \text{ kg HNO}_3 & & \text{kg} & 164 \text{ kg Ca(NO}_3\text{)}_2 \\
 \hline
 & + \dot{m}_8 \text{ (kg / h)} & (1 - (501)(0.00079)) \text{ (kg Ca(NO}_3\text{)}_2\text{)} & 28 \text{ kg N} & \\
 & & \text{kg} & 164 \text{ kg Ca(NO}_3\text{)}_2 & \\
 \hline
 \Rightarrow 0.222\dot{m}_1 = 0.00413\dot{m}_5 + 0.103\dot{m}_8 & & & & (2')
 \end{array}$$

Overall H balance:

$$\begin{array}{r|l|l|l|l}
 1000 \text{ (kg H}_2\text{SO}_4\text{)} & 2 \text{ kg H} & \dot{m}_1 \text{ kg HNO}_3 & 1 \text{ kg H} & \\
 \text{h} & 98 \text{ kg H}_2\text{SO}_4 & \text{h} & 63 \text{ kg HNO}_3 & \\
 \hline
 + \frac{8000 \text{ (kg / h)}}{18 \text{ kg H}_2\text{O}} & 2 \text{ kg H} & 0.04\dot{m}_5 \text{ (kg / h)} & 500(0.00079) \text{ (kg H}_2\text{O)} & 2 \text{ kg H} \\
 & 18 \text{ kg H}_2\text{O} & & \text{kg} & 18 \text{ kg H}_2\text{O} \\
 \hline
 & + \dot{m}_8 \text{ (kg / h)} & 500(0.00079) \text{ (kg H}_2\text{O)} & 2 \text{ kg H} & \\
 & & \text{kg} & 18 \text{ kg H}_2\text{O} & \\
 \hline
 \Rightarrow 909.30 + 0.0159\dot{m}_1 = 0.00175\dot{m}_5 + 0.0439\dot{m}_8 & & & & (3')
 \end{array}$$

Solve eqns (1')-(3') simultaneously using E-Z solve:

$$\dot{m}_1 = 1.155 \times 10^4 \text{ kg / h}; \quad \dot{m}_5 = 1.424 \times 10^3 \text{ kg / h}; \quad \dot{m}_8 = 2.484 \times 10^4 \text{ kg / h}$$

Maximum ratio of nitric acid to sulfuric acid in the feed

$$= \frac{1.155 \times 10^4 \text{ kg / h}}{1000 \text{ kg / h}} = \underline{\underline{11.5 \text{ kg HNO}_3 / \text{kg H}_2\text{SO}_4}}$$

6.84

$$\left. \begin{array}{l} \text{Moles of diphenyl (DP): } \frac{56.0 \text{ g}}{154.2 \text{ g/mol}} = 0.363 \text{ mol} \\ \text{Moles of benzene (B): } \frac{550.0 \text{ ml}}{\text{ml}} \left| \frac{0.879 \text{ g}}{\text{ml}} \right| \frac{1 \text{ mol}}{78.11 \text{ g}} = 6.19 \text{ mol} \end{array} \right\}$$

$$\Rightarrow x_{\text{DP}} = \frac{0.363}{6.19 + 0.363} = 0.0544 \text{ mol DP/mol}$$

$$p_{\text{B}}^*(T) = (1 - x_{\text{DP}}) p_{\text{B}}^*(T) = 0.945(120.67 \text{ mm Hg}) = \underline{\underline{114.0 \text{ mm Hg}}}$$

$$\Delta T_{\text{m}} = \frac{RT_{\text{m0}}^2}{\Delta \hat{H}_{\text{m}}} x_{\text{DP}} = \frac{8.314(273.2 + 5.5)^2}{9837} (0.0554) = 3.6 \text{ K} = 3.6^\circ \text{C} \Rightarrow T_{\text{m}} = 5.5 - 3.6 = \underline{\underline{1.9^\circ \text{C}}}$$

$$\Delta T_{\text{bp}} = \frac{RT_{\text{b0}}^2}{\Delta \hat{H}_{\text{v}}} x_{\text{DP}} = \frac{8.314(273.2 + 80.1)^2}{30,765} (0.0554) = 1.85 \text{ K} = 1.85^\circ \text{C}$$

$$\Rightarrow T_{\text{b}} = 80.1 + 1.85 = \underline{\underline{82.0^\circ \text{C}}}$$

6.85

$$T_{\text{m0}} = 0.0^\circ \text{C}, \Delta T_{\text{m}} = 4.6^\circ \text{C} = 4.6 \text{ K}$$

$$\xrightarrow[\text{Table B.1}]{\text{Eq. 6.5-5}} x_{\text{u}} = \frac{\Delta T_{\text{m}} \Delta \hat{H}_{\text{m}}}{R(T_{\text{m0}})^2} = \frac{(4.6 \text{ K})(600.95 \text{ J/mol})}{(8.314 \text{ J/mol} \cdot \text{K})(273.2 \text{ K})^2} = 0.0445 \text{ mol urea/mol}$$

$$\text{Eq. (6.5-4)} \Rightarrow \Delta T_{\text{b}} = \frac{RT_{\text{b0}}^2}{\Delta \hat{H}_{\text{v}}} x_{\text{u}} = \frac{(8.314)(373.2)^2}{40,656} 0.0445 = 1.3 \text{ K} = \underline{\underline{1.3^\circ \text{C}}}$$

1000 grams of this solution contains  $m_{\text{u}}$  (g urea) and  $(1000 - m_{\text{u}})$  (g water)

$$n_{\text{u1}} (\text{mol urea}) = \frac{m_{\text{u1}} (\text{g})}{60.06 \text{ g/mol}} \quad n_{\text{w1}} (\text{mol water}) = \frac{(1000 - m_{\text{u1}}) (\text{g})}{18.02 \text{ g/mol}}$$

$$x_{\text{u1}} = 0.0445 = \frac{\frac{m_{\text{u1}}}{60.06} (\text{mol urea})}{\left[ \frac{m_{\text{u1}}}{60.06} + \frac{(1000 - m_{\text{u1}})}{18.02} \right] (\text{mol solution})} \Rightarrow m_{\text{u1}} = 134 \text{ g urea}, m_{\text{w1}} = 866 \text{ g water}$$

