2.19 (a)

$$\bar{X} = \frac{\sum_{i=1}^{12} X_i}{12} = 73.5 \qquad s = \sqrt{\frac{\sum_{i=1}^{12} (X - 73.5)^2}{12 - 1}} = 1.2$$

$$\mathrm{C}_{\text{min=}} = \bar{X} - 2s = 73.5 - 2(1.2) = \underline{\underline{71.1}}$$

$$\mathrm{C}_{\text{max=}} = \bar{X} + 2s = 73.5 + 2(1.2) = \underline{\underline{75.9}}$$

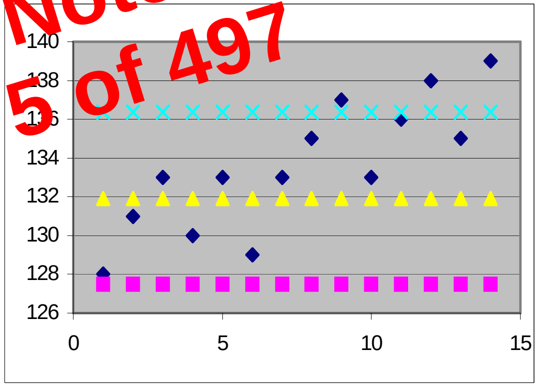
(b) Joanne is more likely to be the statistician, because she wants to make the control limits stricter.

(c) Inadequate cleaning between batches, impurities in raw materials, variations in reactor temperature (failure of reactor control system), problems with the color measurement system, operator carelessness

2.20 (a), (b)

(a) Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
X	134	131	129	133	135	131	134	130	131	136	129	130	133	130	133
Mean(X)	131.9														
Stdev(X)	2.2														
Min	127.5														
Max	136.4														

(b) Run	X	Min	Mean	Max
1	128	127.5	131.9	136.4
2	131	127.5	131.9	136.4
3	133	127.5	131.9	136.4
4	130	127.5	131.9	136.4
5	133	127.5	131.9	136.4
6	129	127.5	131.9	136.4
7	133	127.5	131.9	136.4
8	135	127.5	131.9	136.4
9	137	127.5	131.9	136.4
10	133	127.5	131.9	136.4
11	136	127.5	131.9	136.4
12	138	127.5	131.9	136.4
13	135	127.5	131.9	136.4
14	139	127.5	131.9	136.4



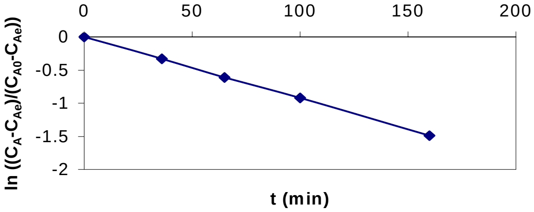
(c) Beginning with Run 11, the process has been near or well over the upper quality assurance limit. An overhaul would have been reasonable after Run 12.

2.21 (a)
$$Q' = \frac{2.36\times10^{-4}\ \mathrm{kg\cdot m^2}}{\mathrm{h}} \left| \frac{2.20462\ \mathrm{lb}}{\mathrm{kg}} \right| \frac{3.2808^2\ \mathrm{ft^2}}{\mathrm{m^2}} \left| \frac{1\quad \mathrm{h}}{3600\ \mathrm{s}} \right.$$

(b)
$$Q'_{\text{approximate}} \approx \frac{(2\times10^{-4})(2)(9)}{3\times10^{3}} \approx 12\times10^{(-4-3)} \approx \underline{\underline{1.2\times10^{-6}\ \mathrm{lb\cdot ft^2/s}}}$$

$$Q'_{\text{exact}} = \underline{\underline{1.56\times10^{-6}\ \mathrm{lb\cdot ft^2/s}}} = \underline{\underline{0.00000156\ \mathrm{lb\cdot ft^2/s}}}$$

2.34 (a) Yes, because when $\ln[(C_A - C_{Ae})/(C_{A0} - C_{Ae})]$ is plotted vs. *t* in rectangular coordinates, the plot is a straight line.



$$\text{Slope} = -0.0093 \Rightarrow \underline{\underline{k = 9.3\times10^{-3}\ \text{min}^{-1}}}$$

(b) $$\ln[(C_A - C_{Ae})/(C_{A0} - C_{Ae})] = -kt \Rightarrow C_A = (C_{A0} - C_{Ae})e^{-kt} + C_{Ae}$$

$$C_A = (0.1823 - 0.0495)e^{-(9.3\times10^{-3})(120)} + 0.0495 \ = 9.300\times10^{-2}\ \text{g/L}$$

$$C = m/V \Rightarrow m = CV = \frac{9.300\times10^{-2}\ \text{g}}{\text{L}}\left|\frac{30.5\ \text{gal}}{}\right|\frac{28.317\ \text{L}}{7.4805\ \text{gal}} = \underline{\underline{10.7\ \text{g}}}$$

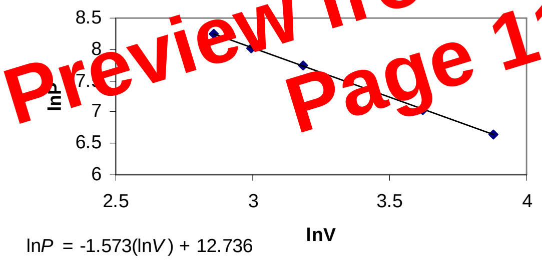
2.35 (a) ft^3 and h^{-2}, respectively

(b) $\ln(V)$ vs. t^2 in rectangular coordinates, slope=2 and intercept= $\ln(3.53\times10^{-2})$; or

V(logarithmic axis) vs. t^2 in semilog coordinates, slope=2, intercept=3.53×10^{-2}

(c) $\underline{\underline{V(\text{m}^3) = 1.00\times10^{-3}\exp(1.5\times10^{-7}\,\text{t}^2)}}$

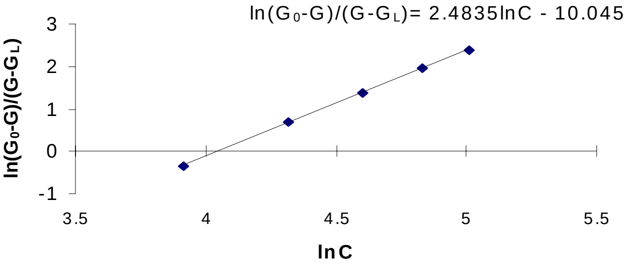
2.36 $PV^k = C \Rightarrow P = C/V^k \Rightarrow \ln P = \ln C - k\ln V$



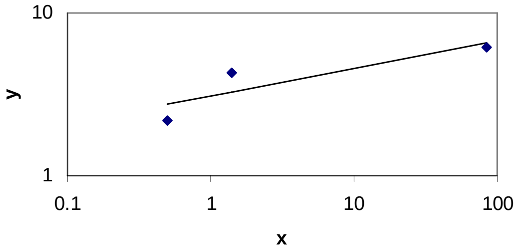
$$k = -\text{slope} = -(-1.573) = \underline{\underline{1.573}}\ (\text{dimensionless})$$

$$\text{Intercept} = \ln C = 12.736 \Rightarrow C = e^{12.736} = \underline{\underline{3.40\times10^5\ \text{mm Hg}\cdot\text{cm}^{4.719}}}$$

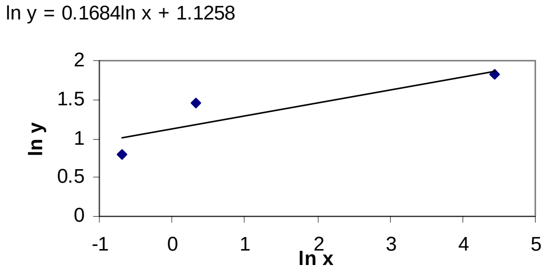
2.37 (a) $$\frac{G - G_L}{G_0 - G} = \frac{1}{K_L C^m} \Rightarrow \frac{G_0 - G}{G - G_L} = K_L C^m \Rightarrow \ln\frac{G_0 - G}{G - G_L} = \ln K_L + m\ln C$$



2.41 (a) and (c)



(b) $y = ax^b \Rightarrow \ln y = \ln a + b \ln x;$ Slope = b, Intercept = ln a

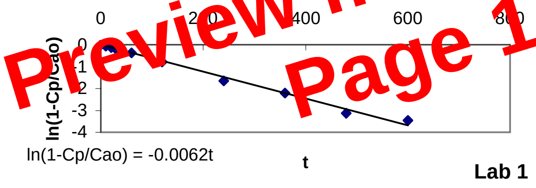


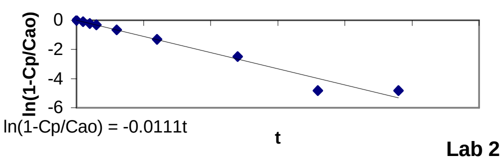
$b = \text{slope} = \underline{\underline{0.168}}$

$\text{Intercept} = \ln a = 1.1258 \Rightarrow a = \underline{\underline{3.08}}$

2.42 (a) ln(1-C_p/C_{A0}) vs. t in rectangular coordinates. Slope=-k, intercept=0

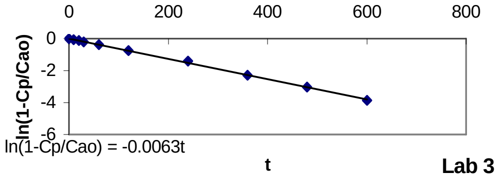
(b)

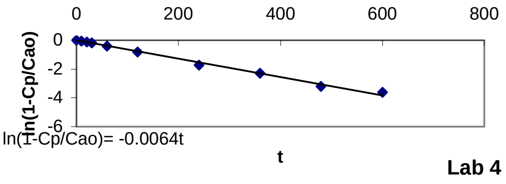




$k = \underline{\underline{0.0062 \text{ s}^{-1}}}$

$k = \underline{\underline{0.0111 \text{ s}^{-1}}}$





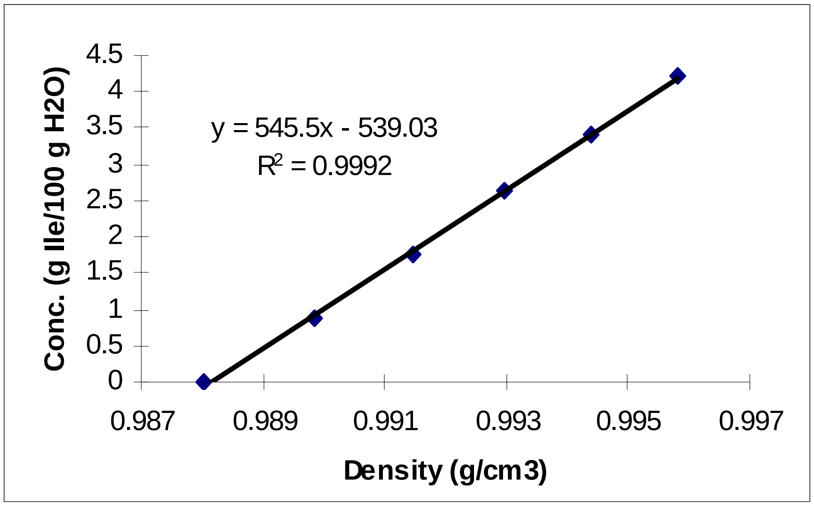
$k = \underline{\underline{0.0063 \text{ s}^{-1}}}$

$k = \underline{\underline{0.0064 \text{ s}^{-1}}}$

(c) Disregarding the value of k that is very different from the other three, k is estimated with the average of the calculated k's. $k = \underline{\underline{0.0063 \text{ s}^{-1}}}$

(d) Errors in measurement of concentration, poor temperature control, errors in time measurements, delays in taking the samples, impure reactants, impurities acting as catalysts, inadequate mixing, poor sample handling, clerical errors in the reports, dirty reactor.

3.12 (a)



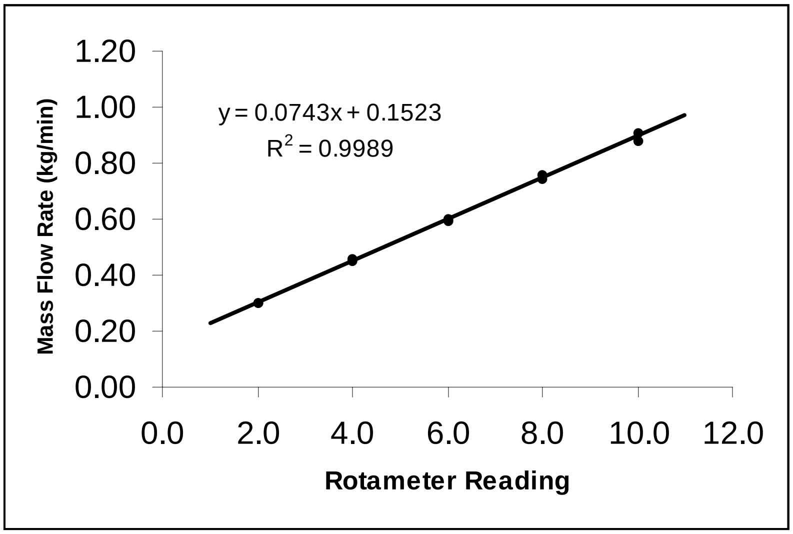
From the plot above, $r = 545.5\rho - 539.03$

(b) For $\rho = 0.9940 \text{ g}/\text{cm}^3$, $r = 3.197 \text{ g Ile}/100\text{g H}_2\text{O}$

$$\dot{m}_{Ile} = \frac{150 \text{ L}}{\text{h}} \left| \frac{0.994 \text{ g}}{\text{cm}^3} \right| \frac{1000 \text{ cm}^3}{\text{L}} \left| \frac{3.197 \text{ g Ile}}{103.197 \text{ g sol}} \right| \frac{1 \text{ kg}}{1000 \text{ g}} = \underline{\underline{4.6 \text{ kg Ile}/\text{h}}}$$

(c) The measured solution density is 0.9940 g ILE/cm³ solution *at 50°C*. For the calculation of Part (b) to be correct, the density would have to be changed to its equivalent at 47°C. Presuming that the dependence of solution density on *T* is the same as that of pure water, the solution density at 47°C would be higher than 0.9940 g ILE/cm³. The ILE mass flow rate calculated in Part (b) is therefore $\underline{\underline{\text{too low}}}$.

3.13 (a)



3.13 (cont'd)

From the plot, $R = 5.3 \Rightarrow \dot{m} = 0.0743\,(5.3) + 0.1523 = \underline{\underline{0.55 \text{ kg / min}}}$

(b)

Rotameter Reading	Collection Time (min)	Collected Volume (cm3)	Mass Flow Rate (kg/min)	Difference Duplicate (D_i)	Mean D_i
2	1	297	0.297		0.0104
2	1	301	0.301	0.004	
4	1	454	0.454		
4	1	448	0.448	0.006	
6	0.5	300	0.600		
6	0.5	298	0.596	0.004	
8	0.5	371	0.742		
8	0.5	377	0.754	0.012	
10	0.5	440	0.880		
10	0.5	453	0.906	0.026	

$$\overline{D}_i = \frac{1}{5}(0.004 + 0.006 + 0.004 + 0.012 + 0.026) = \underline{\underline{0.0104 \text{ kg / min}}}$$

95% confidence limits: $(0.610 \pm 1.74\overline{D}_i)$ kg / min $= \underline{\underline{0.610 \pm 0.018 \text{ kg / min}}}$

There is roughly a 95% probability that the true flow rate is between 0.592 kg / min and 0.628 kg / min.

3.14 **(a)** $$\frac{15.0 \text{ kmol } C_6H_6 \;\big|\; 78.114 \text{ kg } C_6H_6}{\;\big|\; \text{kmol } C_6H_6} = \underline{\underline{1.17 \times 10^3 \text{ kg } C_6H_6}}$$

(b) $$\frac{15.0 \text{ kmol } C_6H_6 \;\big|\; 1000 \text{ mol}}{\;\big|\; \text{kmol}} = \underline{\underline{1.5 \times 10^4 \text{ mol } C_6H_6}}$$

(c) $$\frac{15{,}000 \text{ mol } C_6H_6 \;\big|\; \text{lb-mole}}{\;\big|\; 453.6 \text{ mol}} = \underline{\underline{33.07 \text{ lb-mole } C_6H_6}}$$

(d) $$\frac{15{,}000 \text{ mol } C_6H_6 \;\big|\; 6 \text{ mol C}}{\;\big|\; 1 \text{ mol } C_6H_6} = \underline{\underline{90{,}000 \text{ mol C}}}$$

(e) $$\frac{15{,}000 \text{ mol } C_6H_6 \;\big|\; 6 \text{ mol H}}{\;\big|\; 1 \text{ mol } C_6H_6} = \underline{\underline{90{,}000 \text{ mol H}}}$$

(f) $$\frac{90{,}000 \text{ mol C} \;\big|\; 12.011 \text{ g C}}{\;\big|\; \text{mol C}} = \underline{\underline{1.08 \times 10^6 \text{ g C}}}$$

(g) $$\frac{90{,}000 \text{ mol H} \;\big|\; 1.008 \text{ g H}}{\;\big|\; \text{mol H}} = \underline{\underline{9.07 \times 10^4 \text{ g H}}}$$

(h) $$\frac{15{,}000 \text{ mol } C_6H_6 \;\big|\; 6.022 \times 10^{23}}{\;\big|\; \text{mol}} = \underline{\underline{9.03 \times 10^{27} \text{ molecules of } C_6H_6}}$$

3.20 (a)

Unit	*Function*
Crystallizer	Form solid gypsum particles from a solution
Filter	Separate particles from solution
Dryer	Remove water from filter cake

(b) $$m_{\text{gypsum}} = \frac{1\text{ L slurry}}{} \left| \frac{0.35\text{ kg CaSO}_4\cdot 2\text{H}_2\text{O}}{\text{L slurry}} \right. = \underline{\underline{0.35\text{ kg CaSO}_4\cdot 2\text{H}_2\text{O}}}$$

$$V_{\text{gypsum}} = \frac{0.35\text{ kg CaSO}_4\cdot 2\text{H}_2\text{O}}{} \left| \frac{\text{L CaSO}_4\cdot 2\text{H}_2\text{O}}{2.32\text{ kg CaSO}_4\cdot 2\text{H}_2\text{O}} \right. = \underline{\underline{0.151\text{ L CaSO}_4\cdot 2\text{H}_2\text{O}}}$$

$$\text{CaSO}_4\text{ in gypsum: } m = \frac{0.35\text{ kg } gypsum}{} \left| \frac{136.15\text{ kg CaSO}_4}{172.18\text{ kg } gypsum} \right. = \underline{\underline{0.277\text{ kg CaSO}_4}}$$

$$\text{CaSO}_4\text{ in soln.: } m = \frac{(1-0.151)\text{ L sol}}{} \left| \frac{1.05\text{ kg}}{\text{L}} \right| \frac{0.209\text{ kg CaSO}_4}{100.209\text{ kg sol}} = \underline{\underline{0.00186\text{ kg CaSO}_4}}$$

(c) $$m = \frac{0.35\text{ kg gypsum}}{} \left| \frac{0.05\text{ kg sol}}{0.95\text{ kg gypsum}} \right| \frac{0.209\text{ g CaSO}_4}{100.209\text{ g sol}} = 3.84\times 10^{-5}\text{ kg CaSO}_4$$

$$\underline{\%\text{recovery}} = \frac{0.277\text{ g} + 3.84\times 10^{-5}\text{ g}}{0.277\text{ g} + 0.00186\text{ g}}\times 100\% = \underline{\underline{99.3\%}}$$

3.21

$$\left.\begin{array}{l} \underline{\text{CSA}}: \dfrac{45.8\text{ L}}{\text{min}} \left| \dfrac{0.90\text{ kg}}{\text{L}} \right| \dfrac{\text{kmol}}{75\text{ kg}} = 0.5496\,\dfrac{\text{kmol}}{\text{min}} \\ \underline{\text{FB}}: \dfrac{55.2\text{ L}}{\text{min}} \left| \dfrac{0.75\text{ kg}}{\text{L}} \right| \dfrac{\text{kmol}}{90\text{ kg}} = 0.4600\,\dfrac{\text{kmol}}{\text{min}} \end{array}\right\} \Rightarrow \frac{0.5496}{0.4600} = \underline{\underline{1.2\,\frac{\text{mol CSA}}{\text{mol FB}}}}$$

<u>She was wrong.</u>

<u>The mixer would come to a grinding halt and the motor would overheat.</u>

3.22 (a) $$\frac{150\text{ mol EtOH}}{} \left| \frac{46.07\text{ g EtOH}}{\text{mol EtOH}} \right. = 6910\text{ g EtOH}$$

$$\frac{6910\text{ g EtOH}}{} \left| \frac{0.600\text{ g H}_2\text{O}}{0.400\text{ g EtOH}} \right. = 10365\text{ g H}_2\text{O}$$

$$V = \frac{6910\text{ g EtOH}}{} \left| \frac{\text{L}}{789\text{ g EtOH}} \right. + \frac{10365\text{ g H}_2\text{O}}{} \left| \frac{\text{L}}{1000\text{ g H}_2\text{O}} \right. = 19.123\text{ L} \Rightarrow \underline{\underline{19.1\text{ L}}}$$

$$SG = \frac{(6910+10365)\text{ g}}{19.1\text{ L}} \left| \frac{\text{L}}{1000\text{ g}} \right. = \underline{\underline{0.903}}$$

(b) $$V' = \frac{(6910+10365)\text{ g mix}}{} \left| \frac{\text{L}}{935.18\text{ g}} \right. = 18.472\text{ L} \Rightarrow \underline{\underline{18.5\text{ L}}}$$

$$\underline{\%\text{error}} = \frac{(19.123-18.472)\text{ L}}{18.472\text{ L}}\times 100\% = \underline{\underline{3.5\%}}$$

3.50 $(T_b)_{\mathrm{H_2O}} = 100°\mathrm{C} \quad (T_m)_{\mathrm{AgCl}} = 455°\mathrm{C}$

(a) $V(\mathrm{mV}) = aT(°\mathrm{C}) + b$

$$\begin{matrix} 5.27 = 100a + b \\ 24.88 = 455a + b \end{matrix} \Rightarrow \begin{matrix} a = 0.05524 \ \ \mathrm{mV}/°\mathrm{C} \\ b = -0.2539 \ \mathrm{mV} \end{matrix}$$

$$\underline{\underline{V(\mathrm{mV}) = 0.05524T(°\mathrm{C}) - 0.2539}}$$

$$\Downarrow$$

$$\underline{\underline{T(°\mathrm{C}) = 18.10V(\mathrm{mV}) + 4.596}}$$

(b) $10.0\ \mathrm{mV} \to 13.6\ \mathrm{mV} \Rightarrow 185.6°\mathrm{C} \to 250.8°\mathrm{C} \Rightarrow \dfrac{dT}{dt} = \dfrac{(250.8 - 185.6)°\mathrm{C}}{20\ \mathrm{s}} = \underline{\underline{3.26\ °\mathrm{C/s}}}$

3.51 **(a)** $\ln T = \ln K + n \ln R \quad [T = KR^n]$

$$n = \frac{\ln(250.0/110.0)}{\ln(40.0/20.0)} = 1.184$$

$$\ln K = \ln\ 110.0 - 1.184(\ln 20.0) = 1.154 \Rightarrow K = 3.169 \Rightarrow \underline{\underline{T = 3.169R^{1.184}}}$$

(b) $R = \left(\dfrac{320}{3.169}\right)^{1/1.184} = \underline{\underline{49.3}}$

(c) Extrapolation error, thermocouple reading wrong.

3.52 **(a)** $PV = 0.08206nT$

$$P(\mathrm{atm}) = \frac{P'(\mathrm{psig}) + 14.696}{14.696} \quad , \quad \mathrm{V(L)} = V'(\mathrm{ft}^3) \times \frac{28.317\ \mathrm{ft}^3}{\mathrm{L}}$$

$$n(\mathrm{mol}) = n'(\mathrm{lb\text{-}moles}) \times \frac{453.59\ \mathrm{mol}}{\mathrm{lb-moles}} \quad , \quad \mathrm{T(°K)} = \frac{T'(°\mathrm{F}) - 32}{1.8} + 273.15$$

$$\Rightarrow \frac{(P' + 14.696)}{14.696} \times V' \times 28.317 = 0.08206 \times n' \times \frac{453.59}{1} \times \left[\frac{(T' - 32)}{1.8} + 273.15\right]$$

$$\Rightarrow (P' + 14.696) \times V' = \frac{0.08206 \times 14.696 \times 453.59}{28.317 \times 1.8} \times n' \times (T' + 459.7)$$

$$\Rightarrow \underline{\underline{(P' + 14.696)V' = 10.73n'(T' + 459.7)}}$$

4.5 (cont'd)

b. Overall objective: To produce C_3H_6 from C_3H_8.
Preheater function: Raise temperature of the reactants to raise the reaction rate.
Reactor function: Convert C_3H_8 to C_3H_6.
Absorption tower function: Separate the C_3H_8 and C_3H_6 in the reactor effluent from the other components.
Stripping tower function: Recover the C_3H_8 and C_3H_6 from the solvent.
Distillation column function: Separate the C_3H_5 from the C_3H_8.

4.6 **a.** $\underline{\underline{\text{3 independent balances}}}$ (one for each species)

b. 7 unknowns ($\dot{m}_1, \dot{m}_3, \dot{m}_5, x_2, y_2, y_4, z_4$)
– 3 balances
– 2 mole fraction summations
2 unknowns must be specified

c. $\underline{\underline{y_2}} = 1 - x_2$

A Balance: $5300x_2\left(\frac{\text{kg A}}{\text{h}}\right) = \left[\underline{\underline{\dot{m}_3}} + (1200)(0.70)\right]\left(\frac{\text{kg A}}{\text{h}}\right)$

Overall Balance: $[\dot{m}_1 + 5300]\left(\frac{\text{kg}}{\text{h}}\right) = \left[\dot{m}_3 + 1200 + \underline{\underline{\dot{m}_5}}\right]\left(\frac{\text{kg}}{\text{h}}\right)$

B Balance: $[0.03\dot{m}_1 + 5300x_2]\left(\frac{\text{kg B}}{\text{h}}\right) = \left[1200\underline{\underline{y_4}} + 0.60\dot{m}_5\right]\left(\frac{\text{kg B}}{\text{h}}\right)$

$\underline{\underline{z_4}} = 1 - 0.70 - y_4$

4.7 **a.** $\underline{\underline{\text{3 independent balances}}}$ (one for each species)

b.

Water Balance: $$\frac{400\ g}{\text{min}}\left|\frac{0.885\ \text{g H}_2\text{O}}{\text{g}}\right. = \frac{\underline{\underline{\dot{m}_R}}\ (g)}{(\text{min})}\left|\frac{0.995\ \text{g H}_2\text{O}}{\text{g}}\right. \Rightarrow \underline{\underline{\dot{m}_R = 356\ \text{g/min}}}$$

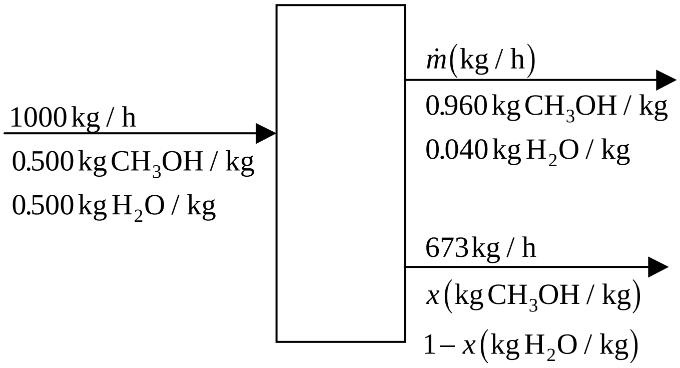
Acetic Acid Balance: $$[(400)(0.115)]\left(\frac{\text{g CH}_3\text{OOH}}{\text{min}}\right) = \left[0.005\dot{m}_R + 0.096\underline{\underline{\dot{m}_E}}\right]\left(\frac{\text{g CH}_3\text{OOH}}{\text{min}}\right)$$

$$\Rightarrow \underline{\underline{\dot{m}_E = 461\ \text{g/min}}}$$

Overall Balance: $$\left[\underline{\underline{\dot{m}_C}} + 400\right]\left(\frac{\text{g}}{\text{min}}\right) = [\dot{m}_R + \dot{m}_E]\left(\frac{\text{g}}{\text{min}}\right) \Rightarrow \underline{\underline{\dot{m}_C = 417\ \text{g/min}}}$$

c. $$[(0.115)(400) - (0.005)(356)]\left(\frac{\text{g}}{\text{min}}\right) = [(0.096)(461)]\left(\frac{\text{g}}{\text{min}}\right) \Rightarrow \underline{\underline{44\ \text{g/min} = 44\ \text{g/min}}}$$

4.12 **a.**



2 unknowns ($\dot{m}, x$)
$-$ 2 balances
0 DF

b. Overall balance: $1000 = \dot{m} + 673 \Rightarrow \dot{m} = 327\ \text{kg/h}$

Methanol balance: $0.500(1000) = 0.960(327) + x(673) \Rightarrow \underline{\underline{x = 0.276\ \text{kg CH}_3\text{OH/kg}}}$

Molar flow rates of methanol and water:

$$\frac{673\,\text{kg}}{\text{h}}\,\Big|\,\frac{0.276\,\text{kg CH}_3\text{OH}}{\text{kg}}\,\Big|\,\frac{1000\,\text{g}}{\text{kg}}\,\Big|\,\frac{\text{mol CH}_3\text{OH}}{32.0\,\text{g CH}_3\text{OH}} = \underline{\underline{5.80\times10^3\ \text{mol CH}_3\text{OH/h}}}$$

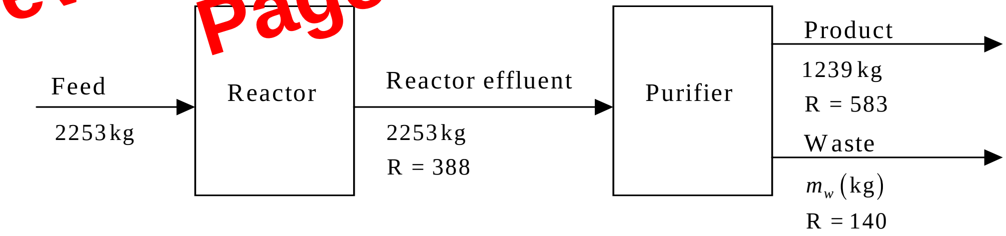
$$\frac{673\,\text{kg}}{\text{h}}\,\Big|\,\frac{0.724\,\text{kg H}_2\text{O}}{\text{kg}}\,\Big|\,\frac{1000\,\text{g}}{\text{kg}}\,\Big|\,\frac{\text{mol H}_2\text{O}}{18\,\text{g H}_2\text{O}} = \underline{\underline{2.71\times10^4\ \text{mol H}_2\text{O/h}}}$$

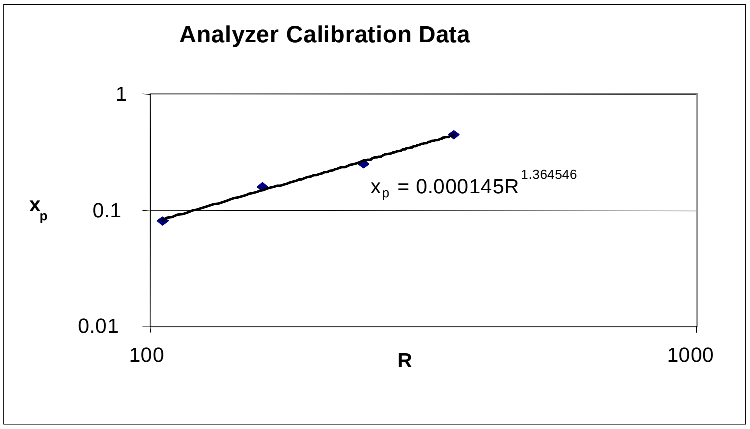
Mole fraction of Methanol:

$$\frac{5.80\times10^3}{5.80\times10^3 + 2.71\times10^4} = \underline{\underline{0.176\ \text{mol CH}_3\text{OH/mol}}}$$

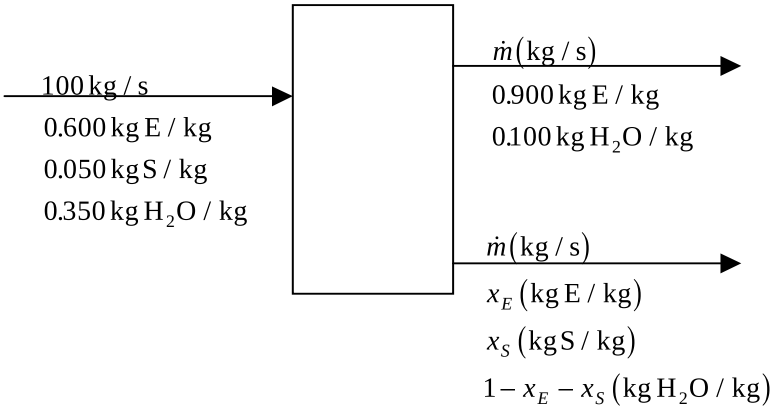
c. Analyzer is wrong, flow rates are wrong, impurities in the feed, a reaction is taking place, the system is not at steady state.

4.13 **a.**





4.15 **a.**



3 unknowns ($\dot{m}, x_E, x_S$)
– 3 balances
0 DF

b. Overall balance: $100 = 2\dot{m} \Rightarrow \dot{m} = 50.0\,(\text{kg/s})$

S balance: $0.050(100) = x_S(50) \Rightarrow \underline{\underline{x_S = 0.100\,(\text{kg S/kg})}}$

E balance: $0.600(100) = 0.900(50) + x_E(50) \Rightarrow x_E = 0.300\ \text{kg E/kg}$

$$\frac{\text{kg E in bottom stream}}{\text{kg E in feed}} = \frac{0.300(50)}{0.600(100)} = \underline{\underline{0.25\frac{\text{kg E in bottom stream}}{\text{kg E in feed}}}}$$

c. $x = aR^b \Rightarrow \ln(x) = \ln(a) + b\ln(R)$

$$b = \frac{\ln(x_2/x_1)}{\ln(R_2/R_1)} = \frac{\ln(0.400/0.100)}{\ln(38/15)} = 1.491$$

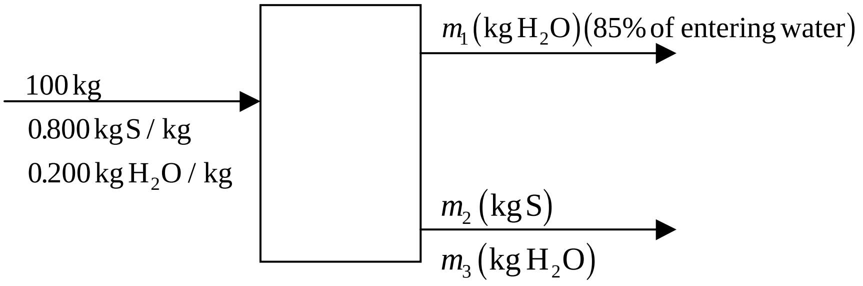
$$\ln(a) = \ln(x_1) - b\ln(R_1) = \ln(0.100) - 1.491\ln(15) = -6.340 \Rightarrow a = 1.764\times10^{-3}$$

$$\underline{\underline{x = 1.764\times10^{-3}R^{1.491}}}$$

$$R = \left(\frac{x}{a}\right)^{\frac{1}{b}} = \left(\frac{0.900}{1.764\times10^{-3}}\right)^{\frac{1}{1.491}} = \underline{\underline{65.5}}$$

d. Device not calibrated – recalibrate. Calibration curve deviates from linearity at high mass fractions – measure against known standard. Impurities in the stream – analyze a sample. Mixture is not all liquid – check sample. Calibration data are temperature dependent – check calibration at various temperatures. System is not at steady state – take more measurements. Scatter in data – take more measurements.

4.18 **a.**



<u>85% drying</u>: $m_1 = 0.850(0.200)(100) = 17.0 \text{ kg H}_2\text{O}$

<u>Sugar balance</u>: $m_2 = 0.800(100) = 80.0 \text{ kg S}$

<u>Overall balance</u>: $100 = 17 + 80 + m_3 \Rightarrow m_3 = 3 \text{ kg H}_2\text{O}$

$$x_w = \frac{3 \text{ kg H}_2\text{O}}{(3+80)\text{ kg}} = \underline{\underline{0.0361 \text{ kg H}_2\text{O / kg}}}$$

$$\frac{m_1}{m_2 + m_3} = \frac{17 \text{ kg H}_2\text{O}}{(80+3)\text{ kg}} = \underline{\underline{0.205 \text{ kg H}_2\text{O / kg wet sugar}}}$$

b.

$$\frac{1000 \text{ tons wet sugar}}{\text{day}}\left|\frac{3 \text{ tons H}_2\text{O}}{100 \text{ tons wet sugar}}\right. = \underline{\underline{30 \text{ tons H}_2\text{O / day}}}$$

$$\frac{1000 \text{ tons WS}}{\text{day}}\left|\frac{0.800 \text{ tons DS}}{\text{ton WS}}\right|\frac{2000 \text{ lb}_\text{m}}{\text{ton}}\left|\frac{\$0.15}{\text{lb}_\text{m}}\right|\frac{365 \text{ days}}{\text{year}} = \underline{\underline{\$8.8 \times 10^7 \text{ per year}}}$$

c.

$$\bar{x}_w = \frac{1}{10}(x_{w1} + x_{w2} + \ldots + x_{w10}) = 0.0504 \text{ kg H}_2\text{O / kg}$$

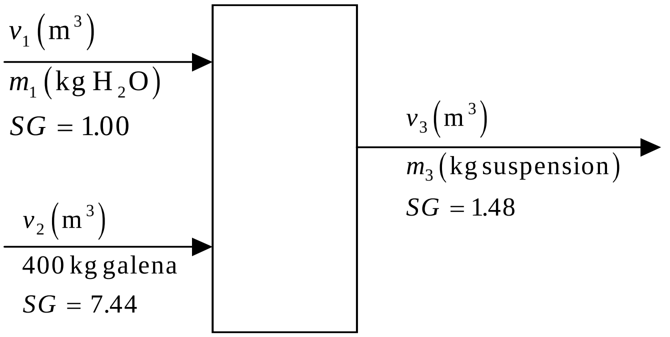
$$\text{SD} = \sqrt{\frac{1}{9}\left[(x_{w1} - \bar{x}_w)^2 + \ldots + (x_{w10} - \bar{x}_w)^2\right]} = 0.00181 \text{ kg H}_2\text{O / kg}$$

Endpoints $= 0.0504 \pm 3(0.00181)$

$\underline{\underline{\text{Lower limit} = 0.0450}}$, $\underline{\underline{\text{Upper limit} = 0.0558}}$

d. The evaporator is probably not working according to design specifications since $x_w = 0.0361 < 0.0450$.

4.19 **a.**



5 unknowns (v_1, v_2, v_3, m_1, m_3)
– 1 mass balance
– 1 volume balance
<u>– 3 specific gravities</u>
0 DF

<u>Total mass balance</u>: $m_1 + 400 = m_3$ (1)

4.26 (cont'd)

8 unknowns ($\dot{n}_1, \dot{n}_3, \dot{v}_1, \dot{m}_2, \dot{m}_4, x_4, y_1, y_3$)
– 3 material balances
– 2 analyzer readings
– 1 meter reading
– 1 gas density formula
– 1 specific gravity
0 DF

b. Orifice meter calibration:

A log plot of $\dot{V}$ vs. h is a line through the points $(h_1 = 100, \dot{V}_1 = 142)$ and $(h_2 = 400, \dot{V}_2 = 290)$.

$$\ln \dot{V} = b \ln h + \ln a \Rightarrow \dot{V} = ah^b$$

$$b = \frac{\ln(\dot{V}_2/\dot{V}_1)}{\ln(h_2/h_1)} = \frac{\ln(290/142)}{\ln(400/100)} = 0.515$$

$$\ln a = \ln \dot{V}_1 - b \ln h_1 = \ln(142) - 0.515 \ln 100 = 2.58 \Rightarrow a = e^{2.58} = 13.2 \Rightarrow \underline{\underline{\dot{V} = 13.2 h^{0.515}}}$$

Analyzer calibration:

$$\ln y = bR + \ln a \Rightarrow y = ae^{bR}$$

$$\left.\begin{array}{l} b = \dfrac{\ln(y_2/y_1)}{R_2 - R_1} = \dfrac{\ln(0.1107/0.00166)}{90 - 20} = 0.0600 \\ \ln a = \ln y_1 - bR_1 = \ln(0.00166) - 0.0600(20) = -7.60 \\ \qquad \Downarrow \\ a = 5.00 \times 10^{-4} \end{array}\right\} \Rightarrow \underline{\underline{y = 5.00 \times 10^{-4} e^{0.0600R}}}$$

c. $h_1 = 210 \text{ mm} \Rightarrow \dot{V}_1 = 13.2(210)^{0.515} = 207.3 \text{ m}^3/\text{min}$

$$\rho_{\text{feed gas}} = \frac{(12.2)[(150 + 14.7)/14.7](\text{atm})}{[(75 + 460)/1.8](\text{K})} = 0.460 \text{ mol / L} = 0.460 \text{ kmol / m}^3$$

$$\Downarrow$$

$$\dot{n}_1 = \frac{207.3 \text{ m}^3}{\text{min}} \left| \frac{0.460 \text{ kmol}}{\text{m}^3} \right. = 95.34 \text{ kmol/min}$$

$$R_1 = 82.4 \Rightarrow y_1 = 5.00 \times 10^{-4} \exp(0.0600 \times 82.4) = 0.0702 \text{ kmol SO}_2/\text{kmol}$$

$$R_3 = 11.6 \Rightarrow y_3 = 5.00 \times 10^{-4} \exp(0.0600 \times 11.6) = 0.00100 \text{ kmol SO}_2/\text{kmol}$$

$$\dot{m}_2 = \frac{1000 \text{ L B}}{\text{min}} \left| \frac{1.30 \text{ kg}}{\text{L B}} \right. = 1300 \text{ kg / min}$$

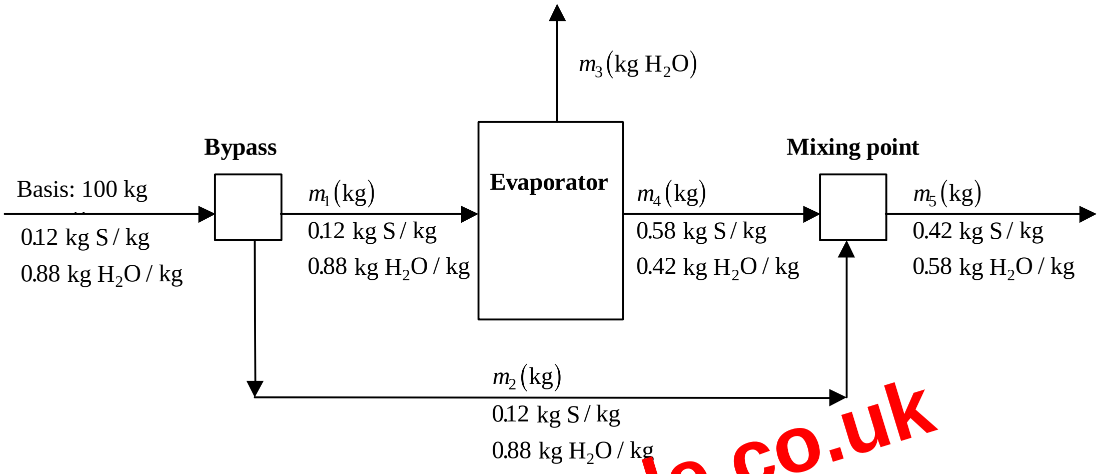
4.31 (cont'd)

c. B fraction in bottoms: $x_B = \underline{\underline{0.100 \text{ mol B/mol}}}$

Moles of overhead: $\dot{n}_1 = \underline{\underline{46.0 \text{ mol}}}$ Moles of bottoms: $\dot{n}_3 = \underline{\underline{54.0 \text{ mol}}}$

Recovery of toluene: $\dfrac{(1-x_B)\dot{n}_3}{0.50(100)} \times 100\% = \dfrac{(1-0.10)(54.02)}{0.50(100)} \times 100\% = \underline{\underline{97\%}}$

4.32 a.



Overall process: 2 unknowns (m_3, m_5)
− 2 balances
0 DF

Bypass: 2 unknowns (m_1, m_2)
− 1 independent balance
1 DF

Evaporator: 3 unknowns (m_1, m_3, m_4)
− 2 balances
1 DF

Mixing point: 3 unknowns (m_2, m_4, m_5)
− 2 balances
1 DF

Overall S balance: $0.12(100) = 0.42\underline{\underline{m_5}}$

Overall mass balance: $100 = \underline{\underline{m_3}} + m_5$

Mixing point mass balance: $\underline{\underline{m_4}} + \underline{\underline{m_2}} = m_5$ (1)

Mixing point S balance: $0.58\underline{\underline{m_4}} + 0.12\underline{\underline{m_2}} = 0.42m_5$ (2)

Solve (1) and (2) simultaneously

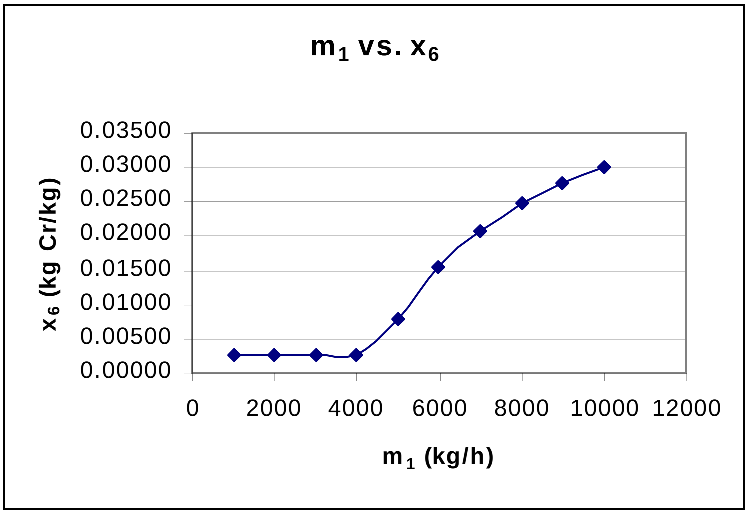
Bypass mass balance: $100 = \underline{\underline{m_1}} + m_2$

b. $m_1 = 90.05 \text{ kg},\ m_2 = 9.95 \text{ kg},\ m_3 = 71.4 \text{ kg},\ m_4 = 18.65 \text{ kg},\ m_5 = \underline{\underline{28.6 \text{ kg product}}}$

Bypass fraction: $\dfrac{m_2}{100} = \underline{\underline{0.095}}$

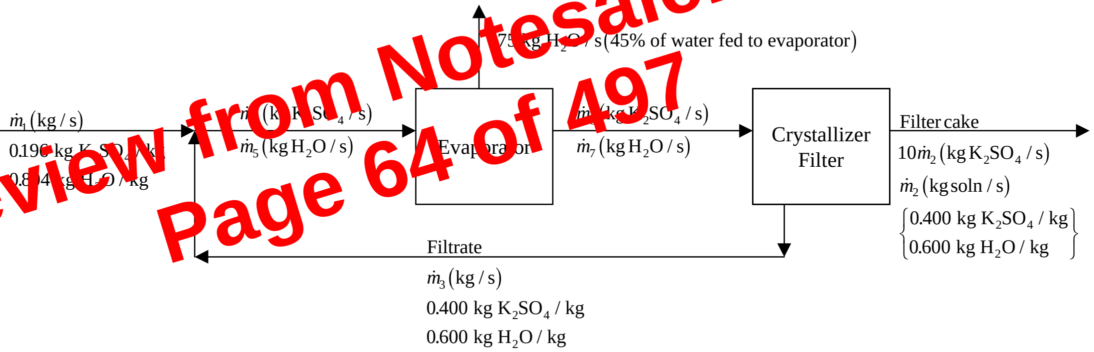
c. Over-evaporating could degrade the juice; additional evaporation could be uneconomical; a stream consisting of 90% solids could be hard to transport.

4.33 (cont'd)



d. Cost of additional capacity – installation and maintenance, revenue from additional recovered Cr, anticipated wastewater production in coming years, capacity of waste lagoon, regulatory limits on Cr emissions.

4.34 **a.**



Let K = K_2SO_4, W = H_2 <u>Basis</u>: 175 kg W evaporated/s

<u>Overall process</u>: 2 unknowns ($\dot{m}_1, \dot{m}_2$)
<u>- 2 balances</u>
0 DF

<u>Mixing point</u>: 4 unknowns ($\dot{m}_1, \dot{m}_3, \dot{m}_4, \dot{m}_5$)
<u>- 2 balances</u>
2 DF

<u>Evaporator</u>: 4 unknowns ($\dot{m}_4, \dot{m}_5, \dot{m}_6, \dot{m}_7$)
– 2 balances
<u>– 1 percent evaporation</u>
1 DF

<u>Crystallizer</u>: 4 unknowns ($\dot{m}_2, \dot{m}_3, \dot{m}_6, \dot{m}_7$)
<u>– 2 balances</u>
2 DF

<u>Strategy</u>:
Overall balances $\Rightarrow \dot{m}_1, \dot{m}_2$
% evaporation $\Rightarrow \dot{m}_5$
Balances around mixing point $\Rightarrow \dot{m}_3, \dot{m}_4$
Balances around evaporator $\Rightarrow \dot{m}_6, \dot{m}_7$

} verify that each chosen subsystem involves no more than two unknown variables

4.37 (cont'd)

Balances around the mixing point involve 3 unknowns (m_3, m_6, x), as do balances around the filter (m_4, m_6, x), but the tub only involves 2 (m_3, m_4) and 2 balances are allowed for each subsystem. Balances around tub $\Rightarrow m_3, m_4$

Balances around mixing point $\Rightarrow m_6, x$ (solves Part (b))

a. <u>95% dirt removal</u>: $m_1 = (0.05)(2.0) = 0.10 \text{ lb}_\text{m}$ dirt

<u>Overall dirt balance</u>: $2.0 = 0.10 + (0.92)m_5 \Rightarrow m_5 = 2.065 \text{ lb}_\text{m}$ dirt

<u>Overall Whizzo balance</u>: $m_2 = [3 + (0.08)(2.065)](\text{lb}_\text{m} \text{ Whizzo}) = \underline{\underline{3.17 \text{ lb}_\text{m} \text{ Whizzo}}}$

b. <u>Tub dirt balance</u>: $2 + 0.03m_3 = 0.10 + 0.13m_4$ (1)

<u>Tub Whizzo balance</u>: $0.97m_3 = 3 + 0.87m_4$ (2)

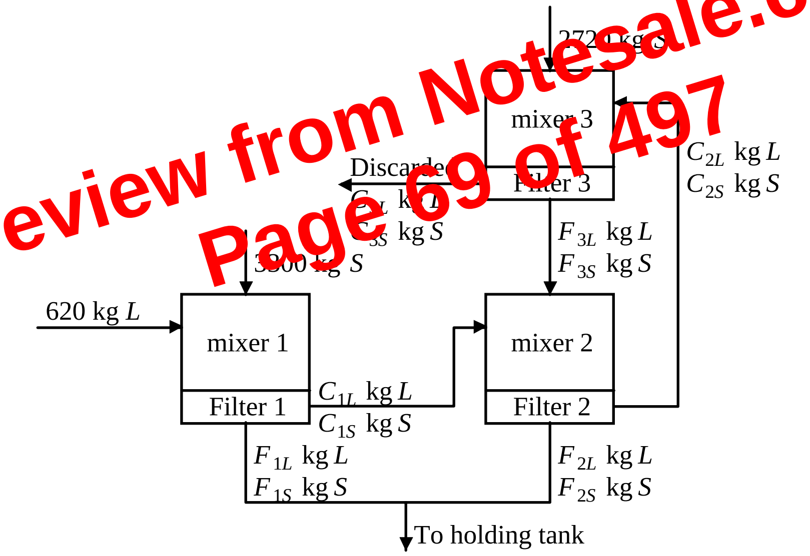
Solve (1) & (2) simultaneously $\Rightarrow m_3 = 20.4 \text{ lb}_\text{m}, m_4 = 19.3 \text{ lb}_\text{m}$

<u>Mixing pt. mass balance</u>: $3.17 + m_6 = 20.4 \text{ lb}_\text{m} \Rightarrow m_6 = 17.3 \text{ lb}_\text{m}$

<u>Mixing pt. Whizzo balance</u>:

$$3.17 + x(17.3) = (0.97)(20.4) \Rightarrow x = 0.961 \text{ lb}_\text{m} \text{ Whizzo/lb}_\text{m} \Rightarrow \underline{\underline{96\% \text{ Whizzo, } 4\% \text{ dirt}}}$$

4.38 a.



$$\begin{array}{rlcr}
\text{mixer/filter 1:} & 0.01(620) = F_{1L} & \Rightarrow & F_{1L} = 6.2 \text{ kg L} \\
\text{balance:} & 620 = 6.2 + C_{1L} & \Rightarrow & C_{1L} = 613.8 \text{ kg L} \\
\text{mixer/filter 2:} & 0.01(613.8 + F_{3L}) = F_{2L} & \left.\right\} & F_{2L} = 6.2 \text{ kg L} \\
\text{balance:} & 613.8 + F_{3L} = F_{2L} + C_{3L} & \Rightarrow & C_{2L} = 613.7 \text{ kg L} \\
\text{mixer/filter 3:} & 0.01C_{2L} = F_{3L} & & F_{3L} = 6.1 \text{ kg L} \\
\text{balance:} & 613.7 = 6.1 + \text{C}_{3L} & \Rightarrow & C_{3L} = 607.6 \text{ kg L}
\end{array}$$

4.39 (cont'd)

b. $$\frac{n_{H_2}}{n_{C_2H_2}} = 1.5 < 2.0 \Rightarrow \underline{\underline{H_2 \text{ is limiting reactant}}}$$

$1.5 \text{ mol } H_2 \text{ fed} \Rightarrow 1.0 \text{ mol } C_2H_2 \text{ fed} \Rightarrow 0.75 \text{ mol } C_2H_2 \text{ required (theoretical)}$

$$\% \text{ excess } C_2H_2 = \frac{1.0 \text{ mol fed} - 0.75 \text{ mol required}}{0.75 \text{ mol required}} \times 100\% = \underline{\underline{33.3\%}}$$

c. $$\frac{4\times 10^6 \text{ tonnes } C_2H_6}{\text{yr}}\left|\frac{1 \text{ yr}}{300 \text{ days}}\right|\frac{1 \text{ day}}{24 \text{ h}}\left|\frac{1 \text{ h}}{3600 \text{ s}}\right|\frac{1000 \text{ kg}}{\text{tonne}}\left|\frac{1 \text{ kmol } C_2H_6}{30.0 \text{ kg } C_2H_6}\right|\frac{2 \text{ kmol } H_2}{1 \text{ kmol } C_2H_6}\left|\frac{2.00 \text{ kg } H_2}{1 \text{ kmol } H_2}\right.$$

$= 20.6 \text{ kg } H_2 / \text{s}$

d. The extra cost will be involved in separating the product from the excess reactant.