$$\Delta T_{\text{b}} = 3.0^\circ \text{C} = 3.0 \text{ K} \Rightarrow x_{\text{u2}} = \frac{\Delta T_{\text{b}} \Delta \hat{H}_{\text{v}}}{R(T_{\text{b0}})^2} = \frac{(3.0 \text{ K})(40,656 \text{ J/mol})}{(8.314 \text{ J/mol} \cdot \text{K})(373.2 \text{ K})^2} = 0.105 \text{ mol urea/mol}$$

$$x_{\text{u2}} = 0.105 = \frac{\frac{m_{\text{u2}}}{60.06} (\text{mol urea})}{\left[ \frac{m_{\text{u2}}}{60.06} + \frac{866}{18.02} \right] (\text{mol solution})} \Rightarrow m_{\text{u2}} = 339 \text{ g urea}$$

$$\Rightarrow \text{Add } (339 - 134) \text{ g urea} = \underline{\underline{205 \text{ g urea}}}$$

$$\mathbf{6.86} \quad x_a^I = \frac{(0.5150 \text{ g})/(110.1 \text{ g/mol})}{(0.5150 \text{ g})/(110.1 \text{ g/mol}) + (100.0 \text{ g})/(94.10 \text{ g/mol})} = 0.00438 \text{ mol solute/mol}$$

$$\Delta T_m = \frac{RT_{m0}^2}{\Delta \hat{H}_m} x_s \Rightarrow \frac{\Delta T_m^I}{\Delta T_m^{II}} = \frac{x_s^I}{x_s^{II}} \Rightarrow x_s^{II} = x_s^I \frac{\Delta T_m^{II}}{\Delta T_m^I} = 0.00438 \frac{0.49^\circ \text{C}}{0.41^\circ \text{C}} = 0.00523 \frac{\text{mol solute}}{\text{mol solution}}$$

$$\Rightarrow \frac{(1 - 0.00523) \text{ mol solvent}}{0.00523 \text{ mol solute}} \quad \left| \quad \frac{94.10 \text{ g solvent}}{1 \text{ mol solvent}} \quad \right| \quad \frac{0.4460 \text{ g solute}}{95.60 \text{ g solvent}} = \underline{\underline{83.50 \text{ g solute/mol}}}$$

$$\Delta \hat{H}_m = \frac{RT_{m0}^2}{\Delta T_m} x_s = \frac{8.314(273.2 - 5.00)^2}{0.49} (0.00523) = 6380 \text{ J/mol} = \underline{\underline{6.38 \text{ kJ/mol}}}$$

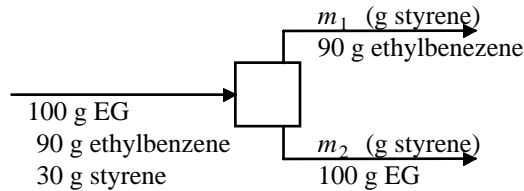
$$\mathbf{6.87 \quad a.} \quad \ln p_s^*(T_{b0}) = -\frac{\Delta H_v^I}{RT_{b0}} + B, \quad \ln p_s^*(T_{bs}) = -\frac{\Delta H_v^{II}}{RT_{bs}} + B$$

$$\text{Assume } \Delta H_v^I \cong \Delta H_v^{II}; T_0 T_s \cong T_0^2$$

$$\Rightarrow \ln P_s^*(T_{b0}) - \ln P_0^*(T_{bs}) = -\frac{\Delta H_v}{R} \left( \frac{1}{T_{b0}} - \frac{1}{T_{bs}} \right) \cong \frac{\Delta H_v}{R} \frac{T_{bs} - T_{b0}}{T_{b0}^2}$$

$$\mathbf{b. \quad \underline{Raoult's Law}:} \quad p_s^*(T_{b0}) = (1-x)p_0^*(T_{bs}) \Rightarrow \ln(1-x) \approx -x = -\frac{\Delta H_v \Delta T_b}{RT_{b0}^2} \Rightarrow \Delta T_b = \underline{\underline{\frac{RT_{b0}^2}{\Delta H_v} x}}$$

**6.88**



$$\underline{\text{Styrene balance:}} \quad m_1 + m_2 = 30 \text{ g styrene}$$

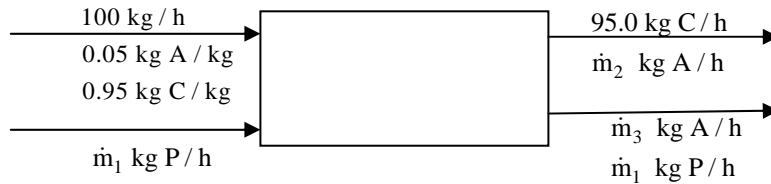
$$\underline{\text{Equilibrium relation:}} \quad \frac{m_2}{100 + m_2} = 0.19 \left( \frac{m_1}{90 + m_1} \right)$$

↓ solve simultaneously

$$m_1 = 25.6 \text{ g styrene in ethylbenzene phase}$$

$$\underline{\underline{m_2 = 4.4 \text{ g styrene in ethylene glycol phase}}}$$

**6.89** Basis: 100 kg/h. A=oleic acid; C=condensed oil; P=propane



a. 90% extraction:  $\dot{m}_3 = (0.09)(0.05)(100 \text{ kg / h}) = 4.5 \text{ kg A / h}$

Balance on oleic acid:  $(0.05)(100) = \dot{m}_2 + 4.5 \text{ kg A / h} \Rightarrow \dot{m}_2 = 0.5 \text{ kg A / h}$

Equilibrium condition:  $0.15 = \frac{0.5 / (\dot{m}_1 + 0.5)}{4.5 / (4.5 + 95)} \Rightarrow \dot{m}_1 = \underline{\underline{73.2 \text{ kg P / h}}}$

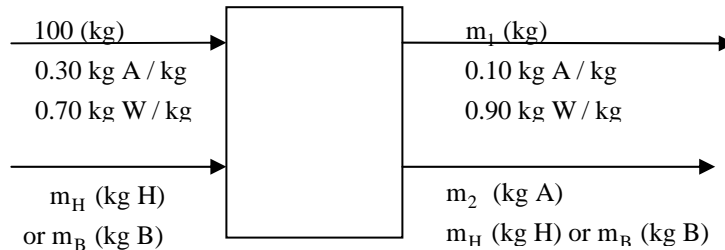
b. Operating pressure must be above the vapor pressure of propane at  $T=85^\circ\text{C}=185^\circ\text{F}$

Figure 6.1-4  $\Rightarrow p_{\text{propane}}^* = \underline{\underline{500 \text{ psi}}} = \underline{\underline{34 \text{ atm}}}$

c. Other less volatile hydrocarbons cost more and/or impose greater health or environmental hazards.

**6.90** a. Benzene is the solvent of choice. It holds a greater amount of acetic acid for a given mass fraction of acetic acid in water.

Basis: 100 kg feed. A=Acetic acid, W=H<sub>2</sub>O, H=Hexane, B=Benzene



Balance on W:  $100 * 0.70 = m_1 * 0.90 \Rightarrow m_1 = 77.8 \text{ kg}$

Balance on A:  $100 * 0.30 = m_2 + 77.8 * 0.10 \Rightarrow m_2 = 22.2 \text{ kg}$

Equilibrium for H:

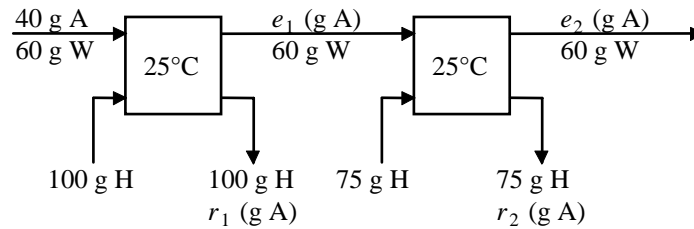
$$K_H = \frac{m_2 / (m_2 + m_H)}{x_A} = \frac{22.2 / (22.2 + m_H)}{0.10} = 0.017 \Rightarrow m_H = \underline{\underline{1.30 \times 10^4 \text{ kg H}}}$$

Equilibrium for B:

$$K_B = \frac{m_2 / (m_2 + m_B)}{x_A} = \frac{22.2 / (22.2 + m_B)}{0.10} = 0.098 \Rightarrow m_B = \underline{\underline{2.20 \times 10^3 \text{ kg B}}}$$

(b) Other factors in picking solvent include cost, solvent volatility, and health, safety, and environmental considerations.

**6.91 a.** Basis: 100 g feed  $\Rightarrow$  40 g acetone, 60 g  $H_2O$ . A = acetone, H = n -  $C_6H_{14}$ , W = water



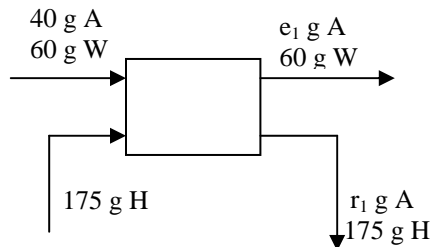
$$x_{A \text{ in H phase}} / x_{A \text{ in W phase}} = 0.343 \quad (x = \text{mass fraction})$$

$$\left. \begin{array}{l} \text{Balance on A – stage 1:} \quad 40 = e_1 + r_1 \\ \text{Equilibrium condition – stage 1:} \quad \frac{r_1 / (100 + r_1)}{e_1 / (60 + e_1)} = 0.343 \end{array} \right\} \Rightarrow \begin{array}{l} e_1 = 27.8 \text{ g acetone} \\ r_1 = 12.2 \text{ g acetone} \end{array}$$

$$\left. \begin{array}{l} \text{Balance on A – stage 2:} \quad 27.8 = e_2 + r_2 \\ \text{Equilibrium condition – stage 2:} \quad \frac{r_2 / (75 + r_2)}{e_2 / (60 + e_2)} = 0.343 \end{array} \right\} \Rightarrow \begin{array}{l} r_2 = 7.2 \text{ g acetone} \\ e_2 = 20.6 \text{ g acetone} \end{array}$$

$$\% \text{ acetone not extracted} = \frac{20.6 \text{ g A remaining}}{40 \text{ g A fed}} \times 100\% = \underline{\underline{51.5\%}}$$

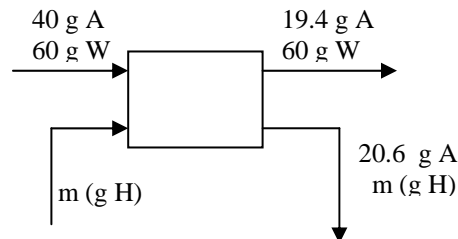
**b.**



$$\left. \begin{array}{l} \text{Balance on A – stage 1:} \quad 40.0 = e_1 + r_1 \\ \text{Equilibrium condition – stage 1:} \quad \frac{r_1 / (175 + r_1)}{e_1 / (60 + e_1)} = 0.343 \end{array} \right\} \Rightarrow \begin{array}{l} r_1 = 17.8 \text{ g acetone} \\ e_1 = 22.2 \text{ g acetone} \end{array}$$

$$\% \text{ acetone not extracted} = \frac{22.2 \text{ g A remaining}}{40 \text{ g A fed}} \times 100\% = \underline{\underline{55.5\%}}$$

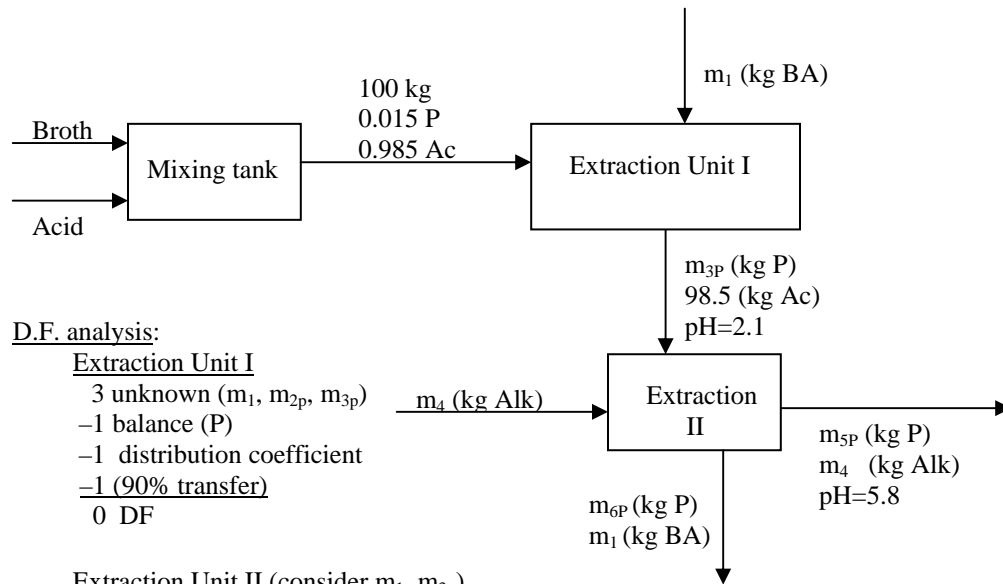
**c.**



$$\text{Equilibrium condition:} \quad \frac{20.6 / (m + 20.6)}{19.4 / (60 + 19.4)} = 0.343 \Rightarrow m = \underline{\underline{225 \text{ g hexane}}}$$

**d.** Define a function  $F = (\text{value of recovered acetone over process lifetime}) - (\text{cost of hexane over process lifetime}) - (\text{cost of an equilibrium stage} \times \text{number of stages})$ . The most cost-effective process is the one for which  $F$  is the highest.