4.40 **a.** $4\,NH_3 + 5\,O_2 \rightarrow 4\,NO + 6\,H_2O$

$$\frac{5 \text{ lb-mole } O_2 \text{ react}}{4 \text{ lb-mole NO formed}} = \underline{\underline{1.25 \text{ lb-mole } O_2 \text{ react / lb-mole NO formed}}}$$

b. $$\left(n_{O_2}\right)_{\text{theoretical}} = \frac{100 \text{ kmol } NH_3}{\text{h}}\left|\frac{5 \text{ kmol } O_2}{4 \text{ kmol } NH_3}\right. = 125 \text{ kmol } O_2$$

$$40\% \text{ excess } O_2 \Rightarrow \left(n_{O_2}\right)_{\text{fed}} = 1.40(125 \text{ kmol } O_2) = \underline{\underline{175 \text{ kmol } O_2}}$$

c. $(50.0 \text{ kg } NH_3)(1 \text{ kmol } NH_3 / 17 \text{ kg } NH_3) = 2.94 \text{ kmol } NH_3$

$(100.0 \text{ kg } O_2)(1 \text{ kmol } O_2 / 32 \text{ kg } O_2) = 3.125 \text{ kmol } O_2$

$$\left(\frac{n_{O_2}}{n_{NH_3}}\right)_{\text{fed}} = \frac{3.125}{2.94} = 1.06 < \left(\frac{n_{O_2}}{n_{NH_3}}\right)_{\text{stoich}} = \frac{5}{4} = 1.25$$

$\Rightarrow \underline{\underline{O_2 \text{ is the limiting reactant}}}$

<u>Required NH₃</u>: $$\frac{3.125 \text{ kmol } O_2}{}\left|\frac{4 \text{ kmol } NH_3}{5 \text{ kmol } O_2}\right. = 2.50 \text{ kmol } NH_3$$

$$\underline{\% \text{excess } NH_3} = \frac{2.94 - 2.50}{2.50} \times 100\% = \underline{\underline{17.6\% \text{ excess } NH_3}}$$

<u>Extent of reaction</u>: $n_{O_2} = \left(n_{O_2}\right)_0 - \nu_{O_2}\xi \Rightarrow 0 = 3.125 - (-5)\xi \Rightarrow \xi = 0.625 \text{ kmol} = \underline{\underline{625 \text{ mol}}}$

<u>Mass of NO</u>: $$\frac{3.125 \text{ kmol } O_2}{}\left|\frac{4 \text{ kmol NO}}{5 \text{ kmol } O_2}\right|\frac{30.0 \text{ kg NO}}{1 \text{ kmol NO}} = \underline{\underline{75.0 \text{ kg NO}}}$$

4.41 **a.** By adding the feeds in stoichiometric proportion, all of the H_2S and SO_2 would be consumed. Automation provides for faster and more accurate response to fluctuations in the feed stream, reducing the risk of release of H_2S and SO_2. It also may reduce labor costs.

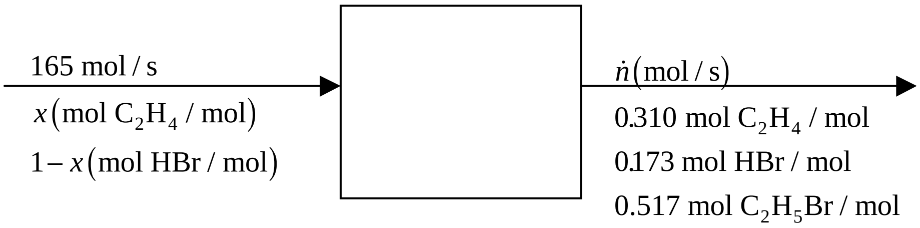
4.41 (cont'd)

$$R_c = \frac{10}{7}(45)\left[(0.0119)(76.5) - 0.0605\right] - \frac{5}{7} = 53.9\ \text{mV}$$

$$\Rightarrow \dot{n}_c = \frac{7}{3}(53.9) + \frac{5}{3} = 127.4\ \text{kmol / h}$$

e. Faulty sensors, computer problems, analyzer calibration not linear, extrapolation beyond range of calibration data, system had not reached steady state yet.

4.42



$$C_2H_4 + HBr \rightarrow C_2H_5Br$$

<u>C balance</u>: $\dfrac{165\,\text{mol}}{\text{s}}\left|\dfrac{x(\text{mol}\,C_2H_4)}{\text{mol}}\right|\dfrac{2\,\text{mol C}}{\text{mol}\,C_2H_4} = \dot{n}(0.310)(2) + \dot{n}(0.517)(2)$ (1)

<u>Br balance</u>: $165(1-x)(1) = \dot{n}(0.173)(1) + \dot{n}(0.517)(1)$ (2)

(Note: An atomic H balance can be obtained as 2*(Eq. 2) + (Eq. 1) and so is not independent)

Solve (1) and (2) simultaneously $\Rightarrow \dot{n} = 108.77\ \text{mol / s},\ x = 0.545\ \text{mol}\ C_2H_4\ /\ \text{mol}$

$\Rightarrow (1-x) = 0.455\ \text{mol HBr / mol}$

Since the C_2H_4/HBr feed ratio (0.545/0.455) is greater than the stoichiometric ration (=1), <u>HBr is the limiting reactant</u>.

$$(\dot{n}_{HBr})_{fed} = (165\,\text{mol / s})(0.455\,\text{mol HBr / mol}) = 75.08\,\text{mol HBr}$$

<u>Fractional conversion of HBr</u> $= \dfrac{75.08 - (0.173)(108.8)}{75.08} = \underline{\underline{0.749\ \text{mol HBr react/mol fed}}}$

$$(\dot{n}_{C_2H_4})_{stoich} = 75.08\,\text{mol}\,C_2H_4$$

$$(\dot{n}_{C_2H_4})_{fed} = (165\,\text{mol/s})(0.545\,\text{mol}\,C_2H_4\text{/mol}) = 89.93\,\text{mol}\,C_2H_4$$

<u>% excess of C_2H_4</u> $= \dfrac{89.93 - 75.08}{75.08} = \underline{\underline{19.8\%}}$

<u>Extent of reaction:</u> $\dot{n}_{C_2H_5Br} = (\dot{n}_{C_2H_5Br})_0 + \nu_{C_2H_5Br}\xi \Rightarrow (108.8)(0.517) = 0 + (1)\xi \Rightarrow \underline{\underline{\xi = 56.2\,\text{mol/s}}}$

4.47 **(cont'd)**

d.

T (K)	x (CO)	x (H_2O)	x (CO_2)	Keq	Keq (Goal Seek)	Extent of Reaction	y (H_2)
1223	0.5	0.5	0	0.6610	0.6610	0.2242	0.224
1123	0.5	0.5	0	0.8858	0.8856	0.2424	0.242
1023	0.5	0.5	0	1.2569	1.2569	0.2643	0.264
923	0.5	0.5	0	1.9240	1.9242	0.2905	0.291
823	0.5	0.5	0	3.2662	3.2661	0.3219	0.322
723	0.5	0.5	0	6.4187	6.4188	0.3585	0.358
623	0.5	0.5	0	15.6692	15.6692	0.3992	0.399
673	0.5	0.5	0	9.7017	9.7011	0.3785	0.378
698	0.5	0.5	0	7.8331	7.8331	0.3684	0.368
688	0.5	0.5	0	8.5171	8.5177	0.3724	0.372
1123	0.2	0.4	0.1	0.8858	0.8863	0.1101	0.110
1123	0.4	0.2	0.1	0.8858	0.8857	0.1100	0.110
1123	0.3	0.3	0	0.8858	0.8856	0.1454	0.145
1123	0.5	0.4	0	0.8858	0.8867	0.2156	0.216

The lower the temperature, the higher the extent of reaction. An equimolar feed ratio of carbon monoxide and water also maximizes the extent of reaction.

4.48 **a.** $\mathrm{A + 2B \rightarrow C}$

$$\ln K_e = \ln A_0 + E/T(K)$$

$$E = \frac{\ln(K_{e1}/K_{e2})}{1/T_1 - 1/T_2} = \frac{\ln(10.5/2.316\times 10^{-4})}{1/373 - 1/573} = 11458$$

$$\ln A_0 = \ln K_{e1} - 11458/T_1 = \ln 10.5 - 11458/373 = -28.37 \Rightarrow A_0 = 4.79\times 10^{-13}$$

$$\underline{\underline{K_e = 4.79\times 10^{-13}\exp(11458/T(K))\ \text{atm}^{-2}}} \Rightarrow \underline{\underline{K_e(450K) = 0.0548\ \text{atm}^{-1}}}$$

b.

$$\left.\begin{array}{l} n_A = n_{A0} - \xi \\ n_B = n_{B0} - 2\xi \\ n_C = n_{C0} + \xi \\ \hline n_T = n_{T0} - 2\xi \end{array}\right\} \Rightarrow \begin{array}{l} y_A = (n_{A0} - \xi)/(n_{T0} - 2\xi) \\ y_B = (n_{B0} - 2\xi)/(n_{T0} - 2\xi) \\ y_C = (n_{C0} + \xi)/(n_{T0} - 2\xi) \\ \hline (n_{T0} = n_{A0} + n_{B0} + n_{C0}) \end{array}$$

At equilibrium,

$$\frac{y_C}{y_A y_B^2}\frac{1}{P^2} = \underline{\underline{\frac{(n_{C0}+\xi_e)(n_{T0}-2\xi_e)^2}{(n_{A0}-\xi_e)(n_{B0}-2\xi_e)^2}\frac{1}{P^2}}} = K_e(T) \text{ (substitute for } K_e(T) \text{ from Part a.)}$$

c. <u>Basis</u>: 1 mol A (CO)

$$n_{A0} = 1 \quad n_{B0} = 1 \quad n_{C0} = 0 \Rightarrow n_{T0} = 2,\ P = 2\ \text{atm},\ T = 423\text{K}$$

$$\frac{\xi_e(2-2\xi_e)^2}{(1-\xi_e)(1-2\xi_e)^2}\frac{1}{4\ \text{atm}^2} = K_e(423) = 0.278\ \text{atm}^{-2} \Rightarrow \xi_e^2 - \xi_e + 0.1317 = 0$$

4.51 (cont'd)

b.

$$\left.\begin{array}{r}(1)\ \Rightarrow\ n_1 = 46.08 \text{ mol } C_2H_6\\ (3)\ \Rightarrow n_2 = 47.4 \text{ mol } H_2O\\ (4)\ \Rightarrow n_3 = 9.3 \text{ mol I}\end{array}\right\}\Rightarrow \underline{\underline{\text{Reactor feed contains 44.8\% } C_2H_6\text{, 46.1\% } H_2O\text{, 9.1\% I}}}$$

$\underline{\text{\% conversion of } C_2H_4}$: $\dfrac{46.08-43.3}{46.08}\times 100\% = \underline{\underline{6.0\%}}$

If all C_2H_4 were converted and the second reaction did not occur, $\left(n_{C_2H_5OH}\right)_{\max} = 46.08$ mol

$\Rightarrow$ $\underline{\text{Fractional Yield of } C_2H_5OH}$: $n_{C_2H_5OH} / \left(n_{C_2H_5OH}\right)_{\max} = (2.5/46.08) = \underline{\underline{0.054}}$

$\underline{\text{Selectivity of } C_2H_5OH \text{ to } (C_2H_5)_2O}$:

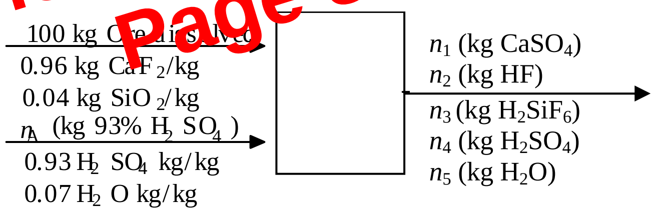
$$\frac{2.5 \text{ mol } C_2H_5OH}{0.14 \text{ mol } (C_2H_5)_2O} = \underline{\underline{17.9 \text{ mol } C_2H_5OH / \text{ mol } (C_2H_5)_2O}}$$

c. Keep conversion low to prevent C_2H_5OH from being in reactor long enough to form significant amounts of $(C_2H_5)_2O$. Separate and recycle unreacted C_2H_4.

4.52 $CaF_2(s) + H_2SO_4(l) \rightarrow CaSO_4(s) + 2HF(g)$

$$\frac{1 \text{ metric ton acid}}{} \left| \frac{1000 \text{ kg acid}}{1 \text{ metric ton acid}} \right| \frac{0.60 \text{ kg HF}}{1 \text{ kg acid}} = 600 \text{ kg HF}$$

$\underline{\text{Basis: 100 kg Ore dissolved (not fed)}}$



$\underline{\text{Atomic balance - Si:}}$

$$\frac{0.04(100) \text{ kg } SiO_2}{} \left| \frac{28.1 \text{ kg Si}}{60.1 \text{ kg } SiO_2} \right. = \frac{n_3 \text{ (kg } H_2SiF_6)}{} \left| \frac{28.1 \text{ kg Si}}{144.1 \text{ kg } H_2SiF_6} \right. \Rightarrow n_3 = 9.59 \text{ kg } H_2SiF_6$$

$\underline{\text{Atomic balance - F:}}$

$$\frac{0.96(100) \text{ kg } CaF_2}{} \left| \frac{38.0 \text{ kg F}}{78.1 \text{ kg } CaF_2} \right. = \frac{n_2 \text{ (kg HF)}}{} \left| \frac{19.0 \text{ kg F}}{20.0 \text{ kg HF}} \right.$$

$$+ \frac{9.59 \text{ kg } H_2SiF_6}{} \left| \frac{114.0 \text{ kg F}}{144.1 \text{ kg } H_2SiF_6} \right. \Rightarrow n_2 = 41.2 \text{ kg HF}$$

$$\frac{600 \text{ kg HF}}{} \left| \frac{100 \text{ kg ore diss.}}{41.2 \text{ kg HF}} \right| \frac{1 \text{ kg ore feed}}{0.95 \text{ kg ore diss.}} = \underline{\underline{1533 \text{ kg ore}}}$$

4.54 (cont’d)

```
  2     FORMAT('0', 15X, 'NA0, NB0, NC0, ND0, NE0 *', 5F6.2/)
        NTO = NA0 + NB0 + NC0 + ND0 + NE0
        NMAX = 10
        X1 = 0.1
        X2 = 0.1
        DO 100 J = 1, NMAX
        NA = NA0 – X1 – X1
        NB = NB0 + X1 + X1
        NC = NC0 + X1 – X2
        ND = ND0 – X2
        NE = NE0 + X2 + X2
        NAS = NA ** 2
        NBS = NB ** 2
        NES = NE ** 2
        NT = NT0 + X1
        F1 = 0.1071 * NAS * NT – NBS * NC
        F2 = 0.01493 * NC * ND – NES
        A11 = –0.4284 * NA * NT * 0.1071 * NAS – 4.0 * NB * NC – NBS
        A12 = NBS
        A21 = 0.01493 * ND
         A22 = –0.01493 * (NC + ND) – 4.0 * NE
        DEN = A11 * A22 – A12 * A21
        D1 = (A12 * F2 – A22 * F1)/DEN
        D2 = (A21 * F1 – A11 * F2)/DEN
        X1C = X1 + D1
        X2C = X2 + D2
        WRITE (6, 3) J, X1, X2, X1C, X2C
  3     FORMAT(20X, 'ITER =', I3, 3X, 'X1A, X2A =', 2F10.5, 6X, 'X1C, X2C =', * 2F10.5)
        IF (ABS(D1/X1C).LT.1.0E–5.AND.ABS(D2/X2C).LT.1.0E–5) GOTO 120
        X1 = X1C
        X2 = X2C
100     CONTINUE
        WRITE (6, 4) NMAX
  4     FORMAT('0', 10X, 'PROGRAM DID NOT CONVERGE IN', I2, 'ITERATIONS'/)
        STOP
120     YA = NA/NT
        YB = NB/NT
        YC = NC/NT
        YD = ND/NT
        YE = NE/NT
        WRITE (6, 5) YA, YB, YC, YD, YE
      5 FORMAT ('0', 15X, 'YA, YB, YC, YD, YE =', 1P5E14.4///)
        GOTO 30
        END
        $DATA
        0.3333   0.00   0.3333   0.3333   0.0
        0.50     0.0    0.0      0.50     0.0
        0.20     0.20   0.20     0.20     0.20
```

```
SOLUTION TO PROBLEM 4.54
NA0, NB0, NC0, ND0, NE0 = 0.33   0.00    0.33    0.33    0.00
ITER = 1   X1A, X2A = 0.10000    0.10000          X1C, X2C = 0.06418       0.05181
ITER = 2   X1A, X2A = 0.06418    0.05181          X1C, X2C = 0.05969       0.02986
ITER = 3   X1A, X2A = 0.05969    0.02486          X1C, X2C = 0.05937       0.02213
```

4.63 **a.** <u>A balance on *i*th tank</u> (input = output + consumption)

$$\dot{v}(\text{L/min})C_{A,\,i-1}(\text{mol/L}) = \dot{v}C_{Ai} + kC_{Ai}C_{Bi}(\text{mol/liter}\cdot\text{min})V(\text{L})$$

$$\Downarrow \div \dot{v},\ \text{note } V/\dot{v} = \tau$$

$$\underline{\underline{C_{A,\,i-1} = C_{Ai} + k\tau C_{Ai}C_{Bi}}}$$

<u>B balance</u>. By analogy, $C_{B,\,i-1} = C_{Bi} + k\tau C_{Ai}C_{Bi}$

Subtract equations $\Rightarrow C_{Bi} - C_{Ai} = C_{B,\,i-1} - C_{A,\,i-1} \underset{\substack{\uparrow \\ \text{from balances on} \\ (i-1)^{\text{st}}\ \text{tank}}}{=} C_{B,\,i-2} - C_{A,\,i-2} = \ldots = C_{B0} - C_{A0}$

b. $C_{Bi} - C_{Ai} = C_{B0} - C_{A0} \Rightarrow C_{Bi} = C_{Ai} + C_{B0} - C_{A0}$. Substitute in A balance from part (a).

$C_{A,\,i-1} = C_{Ai} + k\tau C_{Ai}\left[C_{Ai} + (C_{B0} - C_{A0})\right]$. Collect terms in C_{Ai}^2, C_{Ai}^1, C_{Ai}^0.

$C_{Ai}^2[k\tau] + C_{AL}\left[1 + k\tau(C_{B0} - C_{A0})\right] - C_{A,\,i-1} = 0$

$$\Rightarrow \alpha C_{AL}^2 + \beta C_{AL} + \gamma = 0 \text{ where } \alpha = k\tau,\ \beta = 1 + k\tau(C_{B0} - C_{A0}),\ \gamma = -C_{A,\,i-1}$$

<u>Solution</u>: $C_{Ai} = \dfrac{-\beta + \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}$ (Only + rather than ±: since αγ is negative and the negative solution would yield a negative concentration.)

c.

		N	gamma	CA(N)	xA(N)
k =	36.2	1	-5.670E-02	2.791E-02	0.5077
v =	5000	2	-2.791E-02	1.512E-02	0.7333
V =	2000	3	-1.512E-02	8.631E-03	0.8478
CA0 =	0.0567	4	-8.631E-03	5.076E-03	0.9105
CB0 =	0.1000	5	-5.076E-03	3.038E-03	0.9464
alpha =	14.48	6	-3.038E-03	1.837E-03	0.9676
beta =	1.6270	7	-1.837E-03	1.118E-03	0.9803
		8	-1.118E-03	6.830E-04	0.9880
		9	-6.830E-04	4.182E-04	0.9926
		10	-4.182E-04	2.565E-04	0.9955
		11	-2.565E-04	1.574E-04	0.9972
		12	-1.574E-04	9.667E-05	0.9983
		13	-9.667E-05	5.939E-05	0.9990
		14	-5.939E-05	3.649E-05	0.9994

($x_{\min} = 0.50$, $N = 1$), ($x_{\min} = 0.80$, $N = 3$), ($x_{\min} = 0.90$, $N = 4$), ($x_{\min} = 0.95$, $N = 6$), ($x_{\min} = 0.99$, $N = 9$), ($x_{\min} = 0.999$, $N = 13$).

As $x_{\min} \to 1$, the required number of tanks and hence the process cost becomes infinite.

d. (i) k increases ⇒ N decreases (faster reaction ⇒ fewer tanks)

(ii) $\dot{v}$ increases ⇒ N increases (faster throughput ⇒ less time spent in reactor
⇒ lower conversion per reactor)

(iii) V increases ⇒ N decreases (larger reactor ⇒ more time spent in reactor
⇒ higher conversion per reactor)

4.69 (cont'd)

Air feed rate: $n_0 = \frac{387.5 \text{ mol } O_2}{\text{h}} \left| \frac{1 \text{ kmol air}}{0.21 \text{ kmol } O_2} \right| \frac{1.25 \text{ kmol air fed}}{1 \text{ kmol air req'd.}} = 2306.5 \text{ mol air}$

90% propane conversion $\Rightarrow n_1 = 0.100(75 \text{ mol } C_3H_8) = 7.5 \text{ mol } C_3H_8$

$(67.5 \text{ mol } C_3H_8 \text{ reacts})$

85% hydrogen conversion $\Rightarrow n_2 = 0.150(25 \text{ mol } C_3H_8) = 3.75 \text{ mol } H_2$

95% CO_2 selectivity $\Rightarrow n_3 = \frac{0.95(67.5 \text{ mol } C_3H_8 \text{ react})}{} \left| \frac{3 \text{ mol } CO_2 \text{ generated}}{\text{mol } C_3H_8 \text{ react}} \right.$

$= 192.4 \text{ mol } CO_2$

5% CO selectivity $\Rightarrow n_3 = \frac{0.05(67.5 \text{ mol } C_3H_8 \text{ react})}{} \left| \frac{3 \text{ mol CO generated}}{\text{mol } C_3H_8 \text{ react}} \right. = 10.1 \text{ mol CO}$

H balance: $(75 \text{ mol } C_3H_8)\left(8 \frac{\text{mol H}}{\text{mol } C_3H_8}\right) + (25 \text{ mol } H_2)(2)$

$= (7.5 \text{ mol } C_3H_8)(8) + (3.75 \text{ mol } H_2)(2) + n_5(\text{mol } H_2O)(2) \Rightarrow n_5 = 291.2 \text{ mol } H_2O$

O balance: $(0.21 \times 2306.5 \text{ mol } O_2)(2 \frac{\text{mol O}}{\text{mol } O_2}) = (192.4 \text{ mol } CO_2)(2)$

$+ (10.1 \text{ mol CO})(1) + (291.2 \text{ mol } H_2O)(1) + 2n_6(\text{mol } O_2) \Rightarrow n_6 = 141.3 \text{ mol } O_2$

N_2 balance: $n_7 = 0.79(2306.5) \text{ mol } N_2 = 1822 \text{ mol } N_2$

Total moles of exit gas = (7.5 + 3.75 + 192.4 + 10.1 + 291.2 + 141.3 + 1822) mol

= 2468 mol

CO concentration in exit gas $= \frac{10.1 \text{ mol CO}}{2468 \text{ mol}} \times 10^6 = \underline{\underline{4090 \text{ ppm}}}$

b. If more air is fed to the furnace,

(i) more gas must be compressed (pumped), leading to a higher cost (possibly a larger pump, and greater utility costs)

(ii) The heat released by the combustion is absorbed by a greater quantity of gas, and so the product gas temperature decreases and less steam is produced.

5.24 (cont'd)

Monthly revenue:

$$(4043\ \text{kg/h})(24\ \text{h/day})(30\ \text{days/month})(\$0.60/\text{kg}) = \underline{\underline{\$1,747,000/\text{month}}}$$

c. Mass flow rate at Noxious plant after diversion:

$$\begin{array}{c|c|c|c|c} 400\ \text{m}^3 & 273\ \text{K} & 2.8\ \text{atm} & 1\ \text{kmol} & 44.09\ \text{kg} \\ \hline \text{hr} & 303\ \text{K} & 1\ \text{atm} & 22.4\ \text{m}^3 & \text{kmol} \end{array} = 1986\ \text{kg/hr}$$

Propane diverted $= (4043 - 1986)\ \text{kg/h} = \underline{\underline{2057\ \text{kg/h}}}$

5.25 a. $P_{He} = y_{He} \cdot P = 0.35 \cdot (2.00\ \text{atm}) = \underline{\underline{0.70\ \text{atm}}}$

$P_{CH_4} = y_{CH_4} \cdot P = 0.20 \cdot (2.00\ \text{atm}) = \underline{\underline{0.40\ \text{atm}}}$

$P_{N_2} = y_{N_2} \cdot P = 0.45 \cdot (2.00\ \text{atm}) = \underline{\underline{0.90\ \text{atm}}}$

b. Assume 1.00 mole gas

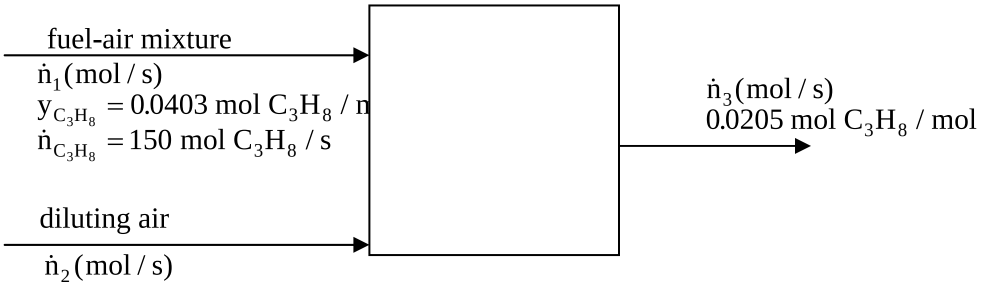
$$\left.\begin{array}{l} 0.35\ \text{mol He}\left(\dfrac{4.004\ \text{g}}{\text{mol}}\right) = 1.40\ \text{g He} \\ 0.20\ \text{mol}\ CH_4\left(\dfrac{16.05\ \text{g}}{\text{mol}}\right) = 3.21\ \text{g}\ CH_4 \\ 0.45\ \text{mol}\ N_2\left(\dfrac{28.02\ \text{g}}{\text{mol}}\right) = 12.61\ \text{g}\ N_2 \end{array}\right\} 17.22\ \text{g} \Rightarrow \text{mass fraction}\ CH_4 = \frac{3.21\ \text{g}}{17.22\ \text{g}} = \underline{\underline{0.186}}$$

c. $\overline{MW} = \dfrac{\text{g of gas}}{\text{mol}} = \underline{\underline{17.2\ \text{g/mol}}}$

d. $$\rho_{gas} = \frac{m}{V} = \frac{n(\overline{MW})}{V} = \frac{P(\overline{MW})}{RT} = \frac{(2.00\ \text{atm})(17.2\ \text{kg/kmol})}{\left(0.08206\ \frac{\text{m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}\right)(363.2\ \text{K})} = \underline{\underline{1.15\ \text{kg/m}^3}}$$

5.26 a. It is safer to release a mixture that is too lean to ignite.
If a mixture that is rich is released in the atmosphere, it can diffuse in the air and the C_3H_8 mole fraction can drop below the UFL, thereby producing a fire hazard.

b.