**6.92 a.** P--penicillin; Ac--acid solution; BA--butyl acetate; Alk--alkaline solution



D.F. analysis:

Extraction Unit I

3 unknown ( $m_1$ ,  $m_{2P}$ ,  $m_{3P}$ )  
 -1 balance (P)  
 -1 distribution coefficient  
-1 (90% transfer)  
 0 DF

Extraction Unit II (consider  $m_1$ ,  $m_{3P}$ )

3 unknowns  
 -1 balance (P)  
 -1 distribution coefficient  
-1 (90% transfer)  
 0 DF

**b.** In Unit I, 90% transfer  $\Rightarrow m_{3P} = 0.90(1.5) = 1.35 \text{ kg P}$

P balance:  $1.5 = m_{2P} + 1.35 \Rightarrow m_{2P} = 0.15 \text{ kg P}$

$$\text{pH}=2.1 \Rightarrow K = 25.0 = \frac{1.35 / (1.35 + m_1)}{0.15 / (0.15 + 98.5)} \Rightarrow m_1 = 34.16 \text{ kg BA}$$

In Unit II, 90% transfer:  $m_{5P} = 0.90(m_{3P}) = 1.215 \text{ kg P}$

P balance:  $m_{3P} = 1.215 + m_{6P} \Rightarrow m_{6P} = 0.135 \text{ kg P}$

$$\text{pH}=5.8 \Rightarrow K = 0.10 = \frac{m_{6P} / (m_{6P} + 34.16)}{1.215 / (1.215 + m_4)} \Rightarrow m_4 = 29.65 \text{ kg Alk}$$

$$\frac{m_1}{100} = \frac{34.16 \text{ kg BA}}{100 \text{ kg broth}} = \underline{\underline{0.3416 \text{ kg butyl acetate / kg acidified broth}}}$$

$$\frac{m_4}{100} = \frac{29.65 \text{ kg Alk}}{100 \text{ kg broth}} = \underline{\underline{0.2965 \text{ kg alkaline solution / kg acidified broth}}}$$

Mass fraction of P in the product solution:

$$x_P = \frac{m_{5P}}{m_4 + m_{5P}} = \frac{1.215 \text{ P}}{(29.65 + 1.215) \text{ kg}} = \underline{\underline{0.394 \text{ kg P / kg}}}$$

- c.** (i). The first transfer (low pH) separates most of the P from the other broth constituents, which are not soluble in butyl acetate. The second transfer (high pH) moves the penicillin back into an aqueous phase without the broth impurities.  
 (ii). Low pH favors transfer to the organic phase, and high pH favors transfer back to the aqueous phase.  
 (iii). The penicillin always moves from the raffinate solvent to the extract solvent.

**6.93** W = water, A = acetone, M = methyl isobutyl ketone

$$\left. \begin{array}{l} x_W = 0.20 \\ x_A = 0.33 \\ x_M = 0.47 \end{array} \right\} \xRightarrow{\text{Figure 6.6-1}} \begin{array}{l} \text{Phase 1: } x_W = 0.07, x_A = 0.35, x_M = 0.58 \\ \text{Phase 2: } x_W = 0.71, x_A = 0.25, x_M = 0.04 \end{array}$$

Basis: 1.2 kg of original mixture,  $m_1$ =total mass in phase 1,  $m_2$ =total mass in phase 2.

$$\begin{array}{l} \text{H}_2\text{O Balance:} \quad 1.2 * 0.20 = 0.07m_1 + 0.71m_2 \\ \text{Acetone balance:} \quad 1.2 * 0.33 = 0.35m_1 + 0.25m_2 \end{array} \Rightarrow \begin{cases} m_1 = 0.95 \text{ kg in MIBK - rich phase} \\ m_2 = 0.24 \text{ kg in water - rich phase} \end{cases}$$

**6.94** Basis: Given feeds: A = acetone, W = H<sub>2</sub>O, M=MIBK

Overall system composition:

$$\begin{array}{l} 5000 \text{ g (30 wt\% A, 70 wt\% W)} \Rightarrow 1500 \text{ g A, 3500 g W} \\ 3500 \text{ g (20 wt\% A, 80 wt\% M)} \Rightarrow 700 \text{ g A, 2800 g M} \end{array} \left\{ \begin{array}{l} 2200 \text{ g A} \\ \Rightarrow 3500 \text{ g W} \\ 2800 \text{ g M} \end{array} \right\} \Rightarrow 25.9\% \text{ A, } 41.2\% \text{ W, } 32.9\% \text{ M} \xRightarrow{\text{Fig. 6.6-1}} \begin{array}{l} \text{Phase 1: 31\% A, 63\% M, 6\% W} \\ \text{Phase 2: 21\% A, 3\% M, 76\% W} \end{array}$$

Let  $m_1$ =total mass in phase 1,  $m_2$ =total mass in phase 2.

$$\begin{array}{l} \text{H}_2\text{O Balance:} \quad 3500 = 0.06m_1 + 0.76m_2 \\ \text{Acetone balance:} \quad 2200 = 0.31m_1 + 0.21m_2 \end{array} \Rightarrow \begin{cases} m_1 = 4200 \text{ g in MIBK - rich phase} \\ m_2 = 4270 \text{ g in water - rich phase} \end{cases}$$

**6.95** A=acetone, W = H<sub>2</sub>O, M=MIBK

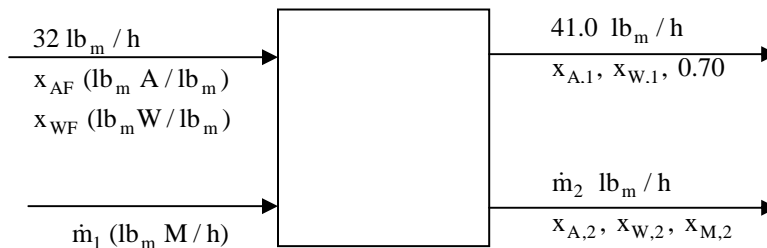


Figure 6.6-1  $\Rightarrow$  Phase 1:  $x_M = 0.700 \Rightarrow x_{w,1} = 0.05$ ;  $x_{A,1} = 0.25$ ;