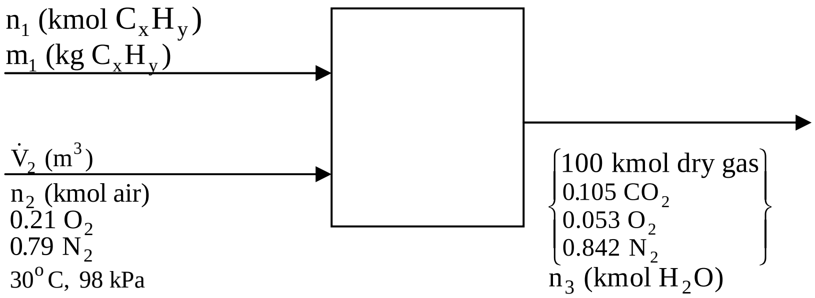


$$\dot{n}_1 = \begin{array}{c|c} 150\ \text{mol}\ C_3H_8 & \text{mol} \\ \hline \text{s} & 0.0403\ \text{mol}\ C_3H_8 \end{array} = 3722\ \text{mol/s}$$

Propane balance: $150 = 0.0205 \cdot \dot{n}_3 \Rightarrow \dot{n}_3 = 7317\ \text{mol/s}$

5.35

<u>Basis:</u> 100 kmol dry product gas



a. $\underline{N_2 \text{ balance}}:\ 0.79n_2 = 0.842(100) \Rightarrow n_2 = 106.6 \text{ kmol air}$

$\underline{\text{O balance}}:\ 2(0.21n_2) = 100[2(0.105) + 2(0.053)] + n_3 \Rightarrow n_3 = 13.17 \text{ kmol } H_2O$

$$\underline{\text{C balance}}:\ \frac{n_1\ (\text{kmol } C_xH_y)}{} \bigg| \frac{x\ (\text{kmol C})}{(\text{kmol } C_xH_y)} = 100(0.105) \Rightarrow n_1x = 10.5 \qquad (1)$$

$$\underline{\text{H balance}}:\ n_1y = 2n_3 \xrightarrow{n_3=13.17} n_1y = 26.34 \qquad (2)$$

$$\text{Divide (2) by (1)} \Rightarrow \frac{y}{x} = \frac{26.34}{10.5} = \underline{\underline{2.51 \text{ mol H / mol C}}}$$

$\underline{O_2 \text{ fed}}:\ 0.21(106.6 \text{ kmol air}) = 22.4 \text{ kmol}$

$\underline{O_2 \text{ in excess}} = 5.3 \text{ kmol} \Rightarrow \underline{\text{Theoretical } O_2} = (22.4 - 5.3) \text{ kmol} = 17.1 \text{ kmol}$

$$\underline{\%\text{ excess}} = \frac{5.3 \text{ kmol } O_2}{17.1 \text{ kmol } O_2} \times 100\% = \underline{\underline{31\% \text{ excess air}}}$$

b. $$V_2 = \frac{106.6 \text{ kmol } N_2}{} \bigg| \frac{22.4 \text{ m}^3 \text{ (STP)}}{\text{kmol}} \bigg| \frac{101.3 \text{ kPa}}{98 \text{ kPa}} \bigg| \frac{303 \text{ K}}{273 \text{ K}} = 2740 \text{ m}^3$$

$$m_1 = \frac{n_1x\ (\text{kmol C})}{} \bigg| \frac{12.0 \text{ kg}}{\text{kmol}} + \frac{n_1y\ (\text{kmol H})}{} \bigg| \frac{1.01 \text{ kg}}{\text{kmol}} \xrightarrow[n_1y=26.34]{n_1x=10.5} m_1 = 152.6 \text{ kg}$$

$$\frac{V_2}{m_1} = \frac{2740 \text{ m}^3 \text{ air}}{152.6 \text{ kg fuel}} = \underline{\underline{18.0\ \frac{\text{m}^3 \text{ air}}{\text{kg fuel}}}}$$

5.36 $3N_2H_4 \rightarrow 6xH_2 + (1+2x)N_2 + (4-4x)NH_3$

a. $\underline{\underline{0 \le x \le 1}}$

b. $$n_{N_2H_4} = \frac{50 \text{ L}}{} \bigg| \frac{0.82 \text{ kg}}{\text{L}} \bigg| \frac{1 \text{ kmol}}{32.06 \text{ kg}} = 1.28 \text{ kmol}$$

$$n_{\text{product}} = 1.28 \text{ kmol } N_2H_4 \left[\frac{6x \text{ kmol } H_2}{3 \text{ kmol } N_2H_4} + \frac{(1+2x) \text{ kmol } N_2}{3 \text{ kmol } N_2H_4} + \frac{(4-4x) \text{ kmol } NH_3}{3 \text{ kmol } N_2H_4} \right]$$

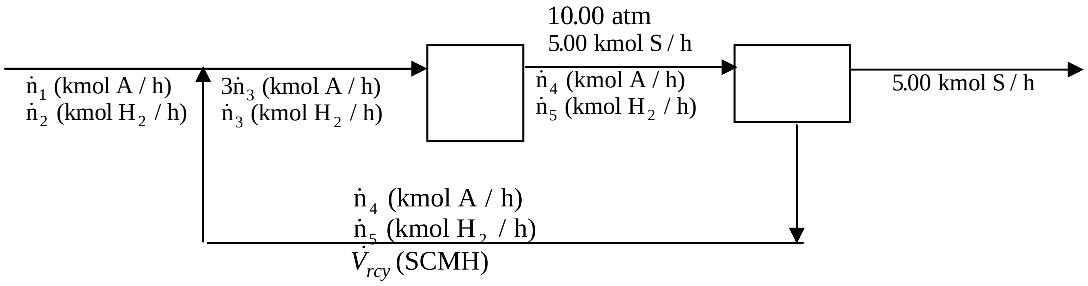
$$= \frac{1.28}{3}(6x + 1 + 2x + 4 - 4x) = 1.707x + 2.13 \text{ kmol}$$

5.49 (cont'd)

c. A semilog plot of K_p vs. $\frac{1}{T}$ is a straight line. Fitting the line to the exponential law yields

$$\ln K_p = -\frac{7367}{T} + 22.747 \Rightarrow K_p = 7.567 \times 10^9 \exp\left(\frac{-7367}{T}\right) \Rightarrow \begin{array}{l} a = 7.567 \times 10^9 \text{ atm} \\ \underline{\underline{b = 7367\text{K}}} \end{array}$$

5.50



$A + H_2 \rightleftarrows S$

$$\underline{\text{Overall A balance:}}\ n_1 = \frac{5.00 \text{ kmol S}}{\text{h}}\left|\frac{1 \text{ kmol A react}}{1 \text{ kmol S form}}\right. = \underline{5.00 \text{ kmol A / h}}$$

$$\underline{\text{Overall } H_2 \text{ balance:}}\ n_2 = \frac{5.00 \text{ kmol S}}{\text{h}}\left|\frac{1 \text{ kmol } H_2 \text{ react}}{1 \text{ kmol S form}}\right. = \underline{5.00 \text{ kmol } H_2 \text{ / h}}$$

$\underline{\text{Extent of reaction equations:}}$ $\dot{n}_i = \dot{n}_{i0} + \nu_i \dot{\xi}$

$A + H_2 \rightleftarrows S$

A: $\dot{n}_4 = 3\dot{n}_3 - \dot{\xi}$

H_2: $\dot{n}_5 = \dot{n}_3 - \dot{\xi}$

S: $5.00 = \dot{\xi}$ =====>

$$\left.\begin{array}{l} \dot{n}_4 = 3\dot{n}_3 - 5.00 \\ \dot{n}_5 = \dot{n}_3 - 5.00 \\ \underline{\dot{n}_S = 5.00} \\ \dot{n}_{tot} = 4\dot{n}_3 - 5.00 \end{array}\right\} \Rightarrow p_A = y_A P = \frac{\dot{n}_4}{\dot{n}_{tot}} P = \frac{3\dot{n}_3 - 5.00}{4\dot{n}_3 - 5.00} 10.0$$

$$p_{H_2} = y_{H_2} P = \frac{\dot{n}_5}{\dot{n}_{tot}} P = \frac{\dot{n}_3 - 5.00}{4\dot{n}_3 - 5.00} 10.0$$

$$p_S = y_S P = \frac{5.00}{4\dot{n}_3 - 5.00} 10.0$$

$$K_p = \frac{p_S}{p_A p_{H_2}} = \frac{5.00(4\dot{n}_3 - 5.00)}{10.0(3\dot{n}_3 - 5.00)(\dot{n}_3 - 5.00)} = 0.100 \Rightarrow \dot{n}_3 = 11.94 \text{ kmol } H_2 \text{ / h}$$

$\dot{n}_4 = 3(11.94) - 5.00 = 30.82$ kmol A / h

$\dot{n}_5 = 11.94 - 5.00 = 6.94$ kmol H_2 / h

$$\dot{V}_{rcy} = [(30.82 + 6.94) \text{ kmol / h}](22.4 \text{ m}^3\text{(STP) / kmol}) = \underline{\underline{846 \text{ SCMH}}}$$

5.54 (cont'd)

$$CO + 2H_2 \Leftrightarrow CH_3OH(M)$$
$$CO_2 + 3H_2 \Leftrightarrow CH_3OH + H_2O$$

a. Let $\xi_1(\text{kmol/h}) = \text{extent of rxn 1},\ \xi_2(\text{kmol/h}) = \text{extent of rxn 2}$

$$\left.\begin{array}{ll} \underline{CO:} & \dot{n}_1 = 30 - \xi_1 \\ \underline{H_2:} & \dot{n}_2 = 63 - 2\xi_1 - 3\xi_2 \\ \underline{CO_2:} & \dot{n}_3 = 5 - \xi_2 \\ \underline{M:} & \dot{n}_4 = \xi_1 + \xi_2 \\ \underline{H_2O:} & \dot{n}_5 = \xi_2 \\ \underline{N_2:} & \dot{n}_{N_2} = 2 \\ \hline & \dot{n}_{tot} = 100 - 2\xi_1 - 2\xi_2 \end{array}\right\} \Rightarrow (K_p)_1 = \frac{P\cdot y_M}{P\cdot y_{CO}(P\cdot y_{H_2})^2},\quad (K_p)_2 = \frac{(P\cdot y_M)(P\cdot y_{H_2O})}{(P\cdot y_{CO_2})(P\cdot y_{H_2})^3}$$

$$(K_p)_1\cdot P^2 = \frac{\dfrac{\dot{n}_4}{\dot{n}_{tot}}}{\dfrac{\dot{n}_1}{\dot{n}_{tot}}\left(\dfrac{\dot{n}_2}{\dot{n}_{tot}}\right)^2} = \frac{(\xi_1+\xi_2)(100-2\xi_1-2\xi_2)^2}{(30-\xi_1)(63-2\xi_1-3\xi_2)^2} = 84.65 \qquad (1)$$

$$(K_p)_2\cdot P^2 = \frac{\left(\dfrac{\dot{n}_4}{\dot{n}_{tot}}\right)\left(\dfrac{\dot{n}_5}{\dot{n}_{tot}}\right)}{\left(\dfrac{\dot{n}_3}{\dot{n}_{tot}}\right)\left(\dfrac{\dot{n}_2}{\dot{n}_{tot}}\right)^3} = \frac{\xi_2(\xi_1+\xi_2)(100-2\xi_1-2\xi_2)^2}{(5-\xi_2)(63-2\xi_1-3\xi_2)^3} = 1.259 \qquad (2)$$

Solve (1) and (2) for $\xi_1, \xi_2 \Rightarrow\ \xi_1 = 25.27\text{ kmol/h}\quad \xi_2 = 0.0157\text{ kmol/h}$

$$\Rightarrow \begin{array}{ll} \dot{n}_1 = 30.0 - 25.27 = \underline{\underline{4.73\text{ kmol CO/h}}} & \underline{9.98\%\text{ CO}} \\ \dot{n}_2 = 63.0 - 2(25.27) - 3(0.0157) = \underline{\underline{12.4\text{ kmol }H_2\text{/h}}} & \underline{26.2\%\ H_2} \\ \dot{n}_3 = 5.0 - 0.0157 = \underline{\underline{4.98\text{ kmol }CO_2\text{/h}}} & \underline{10.5\%\ CO_2} \\ \dot{n}_4 = 25.27 + 0.0157 = \underline{\underline{25.3\text{ kmol M/h}}} \quad \Rightarrow & \underline{53.4\%\text{ M}} \\ \dot{n}_5 = 0.0157 = \underline{\underline{0.0157\text{ kmol }H_2O\text{/h}}} & \underline{0.03\%\ H_2O} \end{array}$$

$$n_{total} = 49.4\text{ kmol/h}$$

$$\left.\begin{array}{l} \underline{\text{C balance:}}\ \dot{n}_4 = 25.3\text{ kmol/h} \\ \underline{\text{O balance:}}\ \dot{n}_6 + 2\dot{n}_8 = \dot{n}_4 + \dot{n}_5 = 25.44\text{ mol/s} \end{array}\right\} \Rightarrow \begin{array}{l} \dot{n}_6 = \underline{\underline{25.4\text{ kmol CO/h}}} \\ \dot{n}_8 = \underline{\underline{0.02\text{ kmol }CO_2\text{/h}}} \end{array}$$

$$\underline{\text{H balance:}}\ 2\dot{n}_7 = 2(0.9\dot{n}_2) + 4\dot{n}_4 + 2\dot{n}_5 = 123.7 \Rightarrow \dot{n}_7 = \underline{\underline{61.8\text{ mol }H_2\text{/s}}}$$

b. $(\dot{n}_4)_{process} = 237\text{ kmol M/h}$

$$\Rightarrow \text{ Scale Factor} = \frac{237\text{ kmol M/h}}{25.3\text{ kmol/h}}$$

5.65 **a.** $$\rho\left(\mathrm{kg/m^3}\right)=\frac{\mathrm{m\ (kg)}}{\mathrm{V\ (m^3)}}=\frac{\mathrm{(MW)P}}{\mathrm{RT}}$$

$$=\frac{30\ \mathrm{kg/kmol}}{465\ \mathrm{K}}\left|\frac{9.0\ \mathrm{MPa}}{0.08206\,\frac{\mathrm{m^3\cdot atm}}{\mathrm{kmol\cdot K}}}\right|\frac{10\ \mathrm{atm}}{1.013\ \mathrm{MPa}}=\underline{\underline{69.8\ \mathrm{kg/m^3}}}$$

b. $$\left.\begin{aligned}T_r&=465/310=1.5\\P_r&=9.0/4.5=2.0\end{aligned}\right\}\xRightarrow{\text{Fig. 5.4-3}}z=0.84$$

$$\rho=\frac{\mathrm{(MW)P}}{\mathrm{zRT}}=\frac{69.8\ \mathrm{kg/m^3}}{0.84}=\underline{\underline{83.1\ \mathrm{kg/m^3}}}$$

5.66 Moles of CO_2: $$\frac{100\ \mathrm{lb_m\ CO_2}}{}\left|\frac{1\ \mathrm{lb\text{-}mole\ CO_2}}{44.01\ \mathrm{lb_m\ CO_2}}\right.=2.27\ \mathrm{lb\text{-}moles}$$

$$\left.\begin{aligned}T_C&=304.2\ \mathrm{K}\\P_C&=72.9\ \mathrm{atm}\end{aligned}\right\}\Rightarrow P_r=P/P_C=\frac{(1600+14.7)\,\mathrm{psi}}{72.9\ \mathrm{atm}}\left|\frac{1\ \mathrm{atm}}{14.7\ \mathrm{psi}}\right.=1.507$$

$$\hat{V}_r=\frac{\hat{V}P_C}{RT_C}=\frac{10.0\ \mathrm{ft^3}}{2.27\ \mathrm{lb\text{-}moles}}\left|\frac{72.9\ \mathrm{atm}}{304.2\ \mathrm{K}}\right|\frac{\mathrm{lb\text{-}mole\cdot {}^\circ R}}{0.7302\ \mathrm{ft^3\cdot atm}}\left|\frac{1\ \mathrm{K}}{1.8\ \mathrm{{}^\circ R}}\right.=0.80$$

Fig. 5.4-3: $P_r=1.507$, $V_r=0.80\Rightarrow z=0.85$

$$T=\frac{PV}{znR}=\frac{1614.7\ \mathrm{psi}}{0.85}\left|\frac{10.0\ \mathrm{ft^3}}{2.27\ \mathrm{lb\text{-}moles}}\right|\frac{\mathrm{lb\text{-}mole\cdot {}^\circ R}}{0.7302\ \mathrm{ft^3\cdot atm}}\left|\frac{1\ \mathrm{atm}}{14.7\ \mathrm{psi}}\right.=779^\circ\mathrm{R}=\underline{\underline{320\ {}^\circ\mathrm{F}}}$$

5.67 $\underline{O_2}$: $T_C=154.4\ \mathrm{K}$, $P_C=49.7\ \mathrm{atm}$

$$\left.\begin{aligned}T_{r_1}&=298/154.4=1.93\\P_{r_1}&=1/49.7=0.02\end{aligned}\right\}z_1=1.00\quad(\text{Fig. 5.4-2})$$

$$\left.\begin{aligned}T_{r_2}&=358/154.4=2.23\\P_{r_2}&=1000/49.7=20.12\end{aligned}\right\}z_2=1.61\ (\text{Fig. 5.4-4})$$

$$V_2=V_1\frac{z_2}{z_1}\frac{T_2}{T_1}\frac{P_1}{P_2}$$

$$V_2=\frac{127\ \mathrm{m^3}}{\mathrm{h}}\left|\frac{1.61}{1.00}\right|\frac{358\ \mathrm{K}}{298\ \mathrm{K}}\left|\frac{1\ \mathrm{atm}}{1000\ \mathrm{atm}}\right.=\underline{\underline{0.246\ \mathrm{m^3/h}}}$$

5.68 $\underline{O_2}$: $T_C=154.4\ \mathrm{K}$ $\quad T_r=(27+273.2)/154.4=1.94$

$P_C=49.7\ \mathrm{atm}$ $\quad P_{r_1}=175/49.7=3.52\Rightarrow z_1=0.95$ $\quad$ (Fig. 5.3-2)

$P_{r_2}=1.1/49.7=0.02\Rightarrow z_2=1.00$

$$n_1-n_2=\frac{V}{RT}\left(\frac{P_1}{z_1}-\frac{P_2}{z_2}\right)=\frac{10.0\ \mathrm{L}}{300.2\ \mathrm{K}}\left|\frac{\mathrm{mol\cdot K}}{0.08206\ \mathrm{L\cdot atm}}\right|\left(\frac{175\ \mathrm{atm}}{0.95}-\frac{1.1\ \mathrm{atm}}{1.00}\right)=\underline{\underline{74.3\ \mathrm{mol}\ O_2}}$$

5.69 **a.** $\hat{V}=\dfrac{V}{n}=\dfrac{50.0\text{ mL}}{5.00\text{ g}}\left|\dfrac{44.01\text{ g}}{\text{mol}}\right.=440.1\text{ mL / mol}$

$$P=\frac{RT}{\hat{V}}=\frac{82.06\text{ mL}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\left|\frac{1000\text{ K}}{440.1\text{ mL / mol}}\right.=\underline{\underline{186\text{ atm}}}$$

b. For CO_2: $T_c=304.2\text{ K},\ P_c=72.9\text{ atm}$

$$T_r=\frac{T}{T_c}=\frac{1000\text{ K}}{304.2\text{ K}}=3.2873$$

$$V_r^{\text{ideal}}=\frac{\hat{V}P_c}{RT_c}=\frac{440.1\text{ mL}}{\text{mol}}\left|\frac{72.9\text{ atm}}{304.2\text{ K}}\right|\frac{\text{mol}\cdot\text{K}}{82.06\text{ mL}\cdot\text{atm}}=1.28$$

Figure 5.4-3: $V_r^{\text{ideal}}=1.28$ and $T_r=3.29\ \Rightarrow z=1.02$

$$P=\frac{zRT}{\hat{V}}=\frac{1.02}{}\left|\frac{82.06\text{ mL}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right|\frac{\text{mol}}{440.1\text{ mL}}\left|\frac{1000\text{ K}}{}\right.=\underline{\underline{190\text{ atm}}}$$

c. $a=3.654\times10^{6}\text{ mL}^2\cdot\text{atm / mol}^2,\ \ b=29.67\text{ mL / mol},\ \ m=0.8263,\ \ \alpha(1000K)=0.1077$

$$P=\frac{\left(82.06\,\frac{\text{mL}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right)(1000\text{ K})}{(440.1-29.67)\,\frac{\text{mL}}{\text{mol}}}-\frac{(0.1077)\left(3.654\times10^{6}\,\frac{\text{mL}^2\cdot\text{atm}}{\text{mol}^2}\right)}{440.1(440.1+29.67)\,\frac{\text{mL}^2}{\text{mol}^2}}=\underline{\underline{198\text{ atm}}}$$

5.70 **a.** The tank is being purged in case it is later filled with a gas that could ignite in the presence of O_2.

b. Enough N_2 needs to be added to make $x_{O_2}=10\times10^{-6}$. Since the O_2 is so dilute at this condition, the properties of the gas will be that of N_2.

$T_c=126.2\text{ K},\ P_c=33.5\text{ atm},\ T_r=2.36$

$$n_{\text{initial}}=n_1=\frac{PV}{RT}=\frac{1\text{ atm}}{0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\left|\frac{5000\text{ L}}{298.2\text{ K}}\right.=204.3\text{ mol}$$

$$n_{O_2}=204.3\text{ mol air}\left(\frac{0.21\text{ mol }O_2}{\text{mol air}}\right)=42.9\text{ mol }O_2$$

$$\frac{n_{O_2}}{n_2}=10\times10^{-6}\Rightarrow n_2=4.29\times10^{-6}\text{ mol}$$

$$\hat{V}=\frac{5000\text{ L}}{4.29\times10^{6}\text{ mol}}=1.16\times10^{-3}\text{ L / mol}$$

$$\hat{V}_r^{\text{ ideal}}=\frac{\hat{V}P_c}{RT_c}=\frac{1.16\times10^{-3}\text{ L}}{\text{mol}}\left|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}}\right|\frac{33.5\text{ atm}}{126.2\text{ K}}=3.8\times10^{-3}$$

$\Rightarrow$ not found on compressibility charts

Ideal gas: $P=\dfrac{RT}{\hat{V}}=\dfrac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\left|\dfrac{298.2\text{ K}}{1.16\times10^{-3}\text{ L / mol}}\right.=\underline{\underline{2.1\times10^{4}\text{ atm}}}$

The pressure required will be higher than 2.1×10^{4} atm if $z\geq1$, which from Fig. 5.3-3 is very likely.

$$n_{\text{added}}=4.29\times10^{6}-204.3\cong\left(4.29\times10^{6}\text{ mol }N_2\right)(0.028\text{ kg }N_2\text{ / mol})=\underline{\underline{1.20\times10^{5}\text{ kg }N_2}}$$

5.72 **a.** For N_2: $T_c = 126.20\text{ K} = 227.16^{\circ}\text{R}, \quad P_c = 33.5\text{ atm}$

After heater:
$$\left.\begin{array}{l} T_r = \dfrac{609.7^{\circ}\text{R}}{227.16^{\circ}\text{R}} = 2.68 \\[2ex] P_r = \dfrac{600\text{ psia}}{33.5\text{ atm}}\bigg|\dfrac{1\text{ atm}}{14.7\text{ psia}} = 1.2 \end{array}\right\} \Rightarrow z = 1.02$$

$$\dot{n} = \frac{150\text{ SCFM}}{359\text{ SCF/lb-mole}} = 0.418\text{ lb-mole/min}$$

$$\dot{V} = \frac{zRT\dot{n}}{P} = \frac{1.02}{}\bigg|\frac{0.418\text{ lb-mole}}{\text{min}}\bigg|\frac{10.73\text{ ft}^3\cdot\text{psia}}{\text{lb-mole}\cdot{}^{\circ}\text{R}}\bigg|\frac{609.7^{\circ}\text{R}}{600\text{ psia}} = \underline{\underline{4.65\text{ ft}^3/\text{min}}}$$

b.
$$\text{tank} = \frac{0.418\text{ lb-mole}}{\text{min}}\bigg|\frac{28\text{ lb}_m/\text{lb-mole}}{(0.81)62.4\text{ lb}_m/\text{ft}^3}\bigg|\frac{60\text{ min}}{\text{h}}\bigg|\frac{24\text{ h}}{\text{day}}\bigg|\frac{7\text{ days}}{\text{week}}\bigg|\frac{2\text{ weeks}}{}$$

$$= \underline{\underline{4668\text{ ft}^3 = 34{,}900\text{ gal}}}$$

5.73 **a.** For CO: $T_c = 133.0\text{ K}, \quad P_c = 34.5\text{ atm}$

Initially:
$$\left.\begin{array}{l} T_{r1} = \dfrac{300\text{ K}}{133.0\text{ K}} = 2.26 \\[2ex] P_{r1} = \dfrac{2514.7\text{ psia}}{34.5\text{ atm}}\bigg|\dfrac{1\text{ atm}}{14.7\text{ psia}} = 5.0 \end{array}\right\} \overset{\text{Fig. 5.4-3}}{\Rightarrow} z = 1.02$$

$$n_1 = \frac{2514.7\text{ psia}}{1.02}\bigg|\frac{150\text{ L}}{300\text{ K}}\bigg|\frac{1\text{ atm}}{14.7\text{ psia}}\bigg|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}} = 1022\text{ mol}$$

After 60h:
$$\left.\begin{array}{l} T_{r1} = \dfrac{300\text{ K}}{133.0\text{ K}} = 2.26 \\[2ex] P_{r1} = \dfrac{2258.7\text{ psia}}{34.5\text{ atm}}\bigg|\dfrac{1\text{ atm}}{14.7\text{ psia}} = 4.5 \end{array}\right\} \overset{\text{Fig. 5.4-3}}{\Rightarrow} z = 1.02$$

$$n_2 = \frac{2259.7\text{ psia}}{1.02}\bigg|\frac{150\text{ L}}{300\text{ K}}\bigg|\frac{1\text{ atm}}{14.7\text{ psia}}\bigg|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}} = 918\text{ mol}$$

$$\dot{n}_{\text{leak}} = \frac{n_1 - n_2}{60\text{ h}} = \underline{\underline{1.73\text{ mol/h}}}$$

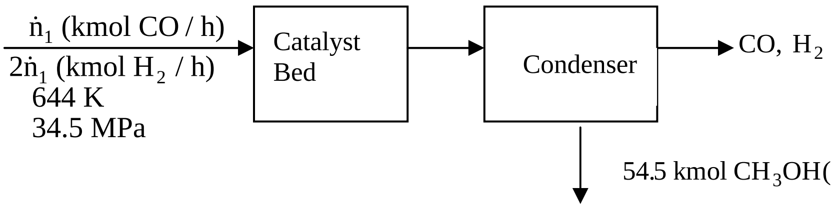
b.
$$n_2 = y_2 n_{\text{air}} = y_2\frac{PV}{RT} = \frac{200\times10^{-6}\text{ mol CO}}{\text{mol air}}\bigg|\frac{1\text{ atm}}{0.08206\,\frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\bigg|\frac{30.7\text{ m}^3}{300\text{ K}}\bigg|\frac{1000\text{ L}}{\text{m}^3} = 0.25\text{ mol}$$

$$t_{\min} = \frac{n_2}{\dot{n}_{\text{leak}}} = \frac{0.25\text{ mol}}{1.73\text{ mol/h}} = \underline{\underline{0.14\text{ h}}}$$

$$\Rightarrow \underline{\underline{t_{\min}\text{ would be greater because the room is not perfectly sealed}}}$$

c. (i) CO may not be evenly dispersed in the room air; (ii) you could walk into a high concentration area; (iii) there may be residual CO left from another tank; (iv) the tank temperature could be higher than the room temperature, and the estimate of gas escaping could be low.