Phase 2:  $x_{w,2} = 0.81$ ;  $x_{A,2} = 0.81$ ;  $x_{M,2} = 0.03$

$$\begin{array}{l} \text{Overall mass balance:} \quad 32.0 \text{ lb}_m / \text{h} + \dot{m}_1 = 41.0 \text{ lb}_m / \text{h} + \dot{m}_2 \\ \text{MIBK balance:} \quad \dot{m}_1 = 41.0 * 0.7 + \dot{m}_2 * 0.03 \end{array} \Rightarrow \begin{cases} \dot{m}_1 = 28.1 \text{ lb}_m \text{ MIBK} / \text{h} \\ \dot{m}_2 = 19.1 \text{ lb}_m / \text{h} \end{cases}$$



**6.96 a.** Basis: 100 kg; A=acetone, W=water, M=MIBK

System 1:  $x_{a,org} = 0.375$  mol A,  $x_{m,org} = 0.550$  mol M,  $x_{w,org} = 0.075$  mol W

$x_{a,aq} = 0.275$  mol A,  $x_{m,aq} = 0.050$  mol M,  $x_{w,aq} = 0.675$  mol W

$$\left. \begin{array}{l} \text{Mass balance: } m_{aq,1} + m_{org,1} = 100 \\ \text{Acetone balance: } m_{aq,1} * 0.275 + m_{org,1} * 0.375 = 33.33 \end{array} \right\} \Rightarrow \begin{array}{l} m_{aq,1} = 41.7 \text{ kg} \\ m_{org,1} = 58.3 \text{ kg} \end{array}$$

System 2:  $x_{a,org} = 0.100$  mol A,  $x_{m,org} = 0.870$  mol M,  $x_{w,org} = 0.030$  mol W

$x_{a,aq} = 0.055$  mol A,  $x_{m,aq} = 0.020$  mol M,  $x_{w,aq} = 0.925$  mol W

$$\left. \begin{array}{l} \text{Mass balance: } m_{aq,2} + m_{org,2} = 100 \\ \text{Acetone balance: } m_{aq,2} * 0.055 + m_{org,2} * 0.100 = 9 \end{array} \right\} \Rightarrow \begin{array}{l} m_{aq,2} = 22.2 \text{ kg} \\ m_{org,2} = 77.8 \text{ kg} \end{array}$$

b.  $K_{a,1} = \frac{x_{a,org,1}}{x_{a,aq,1}} = \frac{0.375}{0.275} = 1.36; \quad K_{a,2} = \frac{x_{a,org,2}}{x_{a,aq,2}} = \frac{0.100}{0.055} = 1.82$

High  $K_a$  to extract acetone from water into MIBK; low  $K_a$  to extract acetone from MIBK into water.

c.  $\beta_{aw,1} = \frac{x_{a,org} / x_{w,org}}{x_{a,aq} / x_{w,aq}} = \frac{0.375 / 0.075}{0.275 / 0.675} = 12.3; \quad \beta_{aw,2} = \frac{0.100 / 0.040}{0.055 / 0.920} = 41.8$

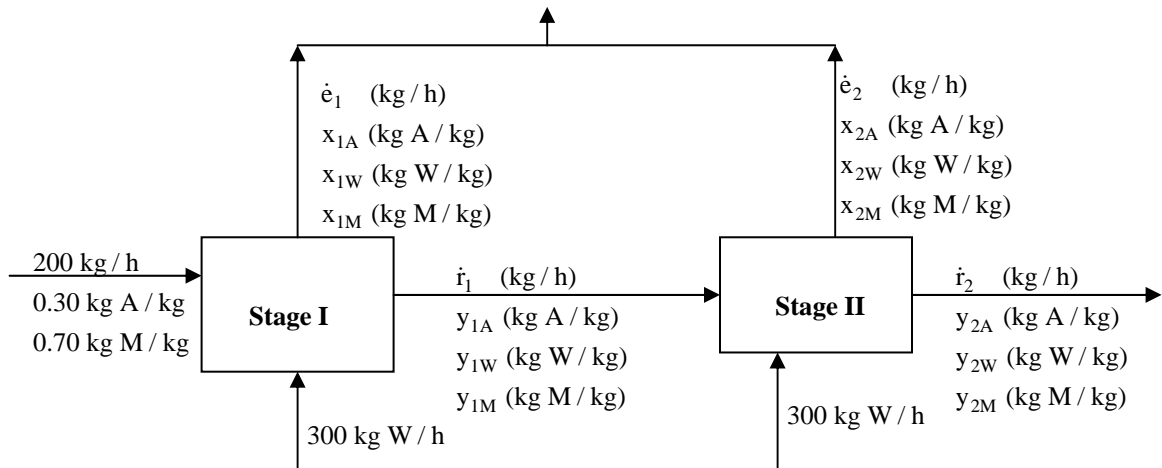
If water and MIBK were immiscible,  $x_{w,org} = 0 \Rightarrow \beta_{aw} \rightarrow \infty$

d. Organic phase= extract phase; aqueous phase= raffinate phase

$$\beta_{a,w} = \frac{(x_a / x_w)_{org}}{(x_a / x_w)_{aq}} = \frac{(x_a)_{org} / (x_a)_{aq}}{(x_w)_{org} / (x_w)_{aq}} = \frac{K_a}{K_w}$$

When it is critically important for the raffinate to be as pure (acetone-free) as possible.