5.78 $\underline{\text{Basis: } 54.5 \text{ kmol CH}_3\text{OH/h}}$ $\quad CO + 2H_2 \rightarrow CH_3OH$



a. $$\dot{n}_1 = \begin{array}{c|c|c} 54.5 \text{ kmol CH}_3\text{OH} & 1 \text{ kmol CO react} & 1 \text{ kmol CO fed} \\ \hline \text{h} & 1 \text{ kmol CH}_3\text{OH} & 0.25 \text{ kmol CO react} \end{array} = 218 \text{ kmol/h CO}$$

$$2\dot{n}_1 = 2(218) = 436 \text{ kmol } H_2/\text{h} \Rightarrow (218+436) = 654 \text{ kmol/h (total feed)}$$

$\underline{CO}$: $T_c = 133.0$ K $\quad P_c = 34.5$ atm

$\underline{H_2}$: $T_c = 33$ K $\quad P_c = 12.8$ atm

$\Downarrow$ Newton's corrections

$$T_c' = \frac{1}{3}(133.0) + \frac{2}{3}(33+8) = 71.7 \text{ K}$$

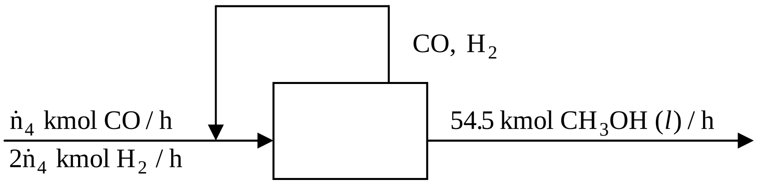
$$P_c' = \frac{1}{3}(34.5) + \frac{2}{3}(12.8+8) = 25.4 \text{ atm}$$

$$\left.\begin{array}{l} T_r = 644/71.7 = 8.98 \\ P_r = \begin{array}{c|c} 34.5 \text{ MPa} & 10 \text{ atm} \\ \hline 24.5 \text{ atm} & 1.013 \text{ MPa} \end{array} = 13.45 \end{array}\right\} \xrightarrow{\text{Fig. 5.4-4}} z = 1.18$$

$$\dot{V}_{\text{feed}} = \begin{array}{c|c|c|c|c} 1.18 & 654 \text{ kmol} & 644 \text{ K} & 0.08206 \text{ m}^3 \cdot \text{atm} & 1.013 \text{ MPa} \\ \hline & \text{h} & 34.5 \text{ MPa} & \text{kmol} \cdot \text{K} & 10 \text{ atm} \end{array} = \underline{\underline{120 \text{ m}^3/\text{h}}}$$

$$V_{\text{cat}} = \begin{array}{c|c} 120 \text{ m}^3/\text{h} & 1 \text{ m}^3 \text{ cat} \\ \hline & 25{,}000 \text{ m}^3/\text{h} \end{array} = \underline{\underline{0.0048 \text{ m}^3 \text{ catalyst (4.8 L)}}}$$

b.



Overall C balance $\Rightarrow \dot{n}_4 = 54.5$ mol CO/h

$\underline{\text{Fresh feed:}}$ 54.5 kmol CO/h
109.0 kmol H_2/h
163.5 kmol feed gas/h

$$\dot{V}_{\text{feed}} = \begin{array}{c|c|c|c|c} 1.18 & 163.5 \text{ kmol} & 644 \text{ K} & 0.08206 \text{ m}^3 \cdot \text{atm} & 1.013 \text{ MPa} \\ \hline & \text{h} & 34.5 \text{ MPa} & \text{kmol} \cdot \text{K} & 10 \text{ atm} \end{array} = \underline{\underline{29.9 \text{ m}^3/\text{h}}}$$

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

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

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

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

6.10 **a**. <u>The solvent with the lower flash point is easier to ignite and more dangerous</u>. 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, $y_M = 0.06 \Rightarrow p_M = p^*_M = 0.06 \times 760 \text{ mm Hg} = 45.60 \text{ mm Hg}$

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

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

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

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

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

c. (iv) (the gauge pressure)

6.12 **a.** $T_1 = 58.3°\text{C}$, $p_1* = 755 \text{ mm Hg} - (747-52)\text{mm Hg} = 60 \text{ mm Hg}$

$T_2 = 110°\text{C}$, $p_2* = 755 \text{ mm Hg} - (577-222)\text{mm Hg} = 400 \text{ mm Hg}$

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

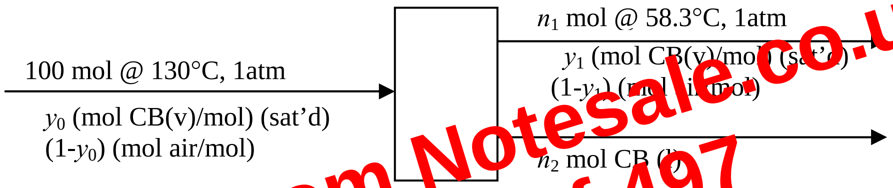
$$a = \frac{\ln(p_2*/p_1*)}{\frac{1}{T_2} - \frac{1}{T_1}} = \frac{\ln(400/60)}{\frac{1}{110+273.2} - \frac{1}{58.3+273.2}} = -4661.4$$

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

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

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

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



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

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

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°C.

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

$$y_{H_2O}\text{P} = 0.87 p*(25.56°\text{C}) \xRightarrow{\text{Table B.3}} y_{H_2O} = \frac{0.87(24.559 \text{ mm Hg})}{759.5 \text{ mm Hg}} = \underline{\underline{0.0281 \text{ mol } H_2O/\text{mol air}}}$$

Dew Point: $p*(T_{dp}) = yp = 0.0281(759.5) = 21.34 \text{ mm Hg} \xRightarrow{\text{Table B.3}} \underline{\underline{T_{dp} = 23.2°\text{C}}}$

6.13 (cont'd)

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

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

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

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

$$\underline{h_r = 50\%} \Rightarrow y_{H_2O}P = 0.50 p_{H_2O}*(21.1°\text{C})$$

$$\xrightarrow{\text{Table B.3}} \quad y_{H_2O} = \frac{0.50\times 18.765\text{ mm Hg}}{760.0\text{ mm Hg}} = 0.012\frac{\text{mol H}_2\text{O}}{\text{mol}}$$

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

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

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

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

$$\underline{h_r = 80\%} \Rightarrow y_{H_2O}P = 0.80 p_{H_2O}*(21.1°\text{C})$$

$$\xrightarrow{\text{Table B.3}} \quad y_{H_2O} = \frac{0.80\times 18.765\text{ mm Hg}}{760.0\text{ mm Hg}} = 0.020\frac{\text{mol H}_2\text{O}}{\text{mol}}$$

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

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

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

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

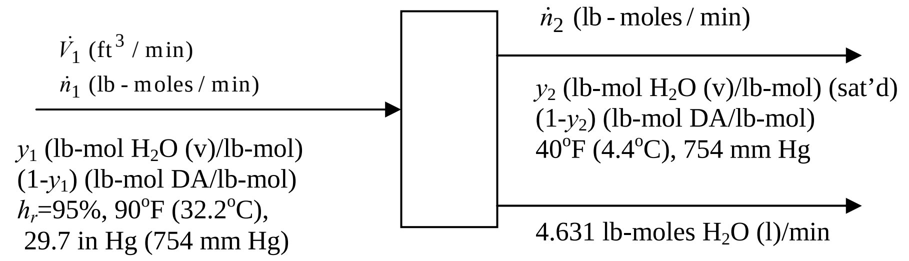
$$\underline{h_r = 80\%} \Rightarrow y_{H_2O}P = 0.80 p_{H_2O}*(32.2°\text{C})$$

$$\xrightarrow{\text{Table B.3}} \quad y_{H_2O} = \frac{0.80\times 36.068\text{ mm Hg}}{760.0\text{ mm Hg}} = 0.038\frac{\text{mol H}_2\text{O}}{\text{mol}}$$

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

Basis: 10 gal water condensed/min

$$\dot{n}_{condensed} = \frac{10 \text{ gal } H_2O}{\text{min}} \left| \frac{1 \text{ ft}^3}{7.4805 \text{ gal}} \right| \frac{62.43 \text{ lb}_m}{\text{ft}^3} \left| \frac{1 \text{ lb-mol}}{18.02 \text{ lb}_m} \right. = 4.631 \text{ lb-mole/min}$$



95% h_r at inlet: $y_{H_2O} P = 0.95 p^*(32.2° \text{C})$

$$\xRightarrow{\text{Table B.3}} y_{H_2O} = \frac{0.95(36.068 \text{ mm Hg})}{754.4 \text{ mm Hg}} = \underline{\underline{0.045 \text{ lb-mol } H_2O/\text{lb-mol}}}$$

Raoult's law: $y_2 P = p^*(4.4°\text{C}) \xRightarrow{\text{Table B.3}} y_2 = \frac{6.274}{754.4} = 0.00817 \text{ lb-mol } H_2O/\text{lb-mol}$

$$\left.\begin{array}{l} \text{Mole balance}: \dot{n}_1 = \dot{n}_2 + 4.631 \\ \text{Water balance}: 0.045\dot{n}_1 = 0.00817\dot{n}_2 + 4.631 \end{array}\right\} \Rightarrow \left\{\begin{array}{l} \dot{n}_1 = 124.7 \text{ lb-moles/min} \\ \dot{n}_2 = 120.1 \text{ lb-moles/min} \end{array}\right.$$

$$\text{Volume in: } \dot{V} = \frac{124.7 \text{ lb-moles}}{\text{min}} \left| \frac{359 \text{ ft}^3 \text{ (STP)}}{\text{lb-moles}} \right| \frac{(460+90)°\text{R}}{492°\text{R}} \left| \frac{760 \text{ mm Hg}}{754 \text{ mm Hg}} \right.$$

$$= \underline{\underline{5.04 \times 10^4 \text{ ft}^3/\text{min}}}$$

6.17 **a.** Assume no water condenses and that the vapor at 15°C can be treated as an ideal gas.

$$p_{\text{final}} = \frac{760 \text{ mm Hg}}{} \left| \frac{(15+273) \text{ K}}{(200+273) \text{ K}} \right. = 462.7 \text{ mm Hg} \Rightarrow (p_{H_2O})_{\text{final}} = 0.20 \times 462.7 = 92.6 \text{ mm Hg}$$

$p^*(15° \text{C}) = 12.79 \text{ mm Hg} < p_{H_2O}$. Impossible $\Rightarrow$ condensation occurs.

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

$$P = p_{H_2O} + p_{\text{air}} = 370.2 + 12.79 = \underline{\underline{383 \text{ mm Hg}}}$$

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

6.24 (cont'd)

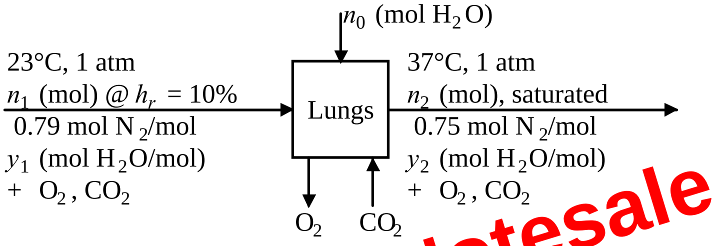
$$-A = \frac{\ln(40.0/5.00)}{\frac{1}{339} - \frac{1}{299}} \Rightarrow A = 5269, \quad B = \ln(5.00) + \frac{5269}{299} = 19.23 \Rightarrow \underline{\underline{p^* = \exp(19.23 - \frac{5269}{T(\text{K})})}}$$

At lower explosion limit, $y = 0.008 \text{ kmol } C_9H_{20}/\text{kmol} \Rightarrow p^*(T) = yP = (0.008)(760 \text{ mm Hg})$

$$= 6.08 \text{ mm Hg} \xrightarrow[\text{Formula for } p^*]{} T = 302 \text{ K} = \underline{\underline{29^\circ\text{C}}}$$

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

$= 356$ mol inhaled/day

Inhaled air--10% r.h.: $y_1 = \frac{0.10 p^*_{H_2O}(23^\circ C)}{P} = \frac{0.10(21.07 \text{ mm Hg})}{760 \text{ mm Hg}} = 2.77 \times 10^{-3} \frac{\text{mol } H_2O}{\text{mol}}$

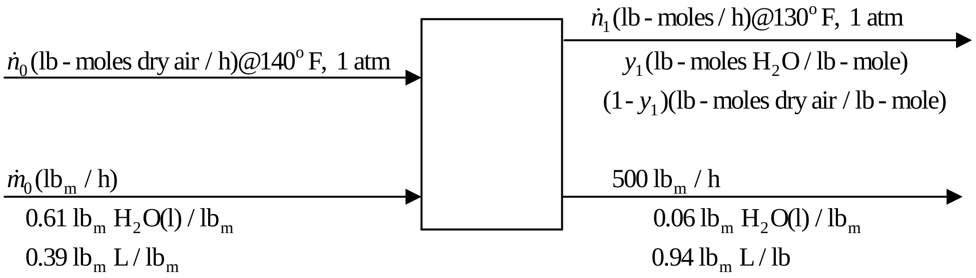
Inhaled air--50% r.h.: $y_1 = \frac{0.50 p^*_{H_2O}(23^\circ C)}{P} = \frac{0.50(21.07 \text{ mm Hg})}{760 \text{ mm Hg}} = 1.39 \times 10^{-2} \frac{\text{mol } H_2O}{\text{mol}}$

H_2O balance: $n_0 = n_2y_2 - n_1y_1 \Rightarrow (n_0)_{10\% \text{ rh}} - (n_0)_{50\% \text{ rh}} = (n_1y_1)_{50\%} - (n_1y_1)_{10\%}$

$$= \left(356 \frac{\text{mol}}{\text{day}}\right)\left[(0.0139 - 0.00277)\frac{\text{mol } H_2O}{\text{mol}}\right]\left(\frac{18.0 \text{ g}}{1 \text{ mol}}\right) = \underline{\underline{71 \text{ g/day}}}$$

Although the problem does not call for it, we could also calculate that n_2 = 375 mol exhaled/day, y_2 = 0.0619, and the rate of weight loss by breathing at 23°C and 50% relative humidity is $n_0(18) = (n_2y_2 - n_1y_1)18$ = 329 g/day.

6.34 Basis: 500 $\text{lb}_\text{m}/\text{hr}$ dried leather (L)



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

Humidity of outlet air: $y_1 P = 0.50 p^*_{H_2O}(130° \text{F}) \Rightarrow y_1 = \dfrac{0.50(115 \text{ mm Hg})}{760 \text{ mmHg}} = 0.0756 \dfrac{\text{mol } H_2O}{\text{mol}}$

H_2O balance: $(0.61)(1205 \text{ lb}_\text{m}/\text{hr}) = (0.06)\left(500 \text{ lb}_\text{m}/\text{hr}\right) + \dfrac{(0.0756 n_1)\text{lb-moles } H_2O}{\text{hr}} \Big| \dfrac{18.02 \text{ lb}_\text{m}}{1 \text{ lb-mole}}$

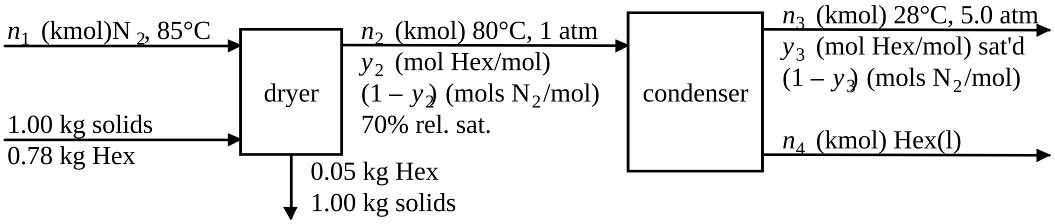
$$\Downarrow$$

$$n_1 = 517.5 \text{ lb-moles/hr}$$

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

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

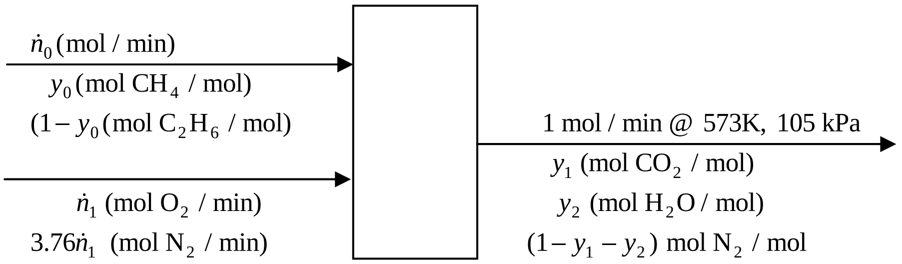
6.35 a. Basis: 1 kg dry solids



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

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

6.38 Basis: 1 mol outlet gas/min



$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O$$

$$p_{CO_2} = 80 \text{ mmHg} \Rightarrow y_1 = \frac{80 \text{ mmHg}}{105000 \text{ Pa}}\bigg|\frac{101325 \text{ Pa}}{760 \text{ mmHg}} = 0.1016 \text{ mol } CO_2 \text{ / mol}$$

100% O_2 conversion: $2n_o y_o + \frac{7}{2}n_o(1-y_o) = n_1$ (1)

C balance: $n_o y_o + 2n_o(1-y_o) = 0.1016$ (2)

N_2 balance: $3.76n_1 = 1 - y_1 - y_2$ (3)

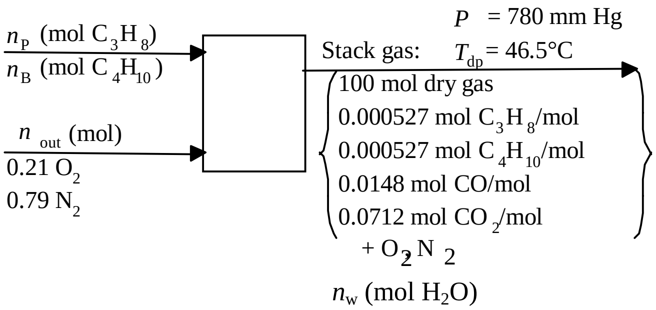
H balance: $4n_o y_o + 6n_o(1-y_o) = 2y_2$ (4)

$$\text{Solve equations 1 to 4} \Rightarrow \begin{cases} n_o = 0.0770 \text{ mol} \\ \underline{\underline{y_o = 0.6924 \text{ mol } CH_4 \text{ / mol}}} \\ n_1 = 0.1912 \text{ mol } O_2 \\ y_2 = 0.1793 \text{ mol } H_2O \text{ / mol} \end{cases}$$

Dew point:

$$p^*_{H_2O}(T_{dp}) = \frac{0.1793(105000) \text{ Pa}}{}\bigg|\frac{760 \text{ mmHg}}{101325 \text{ Pa}} = 141.2 \text{ mmHg} \Rightarrow T_{dp} = \underline{\underline{58.8^o \text{ C}}} \text{ (Table B.3)}$$

6.39 Basis: 100 mol dry stack gas



$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \qquad C_4H_{10} + \frac{13}{2}O_2 \rightarrow 4CO_2 + 5H_2O$$

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

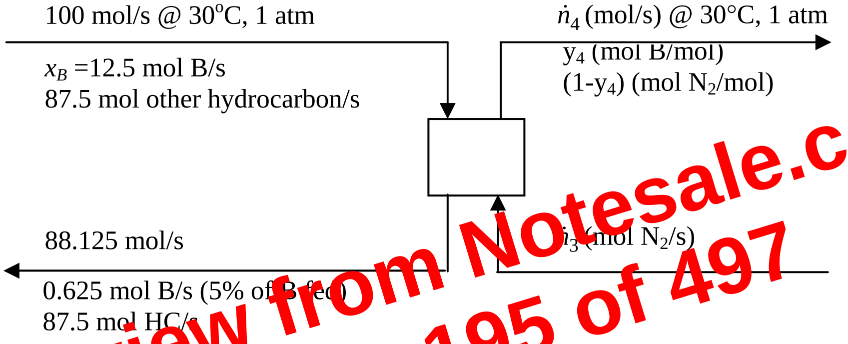
$$\dot{n}_{C_3H_8} = \frac{10.726 \text{ lb-mole}}{\text{h}} \left| \frac{0.006428 \text{ lb-mole } C_3H_3}{\text{lb-mole}} \right. = 0.06895 \text{ lb-mol } C_3H_8/\text{h}$$

The decane flow rate is 1.2 x 10.66 = 12.8 lb-moles $C_{10}H_{22}$/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.** <u>Basis: 100 mol/s liquid feed stream</u> Let B = n-butane, HC = other hydrocarbons



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

<u>Raoult's law</u>: $y_4 P = x_B p_B^*(30^\circ C) \Rightarrow y_4 = \dfrac{x_B p_B^*(30^\circ C)}{P} = \dfrac{0.125 \times 2120}{760} = 0.3487$

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

<u>Total mole balance</u>: $100 + \dot{n}_3 = 34.06 + 88.125 \Rightarrow \dot{n}_3 = 22.18$ 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**),

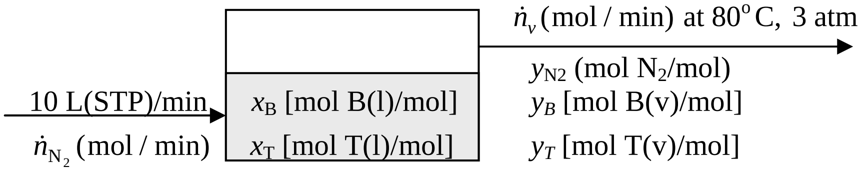
<u>95% n-butane is stripped</u>: $\dot{n}_4 \cdot (0.2790) = (12.5)(0.95) \Rightarrow \dot{n}_4 = 42.56$ mol / s

<u>Total mole balance</u>: $100 + \dot{n}_3 = 42.56 + 88.125 \Rightarrow \dot{n}_3 = 30.68$ 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.

6.56 B = benzene, T = toluene



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

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

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

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

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

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

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

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.** $P = x_{hex}p_{hex}^*(T_{bp}) + x_{hep}p_{hep}^*(T_{bp})$, $y_i = \dfrac{x_i p_i^*(T_{bp})}{P}$, 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 $\Rightarrow \underline{\underline{T_{bp} = 80.5°\text{C}}} \Rightarrow \underline{\underline{y_{hex} = 0.713,\ y_{hep} = 0.287}}$

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

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

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

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: $y_wP = H_wx_w \Rightarrow$

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

c. Solvent/solute mole ratio

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

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

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

Solvent stream entering absorber

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

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

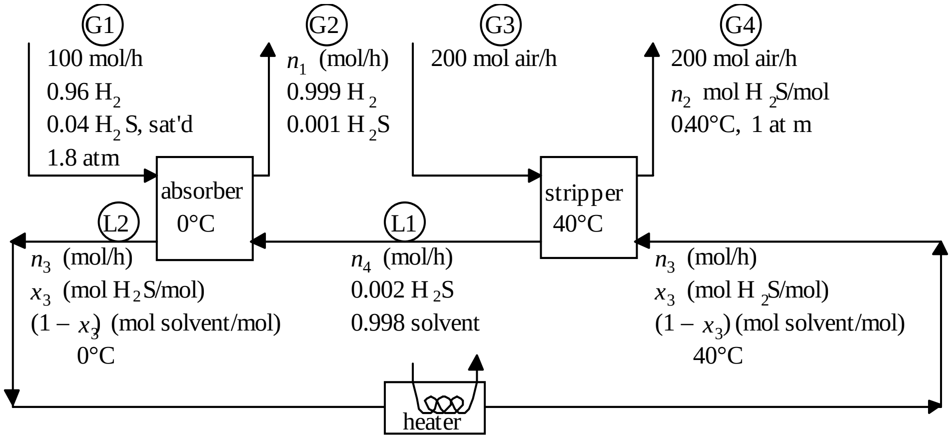
W balance on absorber

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

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

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

6.73 Basis: Given feed rates



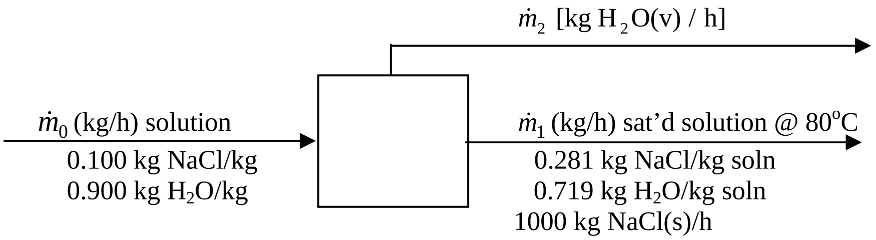
6.79 (cont'd)

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

$\underline{\text{Evaporation rate:}}$ $\underline{\underline{\dot{m}_2 = 9000 \text{ kg } H_2O\text{ / h}}}$

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

b.



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

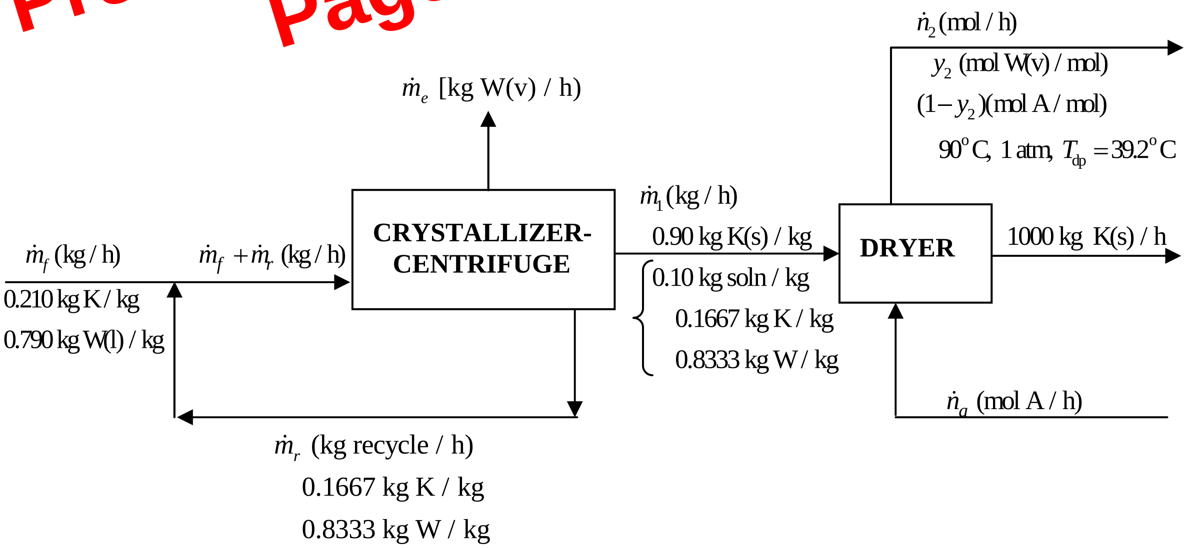
$\underline{\text{NaCl balance}}$: $0.100\dot{m}_0 = 0.281(2500) \Rightarrow \underline{\underline{\dot{m}_0 = 7025 \text{ kg / h}}}$

$\underline{\text{Mass balance}}$: $\dot{m}_0 = 2500 + \dot{m}_2 \Rightarrow \dot{m}_2 = \underline{\underline{4525 \text{ kg } H_2O \text{ evaporate / h}}}$

6.80 $\underline{\text{Basis}}$: 1000 kg $K_2Cr_2O_7$(s)/h . Let K = $K_2Cr_2O_7$, A = dry air, S = solution, W = water.