**6.97** Basis: Given feed rates: A = acetone, W = water, M=MIBK



**6.97(cont'd)**

Overall composition of feed to Stage 1:

$$\left. \begin{array}{l} (200)(0.30) = 60 \text{ kg A/h} \\ 200 - 60 = 140 \text{ kg M/h} \\ 300 \text{ kg W/h} \end{array} \right\} \Rightarrow \begin{array}{l} 500 \text{ kg/h} \\ 12\% \text{ A, } 28\% \text{ M, } 60\% \text{ W} \end{array}$$

Figure 6.6-1  $\Rightarrow$  Extract:  $x_{1A} = 0.095, x_{1W} = 0.880, x_{1M} = 0.025$   
Raffinate:  $y_{1A} = 0.15, y_{1W} = 0.035, y_{1M} = 0.815$

$$\begin{array}{ll} \text{Mass balance} & 500 = \dot{e}_1 + \dot{r}_1 \\ \text{Acetone balance:} & 60 = 0.095\dot{e}_1 + 0.15\dot{r}_1 \end{array} \Rightarrow \begin{cases} \dot{e}_1 = 273 \text{ kg/h} \\ \dot{r}_1 = \underline{\underline{227 \text{ kg/h}}} \end{cases}$$

Overall composition of feed to Stage 2:

$$\left. \begin{array}{l} (227)(0.15) = 34 \text{ kg A/h} \\ (227)(0.815) = 185 \text{ kg M/h} \\ (227)(0.035) + 300 = 308 \text{ kg W/h} \end{array} \right\} \Rightarrow \begin{array}{l} 527 \text{ kg/h} \\ 6.5\% \text{ A, } 35.1\% \text{ MIBK, } 58.4\% \text{ W} \end{array}$$

Figure 6.6-1  $\Rightarrow$  Extract:  $x_{2A} = 0.04, x_{2W} = 0.94, x_{2M} = 0.02$   
Raffinate:  $y_{2A} = 0.085, y_{2W} = 0.025, y_{2M} = 0.89$

$$\begin{array}{ll} \text{Mass balance:} & 527 = \dot{e}_2 + \dot{r}_2 \\ \text{Acetone balance:} & 34 = 0.04\dot{e}_2 + 0.085\dot{r}_2 \end{array} \Rightarrow \begin{cases} \dot{e}_2 = 240 \text{ kg/h} \\ \dot{r}_2 = \underline{\underline{287 \text{ kg/h}}} \end{cases}$$

Acetone removed:

$$\frac{[60 - (0.085)(287)] \text{ kg A removed/h}}{60 \text{ kg A/h in feed}} = \underline{\underline{0.59 \text{ kg acetone removed / kg fed}}}$$

Combined extract:

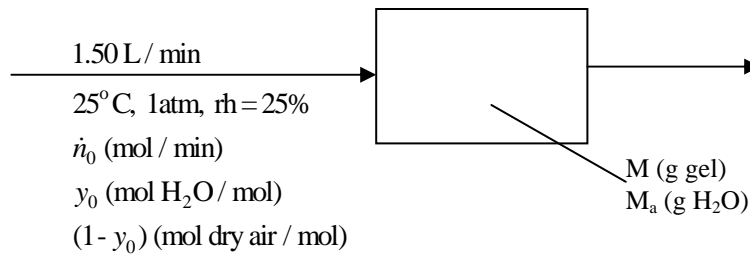
Overall flow rate  $= \dot{e}_1 + \dot{e}_2 = 273 + 240 = 513 \text{ kg/h}$

Acetone:  $\frac{(x_{1A}\dot{e}_1 + x_{2A}\dot{e}_2) \text{ kg A}}{513} = \frac{0.095 * 273 + 0.04 * 240}{513} = \underline{\underline{0.069 \text{ kg A / kg}}}$

Water:  $\frac{(x_{1W}\dot{e}_1 + x_{2W}\dot{e}_2) \text{ kg W}}{\dot{e}_1 + \dot{e}_2} = \frac{0.88 * 273 + 0.94 * 240}{513} = \underline{\underline{0.908 \text{ kg W / kg}}}$

MIBK:  $\frac{(x_{1M}\dot{e}_1 + x_{2M}\dot{e}_2) \text{ kg M}}{(\dot{e}_1 + \dot{e}_2) \text{ kg}} = \frac{0.025 * 273 + 0.02 * 240}{513} = \underline{\underline{0.023 \text{ kg M / kg}}}$

6.98. a.



$$\dot{n}_0 = \frac{P\dot{V}}{RT} = \frac{(1 \text{ atm})(1.50 \text{ L/min})}{(0.08206 \text{ L} \cdot \text{atm} / \text{mol} \cdot \text{K})(298 \text{ K})} = 0.06134 \text{ mol/min}$$

$$\text{r.h.} = 25\% \Rightarrow \frac{P_{\text{H}_2\text{O}}}{P_{\text{H}_2\text{O}}^*(25^\circ \text{C})} = 0.25$$

$$\text{Silica gel saturation condition: } X^* = 12.5 \frac{P_{\text{H}_2\text{O}}}{P_{\text{H}_2\text{O}}^*} = 12.5 * 0.25 = 3.125 \frac{\text{g H}_2\text{O ads}}{100 \text{ g silica gel}}$$

$$\text{Water feed rate: } y_0 = \frac{0.25 P_{\text{H}_2\text{O}}^*(25^\circ \text{C})}{p} = \frac{0.25(23.756 \text{ mm Hg})}{760 \text{ mm Hg}} = 0.00781 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

$$\Rightarrow \dot{m}_{\text{H}_2\text{O}} = \frac{0.06134 \text{ mol}}{\text{min}} \left| \frac{0.00781 \text{ mol H}_2\text{O}}{\text{mol}} \right| \left| \frac{18.01 \text{ g H}_2\text{O}}{\text{mol H}_2\text{O}} \right| = 0.00863 \text{ g H}_2\text{O/min}$$

$$\text{Adsorption in 2 hours} = (0.00863 \text{ g H}_2\text{O/min})(120 \text{ min}) = 1.035 \text{ g H}_2\text{O}$$

$$\text{Saturation condition: } \frac{1.035 \text{ g H}_2\text{O}}{M \text{ (g silica gel)}} = \frac{3.125 \text{ g H}_2\text{O}}{100 \text{ g silica gel}} \Rightarrow M = \underline{\underline{33.1 \text{ g silica gel}}}$$

Assume that all entering water vapor is adsorbed throughout the 2 hours and that P and T are constant.

- b. Humid air is dehumidified by being passed through a column of silica gel, which absorbs a significant fraction of the water in the entering air and relatively little oxygen and nitrogen. The capacity of the gel to absorb water, while large, is not infinite, and eventually the gel reaches its capacity. If air were still fed to the column past this point, no further dehumidification would take place. To keep this situation from occurring, the gel is replaced at or (preferably) before the time when it becomes saturated.