$\underline{\text{Composition of saturated solution:}}$

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



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

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

6.81(cont'd)

<u>O balance</u> (not counting O in the air):

$$n_1(0.700)(932)+100(0.07)(\frac{48}{106})+100(0.93)(\frac{16}{18})$$

$$=(n_{2w})(16)+n_{2c}(32)+(m_3+0.024m_4)(\frac{48}{84})+0.976m_4(\frac{16}{18})$$

$$\Rightarrow 22.4n_1+85.84=16n_{2w}+32n_{2c}+0.5714(m_3+0.024m_4)+0.8676m_4 \qquad (5)$$

<u>Raoult's Law</u> :

$$y_w P = p_w^*(70^o C) \Rightarrow \frac{n_{2w}}{n_{2w}+n_{2c}+n_{2a}} = \frac{233.7 \text{ mm Hg}}{(3*760) \text{ mm Hg}}$$

$$\Rightarrow n_{2w} = 0.1025(n_{2w}+n_{2c}+n_{2a}) \qquad (6)$$

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

$n_1 = 0.8086$ kmol, $n_{2a} = 0.2426$ kmol air, $n_{2c} = 0.500$ kmol CO_2,
$n_{2w} = 0.0848$ kmol H_2O(v), $m_3 = 8.874$ kg $NaHCO_3$(s), $m_4 = 92.50$ kg solution

<u>$NaHCO_3$ balance on filter</u>:

$$m_3+0.024m_4 = 0.024m_5 + m_6[0.86+(0.14)(0.024)]$$

$$\xRightarrow[m_4=92.50]{m_3=8.874} 11.09 = 0.024m_5 + 0.8634m_6 \qquad (7)$$

<u>Mass Balance on filter</u>: $8.874+92.50=101.4=m_5+m_6$ (8)

Solve (7) & (8) $\Rightarrow \begin{matrix} m_5 = 91.09 \text{ kg filtrate} \\ m_6 = 10.31 \text{ kg filter cake} \end{matrix} \Rightarrow (0.86)(10.31) = 8.867$ kg $NaHCO_3$(s)

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

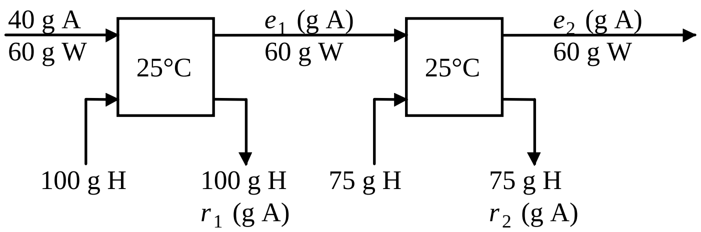
(a) Gas stream leaving reactor

$$\left.\begin{matrix} \dot{n}_{2w} = (0.0848)(56.39) = 4.78 \text{ kmol } H_2O(v) / h \\ \dot{n}_{2c} = (0.500)(56.39) = 28.2 \text{ kmol } O_2 \text{ / h} \\ \dot{n}_{2a} = (0.2426)(56.39) = 13.7 \text{ kmol air / h} \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} 46.7 \text{kmol / h} \\ 0.102 \text{ kmol } H_2O(v) \text{ / kmol} \\ 0.604 \text{ kmol } CO_2 \text{ / kmol} \\ 0.293 \text{ kmol Air / kmol} \end{matrix}\right.$$

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

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

6.91 **a.** Basis: 100 g feed $\Rightarrow$ 40 g acetone, 60 g H_2O. A = acetone, H = n-C_6H_{14}, W = water



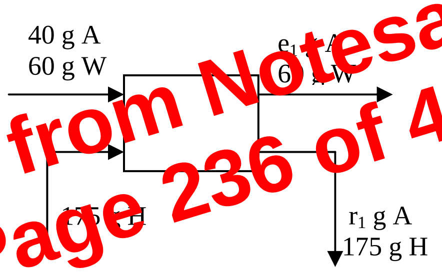
$x_{\text{A in H phase}} / x_{\text{A in W phase}} = 0.343$ (x = mass fraction)

$$\left.\begin{array}{ll}\underline{\text{Balance on A – stage 1:}} & 40 = e_1 + r_1 \\ \underline{\text{Equilibrium condition – stage 1:}} & \dfrac{r_1/(100+r_1)}{e_1/(60+e_1)} = 0.343\end{array}\right\} \Rightarrow \begin{array}{l} e_1 = 27.8 \text{ g acetone} \\ r_1 = 12.2 \text{ g acetone}\end{array}$$

$$\left.\begin{array}{ll}\underline{\text{Balance on A – stage 2:}} & 27.8 = e_2 + r_2 \\ \underline{\text{Equilibrium condition – stage 2:}} & \dfrac{r_2/(75+r_2)}{e_2/(60+e_2)} = 0.343\end{array}\right\} \Rightarrow \begin{array}{l} r_2 = 7.2 \text{ g acetone} \\ e_2 = 20.6 \text{ g acetone}\end{array}$$

$$\underline{\text{\% acetone not extracted}} = \frac{20.6 \text{ g A remaining}}{40 \text{ g A fed}} \times 100\% = \underline{\underline{51.5\%}}$$

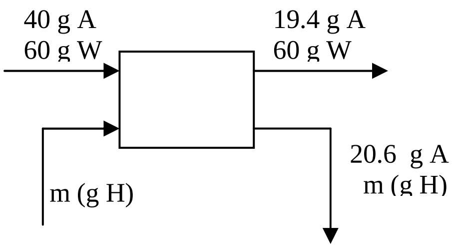
b.



$$\left.\begin{array}{ll}\underline{\text{Balance on A – stage 1:}} & 40.0 = e_1 + r_1 \\ \underline{\text{Equilibrium condition – stage 1:}} & \dfrac{r_1/(175+r_1)}{e_1/(60+e_1)} = 0.343\end{array}\right\} \Rightarrow \begin{array}{l} r_1 = 17.8 \text{ g acetone} \\ e_1 = 22.2\text{g acetone}\end{array}$$

$$\underline{\text{\% acetone not extracted}} = \frac{22.2 \text{ g A remaining}}{40 \text{ g A fed}} \times 100\% = \underline{\underline{55.5\%}}$$

c.

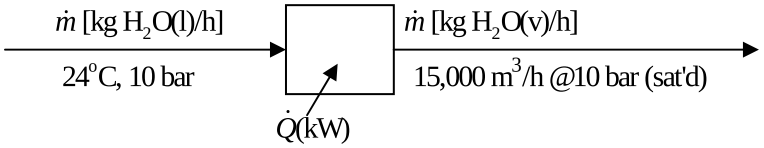


$$\underline{\text{Equilibrium condition}}: \ \frac{20.6/(m+20.6)}{19.4/(60+19.4)} = 0.343 \Rightarrow m = \underline{\underline{225 \text{ g hexane}}}$$

d. Define a function F=(value of recovered acetone over process lifetime)-(cost of hexane over process lifetime) – (cost of an equilibrium stage x number of stages). The most cost-effective process is the one for which F is the highest.

7.26 $\hat{H}\left(H_2O(l),\ 24°C,\ 10\text{ bar}\right)=100.6\ \text{kJ/kg}$ (Table B.5 for saturated liquid at 24°C; assume $\hat{H}$ independent of P).

$$\hat{H}(10\text{ bar, sat'd steam})=2776.2\ \text{kJ/kg (Table B.6)}\Rightarrow \Delta\hat{H}=2776.2-100.6=\underline{\underline{2675.6\ \text{kJ/kg}}}$$



$$\dot{m}=\begin{array}{c|c} 15000\ \text{m}^3 & \text{kg} \\ \hline \text{h} & \underset{\text{(Table 8.6)}}{\underset{\uparrow}{0.1943\ \text{m}^3}} \end{array}=7.72\times10^4\ \text{kg/h}$$

$$\underline{\text{Energy balance}}\left(\Delta\dot{E}_p,\ \dot{W}_s=0\right):\ \Delta\dot{H}+\Delta\dot{E}_k=\dot{Q}$$

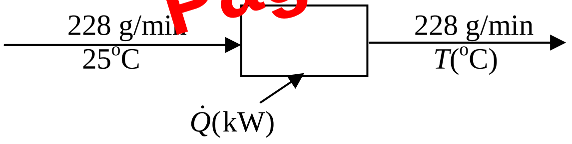
$$\Delta\dot{E}_k=\dot{E}_{k_{final}}-\dot{E}_{k_{initial}}\xRightarrow{\dot{E}_{k_{initial}}\approx0}\Delta\dot{E}_k=\dot{E}_{k_{final}}$$

$$\Delta\dot{E}_k=\frac{\dot{m}u_f^{\,2}}{2}=\begin{array}{c|c|c|c|c} 7.72\times10^4\ \text{kg} & \left(15{,}000\ \text{m}^3/\text{h}\right)^2 & 1 & 1\quad \text{h}^3 & 1\ \text{J} \\ \hline \text{h} & \underset{A=\pi D^2/4}{\underset{\uparrow}{\left[0.15^2\ \pi/4\right]^2\ \text{m}^2}} & 2 & 3600^3\ \text{s}^3 & 1\ \text{kg}\cdot\text{m}^2/\text{s}^2 \end{array}=5.96\text{x}10^5\ \text{J/s}$$

$$\dot{Q}=\dot{m}\Delta\hat{H}+\Delta\dot{E}_k=\begin{array}{c|c|c} 7.72\times10^4\ \text{kg} & 2675.6\ \text{kJ} & 1\ \text{h} \\ \hline \text{h} & \text{kg} & 3600\ \text{s} \end{array}+\begin{array}{c|c} 5.96\times10^5\ \text{J} & 1\ \text{kJ} \\ \hline \text{s} & 10^3\ \text{J} \end{array}$$

$$=57973\ \text{kJ/s}=\underline{\underline{5.80\times10^4\ \text{kW}}}$$

7.27 (a)



$$\underset{\Delta\dot{E}_x,\ \Delta\dot{E}_p,\ \dot{W}_s=0}{\underline{\text{Energy balance:}}}\ \dot{Q}=\Delta\dot{H}\Rightarrow\dot{Q}(\text{W})=\begin{array}{c|c|c} 228\ \text{g} & 1\ \text{min} & (\hat{H}_{out}-\overset{=0}{\cancel{\hat{H}_{in}}})\ \text{J} \\ \hline \text{min} & 60\ \text{s} & \text{g} \end{array}$$

$$\Rightarrow\hat{H}_{\text{out}}(\text{J/g})=0.263\dot{Q}(W)$$

$T(°C)$	25	26.4	27.8	29.0	32.4
$\hat{H}(\text{J/g})=0.263\dot{Q}(W)$	0	4.47	9.28	13.4	24.8

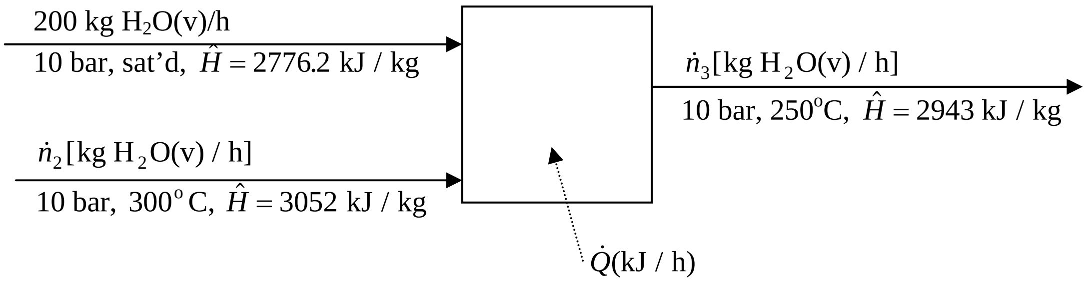
(b) $\hat{H}=b(T-25)\xrightarrow{\text{Fit to data by least squares (App. A.1)}}b=\sum_i\hat{H}_i\,(T_i-25)\Big/\sum_i(T_i-25)^2=3.34$

$$\Rightarrow\underline{\underline{\hat{H}(\text{J/g})=3.34\left[T(°C)-25\right]}}$$

(c) $\dot{Q}=\Delta\dot{H}=\begin{array}{c|c|c|c|c} 350\ \text{kg} & 10^3\text{g} & 1\ \text{min} & 3.34(40-20)\text{J} & \text{kW}\cdot\text{s} \\ \hline \text{min} & \text{kg} & 60\ \text{s} & \text{g} & 10^3\ \text{J} \end{array}=\underline{\underline{390\ \text{kW}}}$ heat input to liquid

(d) Heat is absorbed by the pipe, lost through the insulation, lost in the electrical leads.

7.35 Basis: Given feed rate



$\hat{H}$ from Table B.6 (saturated steam) or Table B.7 (superheated steam)

Mass balance: $200 + \dot{n}_2 = \dot{n}_3$ (1)

$\underset{\Delta\dot{E}_K,\, \Delta\dot{E}_p,\, \dot{W}=0}{\text{Energy balance:}}$ $\dot{Q} = \Delta\dot{H} = \dot{n}_3(2943) - 200(2776.2) - \dot{n}_2(3052)$, $\dot{Q}$ in kJ/h (2)

(a) $\dot{n}_3 = 300 \text{ kg/h} \xrightarrow{(1)} \dot{n}_2 = 100 \text{ kg/h} \xrightarrow{(2)} \dot{Q} = \underline{\underline{2.25 \times 10^4 \text{ kJ/h}}}$

(b) $\dot{Q} = 0 \xrightarrow{(1),(2)} \dot{n}_2 = \underline{\underline{306 \text{ kg/h}}}$, $\dot{n}_3 = \underline{\underline{506 \text{ kg/h}}}$

7.36 **(a)** T$_{\text{saturation}}$ @ 1.0 bar = 99.6 °C $\Rightarrow T_f = \underline{\underline{99.6^\circ\text{C}}}$

H_2O (1.0 bar, sat'd) $\Rightarrow \hat{H}_l = 417.5$ kJ / kg, $\hat{H}_v = 2675.4$ kJ / kg

H_2O (60 bar, 250° C) = 1085.8 kJ / kg

Mass balance: $m_v + m_l = 100$ kg (1)

$\underset{\Delta\dot{E}_K,\, \dot{Q},\, \Delta\dot{E}_p,\, \dot{W}=0}{\text{Energy balance:}}$ $\Delta\dot{H} = 0$

$$\Rightarrow m_v\hat{H}_v + m_l\hat{H}_l - m_1\hat{H}_1 = m_v\hat{H}_v + m_l\hat{H}_l - (100 \text{ kg})(1085.8 \text{ kJ / kg}) = 0 \qquad (2)$$

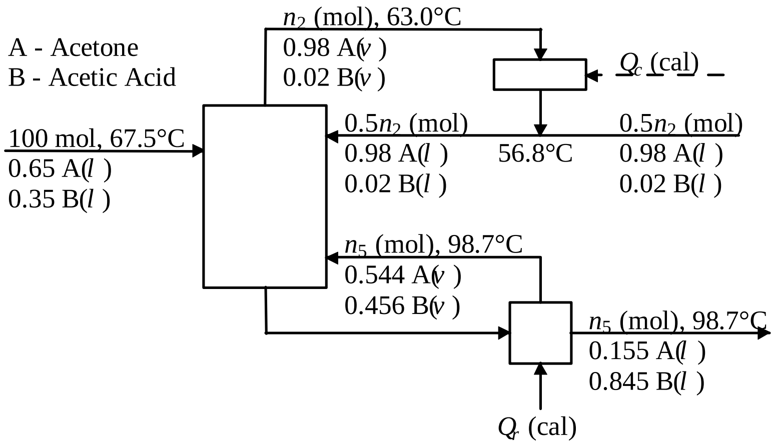
$$\xrightarrow{(1,2)} m_l = 70.4 \text{ kg},\ m_v = 29.6 \text{ kg} \quad \Rightarrow y_v = \frac{29.6 \text{ kg vapor}}{100 \text{ kg}} = \underline{\underline{0.296 \frac{\text{kg vapor}}{\text{kg}}}}$$

(b) $\underline{\underline{T \text{ is unchanged.}}}$ The temperature will still be the saturation temperature at the given final pressure. The system undergoes expansion, so assuming the same pipe diameter, $\Delta\dot{E}_k > 0$. $\underline{\underline{y_v \text{ would be less (less water evaporates)}}}$ because some of the energy that would have vaporized water instead is converted to kinetic energy.

(c) $P_f = \underline{\underline{39.8 \text{ bar}}}$ (pressure at which the water is still liquid, but has the same enthalpy as the feed)

(d) Since enthalpy does not change, then when $P_f \geq 39.8$ bar the temperature cannot increase, because a higher temperature would increase the enthalpy. Also, when $P_f \geq 39.8$ bar, the product is only liquid $\Rightarrow$ no evaporation occurs.

7.42 Basis: 100 mol feed



(a) Overall balances:

$$\left.\begin{array}{l}\text{Total moles: } 100 = 0.5n_2 + n_5 \\ A\text{: } 0.65(100) = 0.98(0.5n_2) + 0.155n_5\end{array}\right\} \begin{array}{l} n_2 = 120 \text{ mol} \\ n_5 = 40 \text{ mol}\end{array}$$

Product flow rates: Overhead $0.5(120)0.98 = 58.8 \text{ mol } A$

$0.5(120)0.02 = 1.2 \text{ mol } B$

Bottoms $0.155(40) = 6.2 \text{ mol } A$

$0.845(40) = 33.8 \text{ mol } B$

$$\underset{\Delta E_p,\, W_s=0,\, \Delta E_k \cong 0}{\underline{\text{Overall energy balance:}}}\quad Q = \Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i$$

$$\Rightarrow Q = 58.8(0) + 1.2(0) + 6.2(1385) + 33.8(1312) - 65\underset{\text{interpolate in table}}{\overset{\downarrow}{(354)}} - 35\underset{\text{interpolate in table}}{\overset{\downarrow}{(335)}} = \underline{\underline{1.82 \times 10^4 \text{ cal}}}$$

(b) Flow through condenser: $2(58.8) = 117.6 \text{ mols } A$

$2(1.2) = 2.4 \text{ mols } B$

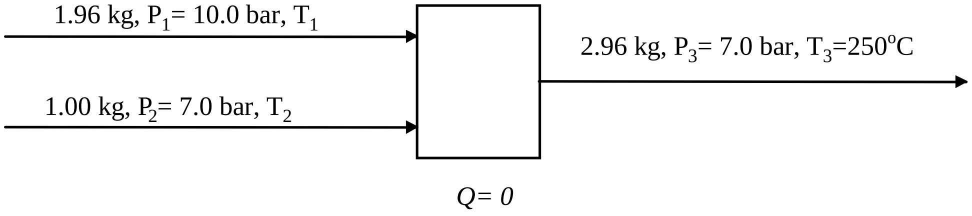
$$\underset{\Delta E_p,\, W_s=0,\, \Delta E_k \cong 0}{\underline{\text{Energy balance on condenser:}}}\quad Q_c = \Delta H$$

$Q_c = 117.6(0 - 7322) + 2.4(0 - 6807) = \underline{\underline{-8.77 \times 10^5 \text{ cal}}}$ heat removed from condenser

Assume negligible heat transfer between system & surroundings other than Q_c & Q_r

$Q_r = Q - Q_c = 1.82 \times 10^4 - \left(-8.77 \times 10^5\right) = \underline{\underline{8.95 \times 10^5 \text{ cal}}}$ heat added to reboiler

7.43



7.49 (a) Pressure in cylinder $= \dfrac{\text{weight of piston}}{\text{area of piston}} + \text{atmospheric pressure}$

$$P = \frac{30.0\ \text{kg}}{400.0\ \text{cm}^2}\left|\frac{9.807\ \text{N}}{\text{kg}}\right|\frac{(100\ \text{cm})^2}{1^2(\text{m})^2}\left|\frac{1.0\ \text{bar}}{10^5\ \text{N/m}^2}\right| + \frac{1\ \text{atm}}{}\left|\frac{1.013\ \text{bar}}{\text{atm}}\right. = \underline{\underline{1.08\ \text{bar}}}$$

$$\Rightarrow T_{sat} = 101.8^\circ\text{C}$$

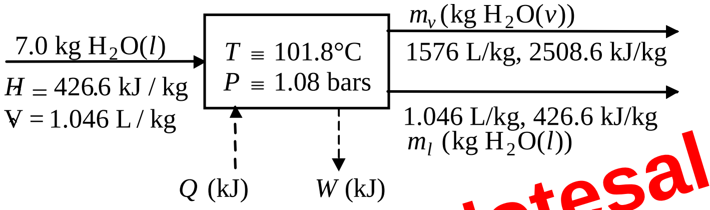
Heat required to bring the water and block to the boiling point

$$Q = \Delta U = m_w\left(\hat{U}_{wl}(1.08\ \text{bar, sat'd}) - \hat{U}_{wl}(\text{l, }20^\circ\text{C})\right) + m_{Al}\left(\hat{U}_{Al}(T_{sat}) - \hat{U}_{Al}(20^\circ\text{C})\right)$$

$$= \frac{7.0\ \text{kg}}{}\left|\frac{(426.6-83.9)\text{kJ}}{\text{kg}}\right. + \frac{3.0\ \text{kg}}{}\left|\frac{[0.94(101.8-20)]\text{kJ}}{\text{kg}}\right. = 2630\ \text{kJ}$$

2630 kJ < 3310 kJ $\Rightarrow$ $\underline{\underline{\text{Sufficient heat for vaporization}}}$

(b) $\underline{\underline{T_f = T_{sat} = 101.8^\circ\text{C}}}$. Table B.5 $\Rightarrow$ $\begin{matrix}\hat{V}_l = 1.046\ \text{L/kg},\ \hat{U}_l = 426.6\ \text{kJ/kg} \\ \hat{V}_v = 1576\ \text{L/kg},\ \hat{U}_v = 2508.6\ \text{kJ/kg}\end{matrix}$



(Since the Al block stays at the same temperature in this stage of the process, we can ignore it -i.e., $\hat{U}_{\text{in}} = \hat{U}_{\text{out}}$)

Water balance: $7.0 = m_l + m_v$ **(1)**

Work done by the piston: $W = F\Delta z = \left[w_{\text{piston}} + P_{\text{atm}}A\right]\Delta z$

$$= \left[\frac{w}{A} + P_{\text{atm}}\right](A\Delta z) = P\Delta V \Rightarrow W = (1.08\ \text{bar})\left[1576m_v + 1.046m_l - (1.046)(7.0)\right]\text{L}$$

$$\times \frac{8.314\ \text{J / mol}\cdot\text{K}}{0.08314\ \text{liter - bar / mol}\cdot\text{K}}\left|\frac{1\ \text{kJ}}{10^3\ \text{J}}\right. = (170.2m_v + 0.113m_l - 0.7908)\text{kJ}$$

Energy balance: $\Delta U = Q - W$

$$\Rightarrow \overbrace{2508.6m_v + 426.6m_L - 426.6(7)}^{\Delta U} = \overbrace{(3310-2630)}^{Q} - \overbrace{(170.2m_v + 0.113m_L - 0.7908)}^{W}$$

$$\Rightarrow 2679m_v + 426.7m_L - 3667 = 0 \quad \textbf{(2)}$$

Solving (1) and (2) simultaneously yields $m_v = 0.302$ kg, $m_l = 6.698$ kg

Liquid volume $= (6.698\ \text{kg})(1.046\ \text{L/kg}) = \underline{\underline{7.01\ \text{L liquid}}}$

Vapor volume $= (0.302\ \text{kg})(1576\ \text{L/kg}) = \underline{\underline{476\ \text{L vapor}}}$

Piston displacement: $\Delta z = \dfrac{\Delta V}{A} = \dfrac{[7.01 + 476 - (7.0)(1.046)]\text{L}}{}\left|\dfrac{10^3\ \text{cm}^3}{1\ \ \text{L}}\right|\dfrac{1}{400\ \text{cm}^2} = \underline{\underline{1190\ \text{cm}}}$

(c) $T_{\text{upper}} \Rightarrow$ All 3310 kJ go into the block before a measurable amount is transferred to the water. Then $\Delta U_{AL} = Q \Rightarrow (3.0\ \text{kg})\left[0.94(T_u - 20)\ \text{kJ/kg}\right] = 3310 \Rightarrow T_u = 1194^\circ\text{C}$ *if melting is neglected.* In fact, the bar would melt at $\underline{660^\circ\text{C}}$.

8.3 (cont'd)

b. $C_p = C_v + R$

$$C_p[\text{kJ / (mol}\cdot{}^\text{o}\text{ C)}] = (0.0252 + 1.547\times10^{-5}T - 3.012\times10^{-9}T^2) + 0.008314$$

$$= \underline{\underline{0.0335 + 1.547\times10^{-5}T - 3.012\times10^{-9}T^2}}$$

$$Q = \Delta H = n\int_{T_1}^{T_2} C_p dT$$

$$= (0.245\text{ mol})\cdot\int_{25}^{1000}[0.0335 + 1.547\times10^{-5}T - 3.012\times10^{-9}T^2]\,dT\;[\text{kJ / (mol}\cdot{}^\text{o}\text{ C)}] = \underline{\underline{9.65\times10^3\text{ J}}}$$

<u>Piston moves upward</u> (gas expands).

c. The difference is the work done on the piston by the gas in the constant pressure process.

8.4 **a.** $\left(C_p\right)_{\text{C}_6\text{H}_6(l)}\left(40^\text{o}\text{C}\right) = 0.1265 + 23.4\times10^{-5}\left(40\right) = \underline{\underline{0.1360\text{ [kJ/(mol}\cdot\text{K)]}}}$

b. $\left(C_p\right)_{\text{C}_6\text{H}_6(v)}\left(40^\circ\text{ C}\right) = 0.07406 + 32.95\times10^{-5}(40) - 25.20\times10^{-8}(40)^2 + 77.57\times10^{-12}(40)^3$

$$= \underline{\underline{0.08684\text{ [kJ / (mol}\cdot{}^\text{o}\text{ C)]}}}$$

c. $\left(C_p\right)_{\text{C}(s)}\left(313\text{ K}\right) = 0.01118 + 1.095\times10^{-5}(313) - 4.891\times10^2(313)^{-2} = \underline{\underline{0.009615\text{ [kJ / (mol}\cdot\text{K)]}}}$

d. $\Delta\hat{H}_{\text{C}_6\text{H}_6(v)} = 0.07406T + \dfrac{32.95\times10^{-5}}{2}T^2 - \dfrac{25.20\times10^{-8}}{3}T^3 + \dfrac{77.57\times10^{-12}}{4}T^4\Bigg]_{40}^{300} = \underline{\underline{31.71\text{ kJ/mol}}}$

e. $\Delta\hat{H}_{C(s)} = 0.01118T + \dfrac{1.095\times10^{-5}}{2}T^2 + 4.891\times10^2\,T^{-1}\Bigg]_{313}^{573} = \underline{\underline{3.459\text{ kJ / mol}}}$

8.5 $\text{H}_2\text{O (v, }100^\text{o}\text{ C, 1 atm)} \rightarrow \text{H}_2\text{O (v, }350^\text{o}\text{ C, 100 bar)}$

a. $\hat{H} = 2926\text{ kJ/kg} - 2676\text{ kJ/kg} = \underline{\underline{250\text{ kJ/kg}}}$

b. $\hat{H} = \displaystyle\int_{100}^{350}\left[0.03346 + 0.6886\times10^{-5}T + 0.7604\times10^{-8}T^2 - 3.593\times10^{-12}T^3\right]dT$

$$= 8.845\text{ kJ/mol} \Rightarrow \underline{\underline{491.4\text{ kJ/kg}}}$$

Difference results from assumption in (b) that $\hat{H}$ is independent of P. The numerical difference is $\Delta\hat{H}$ for $\text{H}_2\text{O(v, }350^\circ\text{ C, 1 atm)} \rightarrow \text{H}_2\text{O(v, }350^\circ\text{ C, 100 bar)}$

8.6 **b.** $\left(C_p\right)_{\text{n}-\text{C}_6\text{H}_{14}\text{(l)}} = 0.2163\text{ kJ / (mol}\cdot{}^\text{o}\text{ C)} \Rightarrow \Delta\hat{H} = \displaystyle\int_{25}^{80}[0.2163]\,dT = \underline{\underline{11.90\text{ kJ / mol}}}$

The specific enthalpy of liquid n-hexane at 80°C relative to liquid n-hexane at 25°C is 11.90 kJ/mol

c. $\left(C_p\right)_{\text{n}-\text{C}_6\text{H}_{14}\text{(v)}}[\text{kJ / (mol}\cdot{}^\text{o}\text{ C)}] = 0.13744 + 40.85\times10^{-5}T - 23.92\times10^{-8}T^2 + 57.66\times10^{-12}T^3$

$$\Delta\hat{H} = \int_{500}^{0}[0.13744 + 40.85\times10^{-5}T - 23.92\times10^{-8}T^2 + 57.66\times10^{-12}T^3]\,dT = \underline{\underline{-110.7\text{ kJ / mol}}}$$

The specific enthalpy of hexane vapor at 500°C relative to hexane vapor at 0°C is 110.7 kJ/mol. The specific enthalpy of hexane vapor at 0°C relative to hexane vapor at 500°C is –110.7 kJ/mol.

8.36 **a.** Table B.1 $\Rightarrow T_b = 68.74^\circ\text{C},\ \Delta\hat{H}_v(T_b) = 28.85\text{ kJ / mol}$

Assume: n-hexane vapor is an ideal gas, i.e. $\Delta\hat{H}$ is not a function of pressure

$$\begin{tikzcd}
(C_6H_{14})_{l,\,20^\circ C} \arrow[r, "\Delta\hat{H}_{Total}"] \arrow[d, "\Delta\hat{H}_1"] & (C_6H_{14})_{v,\,200^\circ C} \\
(C_6H_{14})_{l,\,68.74^\circ C} \arrow[r, "\Delta\hat{H}_v(T_b)"] & (C_6H_{14})_{v,\,68.74^\circ C} \arrow[u, "\Delta\hat{H}_2"]
\end{tikzcd}$$

$$\Delta\hat{H}_1 = \int_{20}^{68.74} 0.2163\, dT = 10.54\text{ kJ / mol}$$

$$\Delta\hat{H}_2 = \int_{68.74}^{200}\left[0.13744 + 40.85\times10^{-5}T - 23.92\times10^{-8}T^2 + 57.66\times10^{-9}T^3\right]dT$$

$$\Delta\hat{H}_2 = 24.66\text{ kJ / mol}$$

$$\Delta\hat{H}_{Total} = \Delta\hat{H}_1 + \Delta\hat{H}_2 + \Delta\hat{H}_v(T_b) = 10.54 + 24.66 + 28.85 = \underline{\underline{64.05\text{ kJ / mol}}}$$

b. $\Delta\hat{H} = \underline{\underline{-64.05\text{ kJ / mol}}}$

c. $\hat{U}\left(200^\circ C,\ 2\text{ atm}\right) = \hat{H} - P\hat{V}$

Assume ideal gas behavior $\Rightarrow P\hat{V} = RT = 3.93\text{ kJ / mol}$

$$\hat{U} = 64.05 - 3.93 = \underline{\underline{60.12\text{ kJ / mol}}}$$

8.37 $T_b = 100.00^\circ\text{C} \qquad \Delta\hat{H}_v(t_b) = 40.656\ \text{ kJ/mol}$

$$\begin{tikzcd}
H_2O\left(l,\ 50^\circ C\right) \arrow[r, "\Delta\hat{H}_v(50^\circ C)"] \arrow[d, "\Delta\hat{H}_1"] & H_2O\left(v,\ 50^\circ C\right) \\
H_2O\left(l,\ 100^\circ C\right) \arrow[r, "\Delta\hat{H}_v(100^\circ C)"] & H_2O\left(v,\ 100^\circ C\right) \arrow[u, "\Delta\hat{H}_2"]
\end{tikzcd}$$

$$\Delta\hat{H}_1 = \int_{25}^{100} C_{pH_2O(l)}\,dT = 3.77\text{ kJ/mol}$$

$$\Delta\hat{H}_2 = \int_{100}^{25} C_{pH_2O(v)}\,dT = -1.69\text{ kJ/mol}$$

$$\Delta\hat{H}_v(50^\circ C) = 3.77 + \overset{\substack{\text{Table B.1}\\ \downarrow}}{40.656} - 1.69 = \underline{\underline{42.7\ \text{ kJ/mol}}}$$

Steam table: $\begin{array}{c|c|c} (2547.3-104.8)\text{kJ} & 18.01\text{ g} & 1\text{ kg} \\ \hline \text{kg} & 1\text{ mol} & 1000\text{ g} \end{array} = 44.0\ \text{ kJ/mol}$

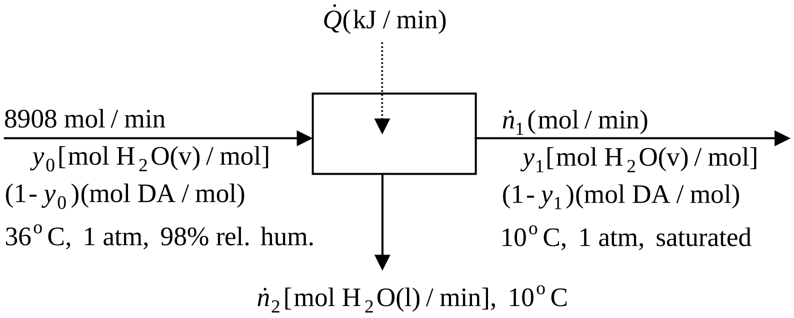
The first value uses physical properties of water at 1 atm (Tables B.1, B.2, and B.8), while the heat of vaporization at 50°C in Table B.5 is for a pressure of 0.1234 bar (0.12 atm). The difference is ΔH for liquid water going from 50°C and 0.1234 bar to 50°C and 1 atm plus ΔH for water vapor going from 50°C and 1 atm to 50°C and 0.1234 bar.

8.38

$$\begin{array}{c|c|c|c|c} 1.75\text{ m}^3 & 879\text{ kg} & 1\text{ kmol} & 1000\text{ mol} & 1\text{ min} \\ \hline 2.0\text{ min} & \text{m}^3 & 78.11\text{ kg} & 1\text{ kmol} & 60\text{ s} \end{array} = 164.1\text{ mol/s}$$

$T_b = 80.1^\circ\text{C}\ ,\ \Delta\hat{H}_v(T_b) = 30.765\ \text{ kJ/mol}$

8.47 Basis: $\frac{226\ \text{m}^3}{\text{min}}\bigg|\frac{273\ \text{K}}{309\ \text{K}}\bigg|\frac{10^3\ \text{mol}}{22.415\ \text{m}^3(\text{STP})} = 8908$ mol humid air/min. DA = Dry air



a. Degree of freedom analysis: 5 unknowns – (1 relative humidity + 2 material balances + 1 saturation condition at outlet + 1 energy balance) = 0 degrees of freedom.

b. Inlet air: $y_0 P = 0.98 \overset{\text{Table B.3}}{\overset{\downarrow}{p_w^*}}(36^\circ\text{C}) \Rightarrow y_0 = \frac{0.98(44.563\ \text{mm Hg})}{760\ \text{mm Hg}} = 0.0575\ \text{mol}\ H_2O(v)/\text{mol}$

Outlet air: $y_1 = p^*(10^\circ\text{C})/P = (9.209\ \text{mm Hg})/(760\ \text{mm Hg}) = 0.0121\ \text{mol}\ H_2O(v)/\text{mol}$

Air balance: $(1-0.0575)(8908\ \text{mol/min}) = (1-0.0121)\dot{n}_1 \Rightarrow \dot{n}_1 = 8499\ \text{mol/min}$

H_2O balance: $0.0575\left(8908\frac{\text{mol}}{\text{min}}\right) = 0.0121\left(8499\frac{\text{mol}}{\text{min}}\right) + \dot{n}_2 \Rightarrow \dot{n}_2 = 409\ \text{mol}\ H_2O(l)/\text{min}$

References: $H_2O(l$, triple point), air (77°F)

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$	
Air	8396	0.3198	8396	–0.4352	$\dot{n}$ in mol/min
$H_2O(v)$	512	46.2	103	45.3	$\hat{H}$ in kJ/mol
$H_2O(l)$	–	–	409	0.741	

Air: $\hat{H}$ from Table B.8

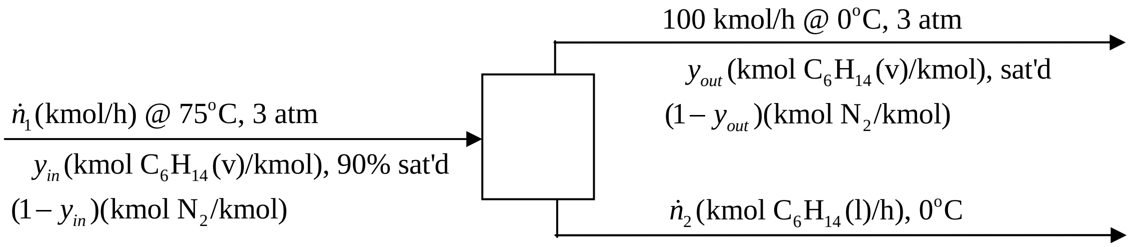
H_2O: $\hat{H}$(kJ / kg) from Table B.5 × (0.018 kg / mol)

Energy balance:

$$Q = \Delta H = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = \frac{-2.50\times10^4\ \text{kJ}}{\text{min}}\bigg|\frac{60\ \text{min}}{1\ \text{h}}\bigg|\frac{9.486\times10^{-4}\ \text{Btu}}{0.001\ \text{kJ}}\bigg|\frac{1\ \text{ton}}{-12000\ \text{Btu/h}} = \underline{\underline{119\ \text{tons}}}$$

8.48

Basis: $\dfrac{746.7\ \text{m}^3\ \text{outlet gas / h}}{} \left| \dfrac{3\ \text{atm}}{1\ \text{atm}} \right| \dfrac{1\ \text{kmol}}{22.4\ \text{m}^3\,(\text{STP})} \right| = 100.0\ \text{kmol / h}$



Antoine:

$$\log p_v^* = 6.88555 - \frac{1175.817}{224.867+T} \qquad p_v^*(0°\text{C}) = 45.24\ \text{mm Hg},\ p_v^*(75°\text{C}) = 920.44\ \text{mm Hg}$$

$$y_{\text{out}} = \frac{p_v^*(0°\,\text{C})}{P} = \frac{45.24}{3(760)} = 0.0198\ \text{kmol}\ \ C_6H_{14}/\text{kmol}\ ,$$

$$y_{\text{in}} = \frac{0.90\,p_v^*(75°\,\text{C})}{P} = \frac{(0.90)(920.44)}{3(760)} = 0.363\,\frac{\text{kmol}\ C_6H_{14}}{\text{kmol}}$$

N_2 balance: $\dot{n}_1(1-0.363) = 100(1-0.0198) \Rightarrow \dot{n}_1 = 153.9\ \text{kmol/h}$

C_6H_{14} balance: $(153.9)(0.363) = (100)(0.0198) + \dot{n}_2 \Rightarrow \dot{n}_2 = 53.89\ \text{kmol}\ C_6H_{14}(l)/\text{h}$

Percent Condensation: $(53.89\ \text{kmol/h condense})/(0.363\times 153.9)(\text{kmol/h in feed})\times 100\% = \underline{\underline{96.5\%}}$

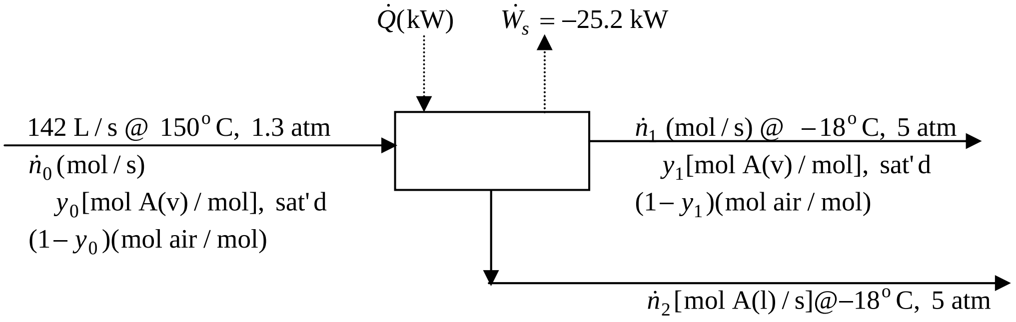
References: N_2(25°C), n-C_6H_{14}(l, 0°C)

Substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
N_2	98000	1.46	98000	−0.726	$\dot{n}$ in mol/h
$n\text{-}C_6H_{14}(r)$	55800	44.75	2000	33.33	$\hat{H}$ in kJ/mol
$n\text{-}C_6H_{14}(l)$	–	–	53800	0.0	

N_2: $\hat{H} = \overline{C}_p(T-25)$, $\quad n-C_6H_{14}$(v): $\hat{H} = \int_0^{68.7} C_{p\ell}\,dT + \Delta\hat{H}_v(68.7) + \int_{68.7}^{T} C_{pv}\,dT$

Energy balance: $Q = \underset{\sum\limits_{\text{out}} n_i\hat{H}_i - \sum\limits_{\text{in}} n_i\hat{H}_i}{\underset{\Uparrow}{\Delta H}} = (-2.64\times 10^6\ \text{kJ/h})(1\ \text{h / 3600 s}) \Rightarrow \underline{\underline{-733\ \text{kW}}}$

8.49 Let A denote acetone.



a. Degree of freedom analysis: 6 unknowns ($\dot{n}_0, \dot{n}_1, \dot{n}_2, y_0, y_1, \dot{Q}$)

−2 material balances
−1 equation of state for feed gas
−1 sampling result for feed gas
−1 saturation condition at outlet
−1 energy balance

0 degrees of freedom

b. Ideal gas equation of state Raoult's law

(1) $\dot{n}_0 = \dfrac{P_0\dot{V}_0}{RT_0}$ **(2)** $y_1 = \dfrac{p_A^*(-18^\circ\text{C})}{5\text{ atm}}$ (Antoine equation for p_A^*)

Feed stream analysis

(3) $y_0\left(\dfrac{\text{mol A}}{\text{mol}}\right) = \dfrac{[(4.973-4.017)\text{ g A}][1\text{ mol A}/58.05\text{ g}]}{[(3.00\text{ L})P_0/RT_0]\text{ mol feed gas}}$

Air balance: $\dot{n}_1 = \dfrac{\dot{n}_0(1-y_0)}{(1-y_1)}$ **(4)** Acetone balance: $\dot{n}_2 = \dot{n}_0 y_0 - \dot{n}_1 y_1$ **(5)**

Reference states: A(l, –18°C), air(25 °C)

Substance	$\dot{n}_{\text{in}}$ (mol/s)	$\hat{H}_{\text{in}}$ (kJ/mol)	$\dot{n}_{\text{out}}$ (mol/s)	$\hat{H}_{\text{out}}$ (kJ/mol)
A(l)	–	–	$\dot{n}_2$	0
A(v)	$\dot{n}_0 y_0$	$\hat{H}_{A0}$	$\dot{n}_1 y_1$	$\hat{H}_{A1}$
air	$\dot{n}_0(1-y_0)$	$\hat{H}_{a0}$	$\dot{n}_1(1-y_1)$	$\hat{H}_{a1}$

(6) $\hat{H}_{\text{A(v)}}(T) = \int_{-18^\circ\text{C}}^{56^\circ\text{C}} (C_p)_{\text{A(l)}}\,dT + (\Delta\hat{H}_v)_{\text{A}} + \int_{56^\circ\text{C}}^{T} (C_p)_{\text{A(v)}}\,dT$

Table B.2 Table B.1 Table B.2

(7) $\hat{H}_{\text{air}}(T)$ from Table B.8

(8) $\dot{Q} = \dot{W}_s + \sum \dot{n}_{\text{out}}\hat{H}_{\text{out}} - \sum \dot{n}_{\text{in}}\hat{H}_{\text{in}}$ ($\dot{W}_s = -25.2$ kJ/s)

8.59 **a.** Salt balance: $x_{L7}\dot{n}_{L7} = x_{L1}\dot{n}_{L1} \Rightarrow \dot{n}_{L1} = \dfrac{(0.035)(5000)}{0.30} = \underline{\underline{583\ \text{kg/h}}}$

Fresh water produced: $n_{L7} - n_{L1} = 5000 - 583 = \underline{\underline{4417\ \text{kg fresh water/h}}}$

b. Final result given in Part (d).

c. Salt balance on i^{th} effect:

$$\dot{n}_{Li}x_{Li} = (\dot{n}_L)_{i+1}(x_L)_{i+1} \Rightarrow x_{Li} = \frac{(\dot{n}_L)_{i+1}(x_L)_{i+1}}{\dot{n}\theta_{Li}} \qquad (1)$$

Energy balance on i^{th} effect:

$$\Delta\dot{H} = 0 \Rightarrow \dot{n}_{vi}\hat{H}_{vi} + (\dot{n}_v)_{L-1}\left(\hat{H}_v\right)_{L-1} + \dot{n}_{Li}\hat{H}_{Li} - (\dot{n}_L)_{L+1}\left(\hat{H}_L\right)_{L+1} - (\dot{n}_v)_{L-1}\left(\hat{H}_v\right)_{L-1} = 0$$

$$\Rightarrow \quad (\dot{n}_v)_{L-1} = \frac{\dot{n}_{vi}\hat{H}_{vi} + \dot{n}_{Li}\hat{H}_{Li} - (\dot{n}_L)_{i+1}\left(\hat{H}_L\right)_{i+1}}{\left(\hat{H}_v\right)_{i-1} - \left(\hat{H}_L\right)_{L-1}} \qquad (2)$$

Mass balance on $(i-1)^{\text{th}}$ effect:

$$\dot{n}_{Li} = (\dot{n}_v)_{i-1} + (\dot{n}_L)_{i-1} \Rightarrow (\dot{n}_L)_{i-1} = \dot{n}_{Li} - (\dot{n}_v)_{i-1} \qquad (3)$$

d.

	P (bar)	**T** (K)	**n_L** (kg/h)	**x_L**	**n_V** (kg/h)	**H_L** (kJ/kg)	**H_V** (kJ/kg)
Fresh steam	2.0	393.4	---	---	981	504.7	2706.3
Effect 1	0.9	369.9	584	0.2997	934	405.2	2670.9
Effect 2	0.7	363.2	1518	0.1153	889	376.8	2660.1
Effect 3	0.5	354.5	2407	0.0727	809	340.6	2646.0
Effect 4	0.3	342.3	3216	0.0544	734	289.3	2625.4
Effect 5	0.2	333.3	3950	0.0443	612	251.5	2609.9
Effect 6	0.1	319.0	4562	0.0384	438	191.8	2584.8
Effect (7)	1.0	300.0	5000	0.0350	---	113.0	---

8.61 **(a)** i) Expt 1 $\Rightarrow \left(\dfrac{m}{V}\right)_{\text{liquid}} = \dfrac{(4.4553-3.2551)\text{kg}}{2.000\text{ L}} = 0.600\dfrac{\text{kg}}{\text{L}} \Rightarrow \underline{\underline{(SG)_{\text{liquid}} = 0.600}}$

ii) Expt 2 $\Rightarrow$ Mass of gas $= (3.2571-3.2551)\text{kg} = 0.0020\text{ kg} = 2.0\text{ g}$

$$\text{Moles of gas} = \frac{2.000\text{ L}}{} \left| \frac{273\text{ K}}{363\text{ K}} \right| \frac{(763-500)\text{mm Hg}}{760\text{ mm Hg}} \left| \frac{1\text{ mol}}{22.4\text{ liters(STP)}} \right. = 0.0232\text{ mol}$$

$$\text{Molecular weight} = (2.0\text{ g})/(0.0232\text{ mol}) = \underline{\underline{86\ \text{g/mol}}}$$

iii) $\underset{(\text{liquid})}{\text{Expt. 1}} \Rightarrow n = \dfrac{2.000\text{ liters}}{} \left| \dfrac{10^3\ \text{cm}^3}{1\text{ liter}} \right| \dfrac{0.600\text{ g}}{\text{cm}^3} \left| \dfrac{1\text{ mol}}{86\text{ g}} \right. = 14\text{ mol}$

Energy balance: The data show that C_v is independent of temperature

$$Q = \Delta U = nC_v\Delta T$$

$$\Rightarrow (C_v)_{\text{liquid}} = \frac{Q}{n\Delta T} = \frac{800\text{ J}}{(14\text{ mols})(2.4\text{ K})} = 24\ \text{J/mol}\cdot\text{K@284.2 K}$$

$$= \frac{800\text{ J}}{(14\text{ mols})(2.4\text{ K})} = 24\ \text{J/mol}\cdot\text{K@331.2 K}$$

$$\Rightarrow \underline{\underline{(C_v)_{\text{liquid}} \equiv 24\ \text{J/mol}\cdot\text{K}}}$$

$\underset{(\text{vapor})}{\text{Expt. 2}} \Rightarrow n = 0.0232\text{ mol [from (ii)]}$

$$C_v = a + bT \Rightarrow Q = 0.0232\int_{T_1}^{T_2}(a+bT)dT = 0.0232\left[a(T_2-T_1) + \frac{b}{2}(T_2^2 - T_1^2)\right]$$

$$\left.\begin{aligned} 1.30\text{ J} &= 0.0232\left[\text{a}(366.9-363.0) + \frac{\text{b}}{2}(366.9^2 - 363.0^2)\right] \\ 1.30\text{ J} &= 0.0232\left[\text{a}(492.7-490.0) + \frac{\text{b}}{2}(492.7^2 - 490.0^2)\right] \end{aligned}\right\} \Rightarrow \begin{aligned} a &= -4.069 \\ b &= 0.05052 \end{aligned}$$

$$\Rightarrow \underline{\underline{(C_v)_{\text{vapor}}(\text{J / mol}\cdot\text{K}) = -4.069 + 0.05052T(\text{K})}}$$

iv) Liquid: $\underline{\underline{C_p \approx C_v \equiv 24\ \text{J/mol}\cdot\text{K}}}$

Vapor: Assuming ideal gas behavior, $C_p = C_v + R = C_v + 8.314\ \text{J/mol}\cdot\text{K}$

$$\Rightarrow \underline{\underline{C_p(\text{J/mol}\cdot\text{K}) = 4.245 + 0.05052T(\text{K})}}$$

v) Expt. 3 $\Rightarrow$ $T = 315K,\ p^* = (763-564)\text{mm Hg} = 199\text{ mm Hg}$
$T = 334K,\ p^* = 401\text{ mm Hg}$
$T = 354K,\ p^* = 761\text{ mm Hg}$
$T = 379K,\ p^* = 1521\text{ mm Hg}$

8.64 (cont'd)

References: B(l, 10°C), I(l, 10°C)

substance	$\dot{n}_{in}$ (mol / h)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{out}$ (mol / h)	$\hat{H}_{out}$ (kJ / mol)
B (l)	8575	0	--	--
B (v)	--	--	8575	42.21
I (l)	15925	0	--	--
I (v)	--	--	15925	41.01

$$\left(\hat{H}_{out}\right)_{\mathrm{B}} = \left(\Delta\hat{H}_v\right)_{\mathrm{B}} + \int_{10}^{180}\left(C_p\right)_{\mathrm{B}} = 42.21\ \mathrm{kJ / mol}$$

$$\left(\hat{H}_{out}\right)_{\mathrm{I}} = \left(\Delta\hat{H}_v\right)_{\mathrm{I}} + \int_{10}^{180}\left(C_p\right)_{\mathrm{I}} = 41.01\ \mathrm{kJ / mol}$$

$$\Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 8575(42.21) - 15825(41.01)$$

$$\underline{\Delta\dot{H} = 1.015\times10^6\ \mathrm{kJ / h}}$$

c. $$Q = 1.015\times10^6\ \mathrm{kJ / h} = \dot{m}_{\mathrm{hf}}\left[2.62\ \mathrm{kJ / \left(kg\cdot^{o}C\right)}\right]\left[(215-45)^{o}\mathrm{C}\right]$$

$$\underline{\underline{\dot{m}_{\mathrm{hf}} = 2280\ \mathrm{kg / h}}}$$

d. $$(2540\ \mathrm{kg / h})\left[2.62\ \mathrm{kJ / \left(kg\cdot^{o}C\right)}\right]\left[(215-45)^{o}\mathrm{C}\right] = 1.131\times10^6\ \mathrm{kJ / h}$$

$$\text{Heat transfer rate} = 1.131\times10^6 - 1.015\times10^6 = \underline{\underline{1.16\times10^5\ \mathrm{kJ / h}}}$$

e. The heat loss leads to a pumping cost for the additional heating fluid and a greater heating cost to raise the additional fluid back to 215°C.

f. Adding the insulation reduces the costs given in part (e). The insulation is probably preferable since it is a one-time cost and the other costs continue as long as the process runs. The final decision would depend on how long it would take for the savings to make up for the cost of buying and installing the insulation.