6.99 a. Let  $c = \text{CCl}_4$

$$\text{Relative saturation} = 0.30 \Rightarrow \frac{p_c}{p_c^*(34^\circ \text{C})} \Rightarrow p_c = 0.30 * (169 \text{ mm Hg}) = \underline{\underline{50.7 \text{ mm Hg}}}$$

- b. Initial moles of gas in tank:

$$n_0 = \frac{P_0 V_0}{RT_0} = \frac{1 \text{ atm}}{0.08206 \text{ L} \cdot \text{atm} / \text{mol} \cdot \text{K}} \left| \frac{50.0 \text{ L}}{307 \text{ K}} \right| = 1.985 \text{ mol}$$

Initial moles of  $\text{CCl}_4$  in tank:

$$n_{c0} = y_{c0} n_0 = \frac{p_{c0}}{P_0} n_0 = \frac{50.7 \text{ mm Hg}}{760 \text{ mm Hg}} \times 1.985 \text{ mol} = 0.1324 \text{ mol CCl}_4$$

**6.99 (cont'd)**

50% CCl<sub>4</sub> adsorbed  $\Rightarrow n_c = 0.500n_{c0} = 0.662 \text{ mol CCl}_4 (= n_{\text{ads}})$

Total moles in tank:  $n_{\text{tot}} = n_0 - n_{\text{ads}} = (1.985 - 0.0662) \text{ mol} = 1.919 \text{ mol}$

Pressure in tank. Assume  $T = T_0$  and  $V = V_0$ .

$$P = \frac{n_{\text{tot}}RT_0}{V_0} = \left( \frac{(1.919)(0.08206)(307)}{50.0} \text{ atm} \right) \left( \frac{760 \text{ mm Hg}}{\text{atm}} \right) = \underline{\underline{735 \text{ mm Hg}}}$$

$$y_c = \frac{n_c}{n_{\text{tot}}} = \frac{0.0662 \text{ mol CCl}_4}{1.919 \text{ mol}} = 0.0345 \frac{\text{mol CCl}_4}{\text{mol}}$$

$$\Rightarrow p_c = 0.0345(760 \text{ mm Hg}) = \underline{\underline{26.2 \text{ mm Hg}}}$$

**c. Moles of air in tank:**  $n_a = n_0 - n_{c0} = (1.985 - 0.1324) \text{ mol air} = 1.853 \text{ mol air}$

$$y_c = \frac{n_c}{n_c + 1.853} = 0.001 \frac{\text{mol CCl}_4}{\text{mol}} \Rightarrow n_c = 1.854 \times 10^{-3} \text{ mol CCl}_4$$

$$\Rightarrow n_{\text{tot}} = n_c + n_{\text{air}} = 1.854 \text{ mol}$$

$$p_c = y_c P = 0.001 \left[ \frac{n_{\text{tot}}RT_0}{V_0} \right] = \frac{1.854 \times 10^{-3} \text{ mol}}{50.0 \text{ L}} \left| \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \right| \frac{307 \text{ K}}{1 \text{ atm}} \left| \frac{760 \text{ mm}}{1 \text{ atm}} \right|$$

$$= 0.710 \text{ mm Hg}$$

$$X^* \left( \frac{\text{g CCl}_4}{\text{g carbon}} \right) = \frac{0.0762 p_c}{1 + 0.096 p_c} \Rightarrow X^* = \frac{0.0762(0.710)}{1 + 0.096(0.710)} = 0.0506 \frac{\text{g CCl}_4 \text{ adsorbed}}{\text{g carbon}}$$

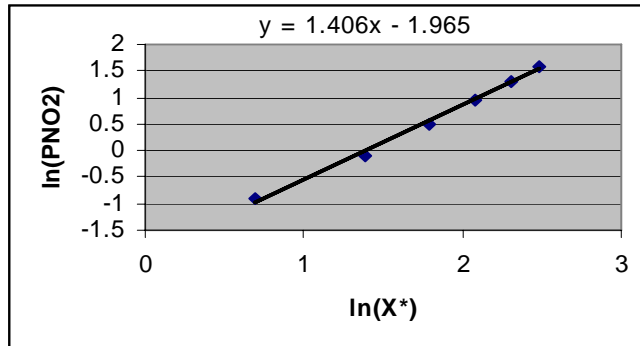
Mass of CCl<sub>4</sub> adsorbed

$$m_{\text{ads}} = (n_{c0} - n_c)(MW)_c = \frac{(0.1324 - 0.001854) \text{ mol CCl}_4}{1 \text{ mol CCl}_4} \left| \frac{153.85 \text{ g}}{1 \text{ mol CCl}_4} \right|$$

$$= 20.3 \text{ mol CCl}_4 \text{ adsorbed}$$

Mass of carbon required:  $m_c = \frac{20.3 \text{ g CCl}_4 \text{ ads}}{0.0506 \frac{\text{g CCl}_4 \text{ ads}}{\text{g carbon}}} = \underline{\underline{400 \text{ g carbon}}}$

**6.100 a.**  $X^* = K_F p_{\text{NO}_2}^\beta \Rightarrow \ln X^* = \ln K_F + \beta \ln p_{\text{NO}_2}^\beta$



**6.100 (cont'd)**

$$\ln X^* = 1.406 \ln p_{\text{NO}_2} - 1.965 \Rightarrow X^* = e^{-1.965} p_{\text{NO}_2}^{1.406} = 0.140 p_{\text{NO}_2}^{1.406}$$

$$\underline{\underline{K_F = 0.140 (\text{kg NO}_2 / 100 \text{ kg gel})(\text{mm Hg})^{-1.406}; \quad \underline{\underline{\beta = 1.406}}}}$$

**b. Mass of silica gel :**  $m_g = \frac{\pi * (0.05 \text{ m})^2 (1 \text{ m})}{1 \text{ m}^3} \left| \frac{10^3 \text{ L}}{\text{L}} \right| \frac{0.75 \text{ kg gel}}{\text{L}} = 5.89 \text{ kg gel}$

Maximum NO<sub>2</sub> adsorbed :

$$p_{\text{NO}_2} \text{ in feed} = 0.010(760 \text{ mm Hg}) = 7.60 \text{ mm Hg}$$

$$m_{\text{ads}} = \frac{0.140(7.60)^{1.406} \text{ kg NO}_2}{100 \text{ kg gel}} \left| \frac{5.89 \text{ kg gel}}{\text{L}} \right| = 0.143 \text{ kg NO}_2$$

Average molecular weight of feed :

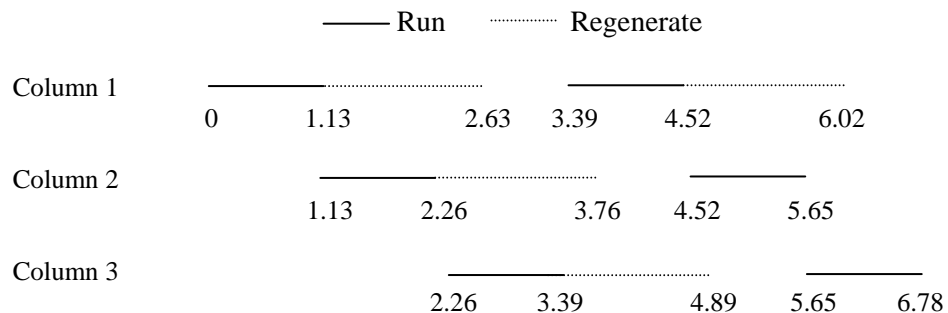
$$\overline{MW} = 0.01(MW)_{\text{NO}_2} + 0.99(MW)_{\text{air}} = (0.01)(46.01) + (0.99)(29.0) = 29.17 \frac{\text{kg}}{\text{kmol}}$$

Mass feed rate of NO<sub>2</sub>:

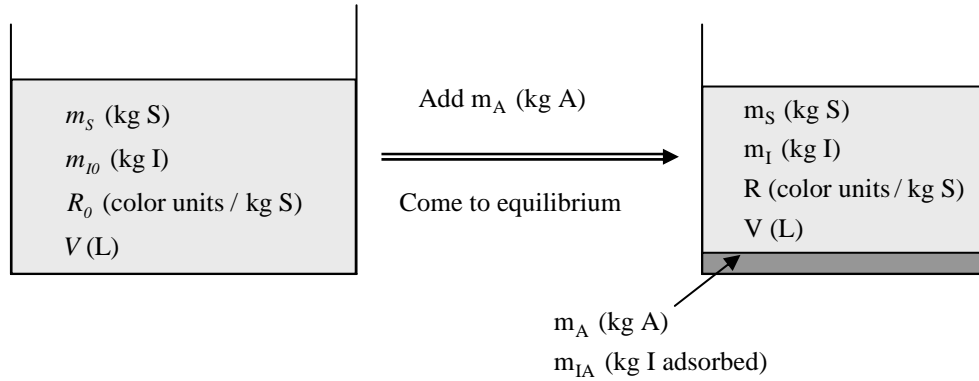
$$\dot{m} = \frac{8.00 \text{ kg}}{\text{h}} \left| \frac{1 \text{ kmol}}{29.17 \text{ kg}} \right| \left| \frac{0.01 \text{ kmol NO}_2}{\text{kmol}} \right| \left| \frac{46.01 \text{ kg NO}_2}{\text{kmol NO}_2} \right| = 0.126 \frac{\text{kg NO}_2}{\text{h}}$$

Breakthrough time:  $t_b = \frac{0.143 \text{ kg NO}_2}{0.126 \text{ kg NO}_2 / \text{h}} = 1.13 \text{ h} = \underline{\underline{68 \text{ min}}}$

- c.** The first column would start at time 0 and finish at 1.13 h, and would not be available for another run until  $(1.13+1.50) = 2.63 \text{ h}$ . The second column could start at 1.13 h and finish at 2.26 h. Since the first column would still be in the regeneration stage, a third column would be needed to start at 2.26 h. It would run until 3.39 h, at which time the first column would be available for another run. The first few cycles are shown below on a Gantt chart.



**6.101** Let S=sucrose, I=trace impurities, A=activated carbon



Assume • no sucrose is adsorbed  
• solution volume (V) is not affected by addition of the carbon

a.  $R(\text{color units/kg S}) = kC_i(\text{kg I / L}) = k \frac{m_I}{V}$  (1)

$$\Rightarrow \Delta R = k(C_{i0} - C_i) = \frac{k}{V}(m_{I0} - m_I) \xrightarrow{m_{IA} = m_{I0} - m_I} \Delta R = \frac{km_{IA}}{V} \quad (2)$$

$$\% \text{ removal of color} = \frac{\Delta R}{R_0} \times 100\% = \frac{km_{IA} / V}{km_{I0} / V} \times 100 = 100 \frac{m_{IA}}{m_{I0}} \quad (3)$$

Equilibrium adsorption ratio:  $X_i^* = \frac{m_{IA}}{m_A}$  (4)

Normalized percentage color removal:

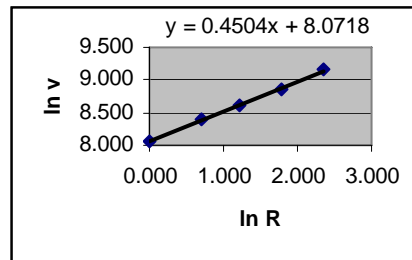
$$\nu = \frac{\% \text{ removal}}{m_A / m_S} \stackrel{(3)}{=} \frac{100 m_{IA} / m_{I0}}{m_A / m_S} = 100 \frac{m_{IA}}{m_A} \frac{m_S}{m_{I0}}$$

$$\Rightarrow \nu = 100 X_i^* \frac{m_S}{m_{I0}} \Rightarrow X_i^* = \frac{m_{I0}}{100 m_S} \nu \quad (5)$$

Freundlich isotherm  $X_i^* = K_F C_i^\beta \stackrel{(1),(5)}{\Rightarrow} \frac{m_{I0}}{100 m_S} \nu = K_F \left(\frac{R}{k}\right)^\beta$

$$\Rightarrow \nu = \frac{100 m_S K_F}{m_{I0} k^\beta} R^\beta = K_F' R^\beta$$

A plot of  $\ln \nu$  vs.  $\ln R$  should be linear: slope =  $\beta$ ; intercept =  $\ln K_F'$



**6.101 (cont'd)**

$$\ln v = 0.4504 \ln p_{NO_2} + 8.0718 \Rightarrow v = e^{8.0718} R^{0.4504} = 3203 R^{0.4504}$$

$$\Rightarrow K'_F = \underline{\underline{3203}}, \quad \beta = \underline{\underline{0.4504}}$$

**b.** 100 kg 48% sucrose solution  $\Rightarrow m_s = 480 \text{ kg}$

95% reduction in color  $\Rightarrow R = 0.025(20.0) = 0.50 \text{ color units / kg sucrose}$

$$v = K'_F R^\beta = 3203(0.50)^{0.4504} = 2344$$

$$\Rightarrow 2344 = \frac{\% \text{ color reduction}}{m_A / m_s} = \frac{97.5}{m_A / 480} \Rightarrow m_A = \underline{\underline{20.0 \text{ kg carbon}}}$$