8.65 **(a)** Basis: 100 g of mixture, SG_{Benzene}=0.879: SG_{Toluene}=0.866

$$n_{\mathrm{total}} = \frac{50\ \mathrm{g}}{78.11\ \mathrm{g / mol}} + \frac{50\ \mathrm{g}}{92.13\ \mathrm{g / mol}} = (0.640+0.542)\ \mathrm{mol} = 1.183\ \mathrm{mol}$$

$$\mathrm{V}_{\mathrm{total}} = \frac{50\ \mathrm{g}}{0.879\ \mathrm{g / cm^3}} + \frac{50\ \mathrm{g}}{0.866\ \mathrm{g / cm^3}} = 114.6\ \mathrm{cm^3}$$

$$\left(x_f\right)_{\mathrm{C_6H_6}} = \frac{0.640\ \mathrm{mol\ C_6H_6}}{1.183\ \mathrm{mol}} = \underline{\underline{0.541\ \mathrm{mol\ C_6H_6/mol}}}$$

$$\underline{\text{Actual feed:}}\ \frac{32.5\ \mathrm{m^3}}{\mathrm{h}}\left|\frac{10^6\mathrm{cm^3}}{1\ \ \mathrm{m^3}}\right|\frac{1.183\ \mathrm{mol\ mixture}}{114.6\ \mathrm{cm^3\ mixture}}\left|\frac{1\ \mathrm{h}}{3600\ \mathrm{s}}\right. = \underline{\underline{93.19\ \mathrm{mol / s}}}$$

$$T = 90°\mathrm{C} \Rightarrow p^*_{\mathrm{C_6H_6}} = 1021\ \mathrm{mm\ Hg}\ ,\ p^*_{\mathrm{C_7H_8}} = 407\ \mathrm{mm\ Hg}\ \ \text{(from Table 6.1-1)}$$

$$\underline{\text{Raoult's law:}\ \ p_{tot}} = x_{\mathrm{C_6H_6}}p^*_{\mathrm{C_6H_6}} + x_{\mathrm{C_7H_8}}p^*_{\mathrm{C_7H_8}} = (0.541)(1021) + (0.459)(407)$$

$$= \frac{739.2\ \mathrm{mmHg}}{}\left|\frac{1\ \mathrm{atm}}{760\ \mathrm{mmHg}}\right. = 0.973\ \mathrm{atm} \Rightarrow \underline{\underline{P_0 > 0.973\ \mathrm{atm}}}$$

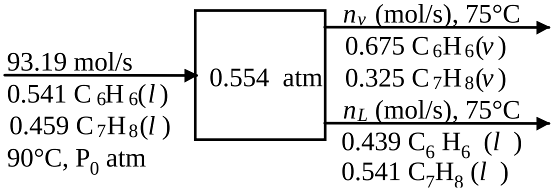
8.65 (cont'd)

(b) $T = 75°\text{C} \Rightarrow p^*_{\text{C}_6\text{H}_6} = 648 \text{ mm Hg}$, $p^*_{\text{C}_7\text{H}_8} = 244 \text{ mm Hg}$ (from Table 6.1-1)

$$\underline{\text{Raoult's law}} \Rightarrow p_{\text{tank}} = x_{\text{C}_6\text{H}_6} p^*_{\text{C}_6\text{H}_6} + x_{\text{C}_7\text{H}_8} p^*_{\text{C}_7\text{H}_8} = (0.439)(648) + (0.561)(244)$$

$$= (284 + 137) \text{mm Hg} = 421 \text{ mmHg} \Rightarrow \underline{\underline{\text{P}_{\text{tank}} = 0.554 \text{ atm}}}$$

$$y_{\text{C}_6\text{H}_6} = \frac{284 \text{ mm Hg}}{421 \text{ mm Hg}} = \underline{\underline{0.675 \text{ mol C}_6\text{H}_6(v)/\text{mol}}}$$



$$\left.\begin{array}{l}\underline{\text{Mole balance:}}\ 93.19 = n_v + n_L \\ \underline{\text{C}_6\text{H}_6 \text{ balance:}}\ (0.541)(93.19) = 0.675 n_v + 0.439 n_L\end{array}\right\} \Rightarrow \begin{array}{l} n_v = \underline{\underline{40.27 \text{ mol vapor/s}}} \\ n_L = \underline{\underline{52.92 \text{ mol liquid/s}}}\end{array}$$

(c) Reference states: $\text{C}_6\text{H}_6(l)$, $\text{C}_6\text{H}_6(l)$ at 75°C

Substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
$\text{C}_6\text{H}_6(v)$	–	–	27.18	31.0	$\dot{n}$ in mol/s
$\text{C}_6\text{H}_6(l)$	50.41	2.16	23.23	0	$\hat{H}$ in kJ/mol
$\text{C}_7\text{H}_8(v)$	–	–	13.09	35.3	
$\text{C}_7\text{H}_8(l)$	42.78	2.64	29.69	0	

$$\underline{\text{C}_6\text{H}_6(l,\ 90°\text{C})}:\ \hat{H} = (0.144)(90 - 75) = 2.16 \text{ kJ/mol}$$

$$\underline{\text{C}_7\text{H}_8(l,\ 90°\text{C})}:\ \hat{H} = (0.176)(90 - 75) = 2.64 \text{ kJ/mol}$$

$$\underline{\text{C}_6\text{H}_6(v,\ 75°\text{C})}:\ \hat{H} = (0.144)(80.1 - 75) + \underset{\Delta\hat{H}_v(80.1°\text{C})}{\underset{\uparrow}{30.77}} + \int_{80.1}^{75} \left[0.074 + 0.330 \times 10^{-3} T\right] dT$$

$$= 31.0 \text{ kJ/mol}$$

$$\underline{\text{C}_7\text{H}_8(v,\ 75°\text{C})}:\ \hat{H} = (0.176)(110.6 - 75) + 33.47 + \int_{110.6}^{75} \left[0.0942 + 0.380 \times 10^{-3} T\right] dT$$

$$= 35.3 \text{ kJ/mol}$$

$$\underline{\text{Energy balance:}}\ \dot{Q} = \Delta\dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = \frac{1082 \text{ kJ}}{\text{s}} \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right. = \underline{\underline{1082 \text{ kW}}}$$

(d) The feed composition changed; the chromatographic analysis is wrong; the heating rate changed; the system is not at steady state; Raoult's law and/or the Antoine equation are only approximations; the vapor and liquid streams are not in equilibrium.

(e) Heat is required to vaporize a liquid and heat is lost from any vessel for which $\text{T} > \text{T}_{\text{ambient}}$. If insufficient heat is provided to the vessel, the temperature drops. To run the experiment isothermally, a greater heating rate is required.

8.74 (cont'd)

The outside air is first cooled to a temperature at which the required amount of water is condensed, and the cold air is then reheated to 55°F. Since h_a remains constant in the second step, the condition of the air following the cooling step must lie at the intersection of the $h_a = 0.0075$ line and the saturation curve $\Rightarrow \underline{\underline{T = 49°\text{ F}}}$

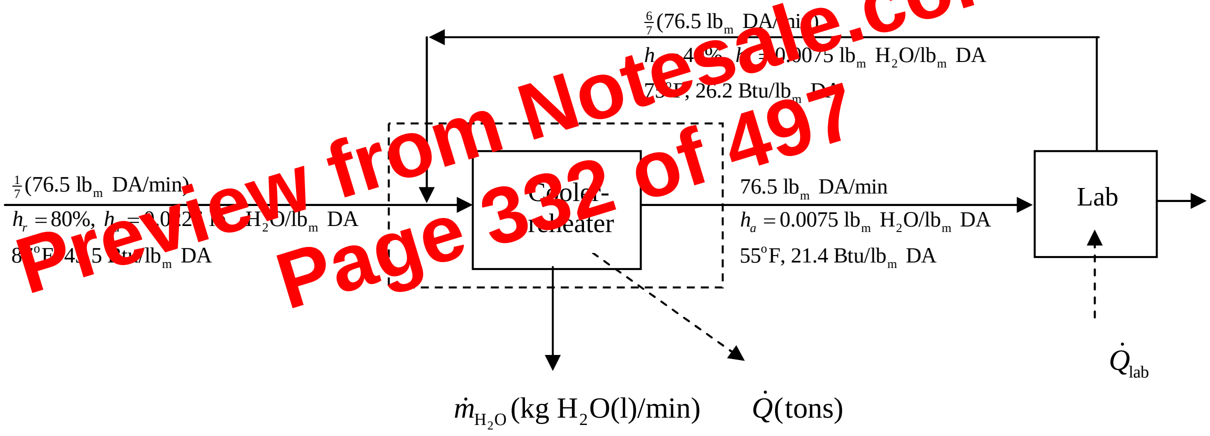
<u>References:</u> Same as Fig. 8.4-2 [including $H_2O(l, 32°\text{ F})$]

substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$	
Air	76.5	45.5	76.5	21.4	$\dot{m}_{\text{air}}$ in lb_m D.A./min
$H_2O(l, 49°\text{ F})$	—	—	1.2	17.0	$\hat{H}_{\text{air}}$ in Btu/lb_m D.A.
					$\dot{m}_{H_2O}$ in lb_m/min, $\hat{H}_{H_2O}$ in Btu/lb_m

$$Q = \Delta H = \frac{(76.5)[21.4 - 45.5] + 1.2(17.0)\ (\text{Btu})}{\text{min}}\left|\frac{60\text{ min}}{1\text{ h}}\right|\frac{1\text{ ton cooling}}{-12{,}000\ \text{Btu/h}}$$

$$= \underline{\underline{9.1\text{ tons cooling}}}$$

b.



<u>Water balance on cooler-reheater (system shown as dashed box in flow chart)</u>

$$\tfrac{1}{7}\left(76.5\ \frac{\text{lb}_\text{m}\ \text{DA}}{\text{min}}\right)\left(0.0226\frac{\text{lb}_\text{m}\ {}_{H_2O}}{\text{lb}_\text{m}\ \text{DA}}\right) + \tfrac{6}{7}(76.5\ )(0.0075) = (76.5)(0.0075) + \dot{m}_{H_2O}$$

$$\Rightarrow\ \dot{m}_{H_2O} = \underline{\underline{0.165\text{ kg }H_2O\text{ condensed/min}}}$$

8.74 (cont'd)

Energy balance on cooler-reheater

References: Same as Fig. 8.4-2 [including H_2O(l, 32°F)]

Substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$	
Fresh air feed	10.93	45.5	—	—	$\dot{m}_{\text{DA}}$ in lb_m dry air/min
Recirculated air feed	65.57	26.2	—	—	$\hat{H}_{\text{air}}$ in Btu/lb_m dry air
Delivered air	—	—	76.5	21.4	$\dot{m}_{H_2O(l)}$ in lb_m/min
Condensed water (49°F)	—	—	0.165	17.0	$\hat{H}_{H_2O(l)}$ in Btu/lb_m

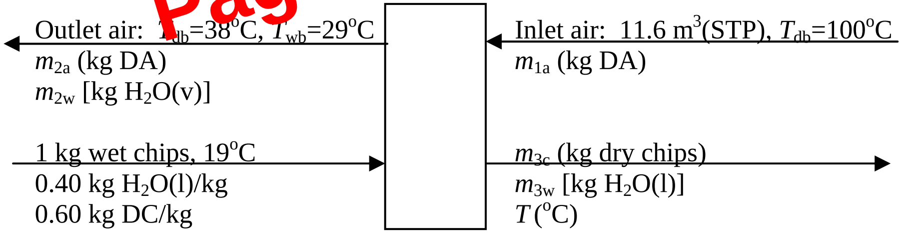
$$\dot{Q} = \Delta\dot{H} = \sum_{\text{out}} \dot{m}_i\hat{H}_i - \sum_{\text{in}} \dot{m}_i\hat{H}_i = \frac{-575.3\text{ Btu}}{\text{min}}\left|\frac{60\text{ min}}{1\text{ h}}\right|\frac{1\text{ ton cooling}}{-12{,}000\text{ Btu/h}} = \underline{\underline{2.9\text{ tons}}}$$

$$\text{Percent saved by recirculating} = \frac{(9.1\text{ tons} - 2.9\text{ tons})}{9.1\text{ tons}} \times 100\% = \underline{\underline{68\%}}$$

Once the system reaches steady state, most of the air passing through the conditioner is cooler than the outside air, and (more importantly) much less water must be condensed (only the water in the fresh feed).

c. Total recirculation could eventually lead to an unhealthy depletion of oxygen and buildup of carbon dioxide in the laboratory.

8.75 Basis: 1 kg wet chips. DA = dry air, DC = dry chips



(a) Dry air: $m_{1a} = \dfrac{11.6\text{ m}^3(\text{STP})\text{ DA}}{}\left|\dfrac{1\text{ kmol}}{22.4\text{ m}^3(\text{STP})}\right|\dfrac{29.0\text{ kg}}{1\text{ kmol}} = 15.02\text{ kg DA} = \text{m}_{2a}$

Outlet air:

$$(T_{\text{db}} = 38°\text{C}, T_{\text{wb}} = 29°\text{C}) \xrightarrow{\text{Fig. 8.4-1}} \hat{H}_2 = (95.3 - 0.48) = \underline{\underline{94.8\ \frac{\text{kJ}}{\text{kg DA}}}} \qquad h_{a_2} = \underline{\underline{0.0223\ \frac{\text{kg H}_2\text{O}}{\text{kg DA}}}}$$

Water in outlet air: $m_{2w} = h_{a_2} m_{2a} = 0.0223(15.02) = \underline{\underline{0.335\text{ kg H}_2\text{O}}}$

(b) H_2O balance: $0.400\text{ kg} = 0.335\text{ kg} + m_{3w} \Rightarrow m_{3w} = 0.065\text{ kg H}_2\text{O}$

8.86 (cont'd)

$$\hat{H}(\text{HCl},\ n=5.75)=\Delta\hat{H}_s(25^\circ\text{C},\ n=5.75)+\frac{1}{n_{\text{HCl}}}\int_{25}^{40} mC_p dT$$

$$=-64.87\ \text{kJ/mol}+\frac{1120\ \text{g}}{8\ \text{mols}}\bigg|\frac{0.66\ \text{cal}}{\text{g}\cdot^\circ\text{C}}\bigg|\frac{(40-25)^\circ\text{C}}{}\bigg|\frac{4.184\ \text{J}}{\text{cal}}\bigg|\frac{\text{kJ}}{10^3\ \text{J}}$$

$$\hat{H}\left(\text{HCl},\ 20^\circ\text{C}\right)=\int_{25}^{20}\left[0.02913-0.1341\times10^{-5}T+0.9715\times10^{-8}T^2-4.335\times10^{-12}T^3\right]dT$$

$$= -0.15\ \text{kJ / mol}$$

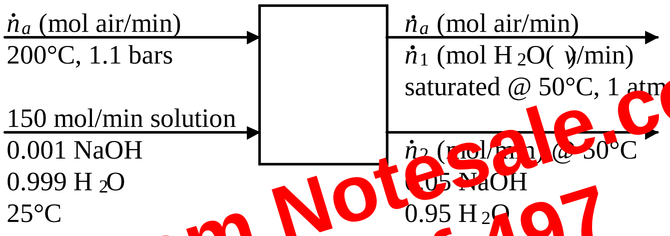
$$Q=\Delta H=\underline{\underline{-471\ \text{kJ/L product}}}$$

c. $Q=0=\Delta H=8\left(\hat{H}\right)-8(-0.15)$

$$-0.15=\hat{H}=-64.87+\frac{1120\ \text{g}}{8\ \text{mol}}\bigg|\frac{0.66\ \text{cal}}{\text{g}\cdot^\circ\text{C}}\bigg|\frac{(T-25)^\circ\text{C}}{}\bigg|\frac{4.184\ \text{J}}{\text{cal}}\bigg|\frac{1\ \text{kJ}}{1000\ \text{J}}$$

$$\underline{\underline{T=192\ ^\circ\text{C}}}$$

8.87 Basis: Given solution feed rate



NaOH balance: $(0.001)(150)=0.05\dot{n}_2\Rightarrow\dot{n}_2=3.0\ \text{mol/min}$

H_2O balance: $(0.999)(150)=\dot{n}_1+0.95(3.0)\Rightarrow\dot{n}_1=147\ \text{mol H}_2\text{O/min}$

Raoult's law: $y_{H_2O}P=\dfrac{\dot{n}_1}{\dot{n}_1+\dot{n}_a}P=p^*_{H_2O}(50^\circ\text{C})\overset{\text{Table B.4}}{=}92.51\ \text{mm Hg}\underset{\substack{\dot{n}_1=147\\P=760}}{\Rightarrow}\dot{n}_a=1061\dfrac{\text{mol air}}{\text{min}}$

$$\dot{V}_{\text{inlet air}}=\frac{1061\ \text{mol}}{\text{min}}\bigg|\frac{22.4\ \text{L(STP)}}{1\ \text{mol}}\bigg|\frac{473\ \text{K}}{273\ \text{K}}\bigg|\frac{1.013\ \text{bars}}{1.1\ \text{bars}}=\underline{\underline{37{,}900\ \text{L/min}}}$$

References for enthalpy calculations: $H_2O(l)$, $NaOH(s)$, air @ 25°C

0.1% solution @ 25°C: $r=\dfrac{999\ \text{mol H}_2\text{O}}{1\ \text{mol NaOH}}\overset{\text{Table B.11}}{\Rightarrow}\Delta\hat{H}_s(25^\circ\text{C})=-42.47\ \text{kJ/mol NaOH}$

5% solution @ 50°C: $r=\dfrac{95\ \text{mol H}_2\text{O}}{5\ \text{mol NaOH}}=\dfrac{19\ \text{mol H}_2\text{O}}{\text{mol NaOH}}\Rightarrow\Delta\hat{H}_s(25^\circ\text{C})=-42.81\dfrac{\text{kJ}}{\text{mol NaOH}}$

Solution mass: $m=\dfrac{1\ \text{mol NaOH}}{}\bigg|\dfrac{40.0\ \text{g}}{1\ \text{mol}}+\dfrac{19\ \text{mol H}_2\text{O}}{}\bigg|\dfrac{18.0\ \text{g}}{1\ \text{mol}}=382\ \dfrac{\text{g solution}}{\text{mol NaOH}}$

$$\hat{H}(50^\circ\text{C})=\Delta\hat{H}_s(25^\circ\text{C})+m\int_{25}^{50}C_p dT$$

$$=-42.81\frac{\text{kJ}}{\text{mol NaOH}}+\frac{382\ \text{g}}{\text{mol NaOH}}\bigg|\frac{4.184\ \text{J}}{1\ \text{g}\cdot^\circ\text{C}}\bigg|\frac{(50-25)^\circ\text{C}}{}\bigg|\frac{1\ \text{kJ}}{10^3\ \text{J}}=-2.85\ \text{kJ}$$

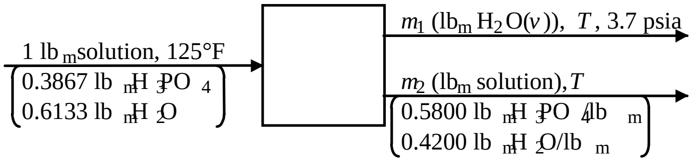
8.89 $P_2O_5 + 3H_2O \rightarrow 2H_3PO_4$

a. $$\text{wt\% } P_2O_5 = \frac{n(141.96)}{m_t} \times 100\% \,, \quad \text{wt\% } H_3PO_4 = \frac{\overbrace{2n}^{\text{mol } H_3PO_4} \; \overset{\text{g } H_3PO_4\text{/mol}}{(98.00)}}{\underset{\text{g total}}{m_c}} \times 100\%$$

where $n = \text{mol } P_2O_5$ and $m_t = \text{total mass}$.

$$\underline{\underline{\text{wt\% } H_3PO_4 = \frac{2(98.00)}{141.96} \text{ wt\% } P_2O_5 = 1.381 \text{ wt\% } P_2O_5}}$$

b. Basis: 1 lb_m feed solution 28 wt% $P_2O_5 \Rightarrow 38.67$ wt% H_3PO_4



H_3PO_4 balance: $0.3867 = 0.5800 m_2 \Rightarrow m_2\, 0.667 \ \text{lb}_\text{m}$ solution

Total balance: $1 = m_1 + m_2 \Rightarrow m_1 = 0.3333 \ \text{lb}_\text{m}\ H_2O(v)$

Evaporation ratio: $\underline{\underline{0.3333 \ \text{lb}_\text{m}\ H_2O(v)/\text{lb}_\text{m} \text{ feed solution}}}$

c. Condensate:

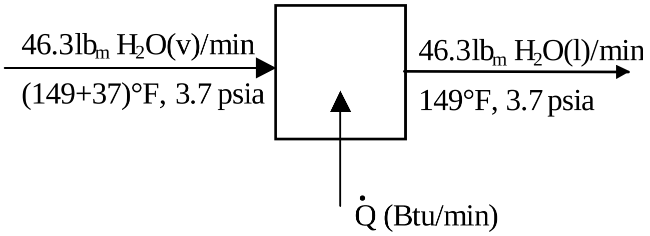
$P = 3.7$ psia (0.255 bar)

$$\xRightarrow{\text{Table B.6}} T_{\text{sat}} = 65.4^\circ\text{C} = 149^\circ\text{F}, \quad V_{\text{liq}} = \frac{0.00102 \text{ m}^3}{\text{kg}} \left| \frac{35.3145 \text{ ft}^3/\text{m}^3}{2.205 \text{ lb}_\text{m}/\text{kg}} \right. = 0.0163 \frac{\text{ft}^3}{\text{lb}_\text{m}\ H_2O(l)}$$

$$\dot{m} = \frac{100 \text{ tons feed}}{\text{day}} \left| \frac{2000 \text{ lb}_\text{m}}{1 \text{ ton}} \right| \frac{1 \text{ lb}_\text{m}\ H_2O}{3 \text{ lb}_\text{m}} \left| \frac{1 \text{ day}}{(24 \times 60) \text{ min}} \right. = 46.3 \text{ lb}_\text{m}/\text{min}$$

$$\dot{V} = \frac{46.3 \text{ lb}_\text{m}}{\text{min}} \left| \frac{0.0163 \text{ ft}^3}{\text{lb}_\text{m}} \right| \frac{7.4805 \text{ gal}}{\text{ft}^3} = \underline{\underline{5.65 \text{ gal condensate/min}}}$$

Heat of condensation process:



8.93 Refs: Sulfuric acid and water @ 25 °C

b.

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
H_2SO_4 H_2O	1 r	$M_A C_{pA}(T_0-25)$ $M_w C_{pw}(T_0-25)$	— —	— —	n in mol $\hat{H}$ in J/mol
$H_2SO_4(aq)$	—	—	1	$\Delta\hat{H}_m(r)+(M_A+rM_w)C_{ps}(T_s-25)$ (J/mol H_2SO_4)	

$$\Delta H = 0 = \Delta\hat{H}_m(r)+(M_A+rM_w)C_{ps}(T_s-25)-M_A C_{pa}(T_0-25)-rM_w C_{pw}(T_0-25)$$

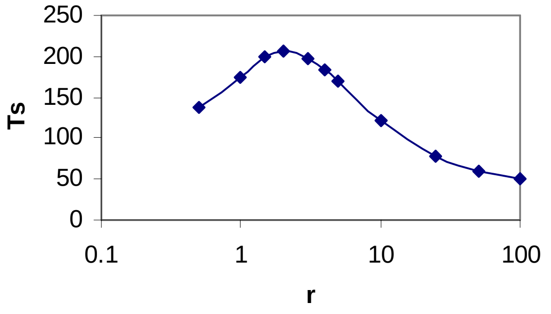
$$= \Delta\hat{H}_m(r)+(98+18r)C_{ps}(T_s-25)-(98C_{pa}+18rC_{pw})(T_0-25)$$

$$\Rightarrow \underline{\underline{T_s = 25+\frac{1}{(98+18r)C_{ps}}\left[(98C_{pa}+18rC_{pw})(T_0-25)-\Delta\hat{H}_m(r)\right]}}$$

c.

	C_p (J/mol-K)	C_p (J/g-K)
$H_2O(l)$	75.4	4.2
H_2SO_4	185.6	1.9

r	C_{ps}	$\Delta\hat{H}_m(r)$	T_s
0.5	1.58	-15,730	137.9
1	1.85	-28,070	174.0
1.5	1.89	-36,900	200.2
2	1.94	-41,920	205.7
3	2.1	-48,990	197.8
4	2.27	-54,060	184.0
5	2.43	-58,030	170.5
10	3.03	-67,030	121.3
25	3.56	-72,300	78.0
50	3.84	-73,340	59.6
100	4	-73,970	50.0



d. Some heat would be lost to the surroundings, leading to a lower final temperature.

9.2 (cont'd)

Heat Output = 1.53×10^5 kW.
The reactor pressure is low enough to have a negligible effect on enthalpy.

d.

$$C_9H_{20}(g) + 14O_2(g) \rightarrow 9CO_2(g) + 10H_2O(l) \qquad (1)$$

$$\Delta\hat{H}_r^o = -6171 \text{ kJ / mol}$$

$$C_9H_{20}(l) + 14O_2(g) \rightarrow 9CO_2(g) + 10H_2O(l) \qquad (2)$$

$$\Delta\hat{H}_r^o = -6124 \text{ kJ / mol}$$

$$(2) - (1) \Rightarrow C_9H_{20}(l) \rightarrow C_9H_{20}(g)$$

$$\Delta\hat{H}_v^o(C_9H_{20}, 25^\circ C) = \;-6124 \text{ kJ / mol} - (-6171 \text{ kJ / mol}) = \underline{\underline{47 \text{ kJ / mol}}}$$

e. Yes. Pure n-nonane can only exist as vapor at 1 atm above 150.6°C, but in a mixture of gases, it can exist as a vapor at lower temperatures.

9.3 **a.** Exothermic. The reactor will have to be cooled to keep the temperature constant. The temperature would increase under adiabatic conditions. The energy required to break the reactant bonds is less than the energy released when the product bonds are formed.

b.

$$C_6H_{14}(g) + \frac{19}{2}O_2(g) \rightarrow 6CO_2(g) + 7H_2O(g) \quad (1) \quad \Delta\hat{H}_r^o = ?$$

$$C_6H_{14}(l) + \frac{19}{2}O_2(g) \rightarrow 6CO_2(g) + 7H_2O(l) \quad (2) \quad \Delta\hat{H}_2 = \Delta\hat{H}_r^o = -1.791 \times 10^6 \text{ Btu/lb-mole}$$

$$C_6H_{14}(g) \rightarrow C_6H_{14}(l) \quad (3) \quad \Delta\hat{H}_3 = -\left(\Delta\hat{H}_v\right)_{C_2H_4} = -13{,}5[illegible]2 \text{ Btu/lb-mole}$$

$$H_2O(l) \rightarrow H_2O(g) \quad (4) \quad \Delta\hat{H}_4 = \left(\Delta\hat{H}_v\right)_{H_2O} = 18{,}934 \text{ Btu/lb-mole}$$

$$(1) = (2) + (3) + 7 \times (4) \overset{\text{Hess's law}}{\Rightarrow} \Delta\hat{H}_1 = \Delta\hat{H}_2 + \Delta\hat{H}_3 + 7\Delta\hat{H}_4 = \underline{\underline{-1.672 \times 10^6 \text{ Btu/lb-mole}}}$$

c.

$$\dot{m} = 120 \text{ lb}_m\text{ / s} \quad \overset{M_{O_2}=32.0}{\Rightarrow} \quad \dot{n} = 3.75 \text{ lb-mole / s.}$$

$$\dot{Q} = \Delta\dot{H} = \frac{\dot{n}_{O_2}\Delta\hat{H}_r^o}{\nu_{O_2}} = \frac{3.75 \text{ lb-mole/s}}{9.5}\left|\frac{-1.672\times10^6 \text{ Btu}}{1 \text{ lb-mole } O_2}\right. = \underline{\underline{-6.60\times10^5 \text{ Btu/s (from reactor)}}}$$

9.4

$$CaC_2(s) + 5H_2O(l) \rightarrow CaO(s) + 2CO_2(g) + 5H_2(g), \; \Delta\hat{H}_r^o = 69.36 \text{ kJ/kmol}$$

a. Endothermic. The reactor will have to be heated to keep the temperature constant. The temperature would decrease under adiabatic conditions. The energy required to break the reactant bonds is more than the energy released when the product bonds are formed.

b.

$$\Delta\hat{U}_r^o = \Delta\hat{H}_r^o - RT\left[\sum_{\substack{\text{gaseous}\\\text{products}}}\nu_i - \sum_{\substack{\text{gaseous}\\\text{reactants}}}\nu_i\right] = 69.36\frac{\text{kJ}}{\text{mol}} - \frac{8.314 \text{ J}}{\text{mol}\cdot\text{K}}\left|\frac{1 \text{ kJ}}{10^3 \text{ J}}\right|\frac{298 \text{ K}}{}\left|\frac{(7-0)}{}\right.$$

$$= \underline{\underline{52.0 \text{ kJ/mol}}}$$

9.4 (cont'd)

$\Delta\hat{U}_r^o$ is the change in internal energy when 1 g-mole of $CaC_2(s)$ and 5 g-moles of $H_2O(l)$ at 25°C and 1 atm react to form 1 g-mole of CaO(s), 2 g-moles of $CO_2(g)$ and 5 g-moles of $H_2(g)$ at 25°C and 1 atm.

c. $$Q = \Delta U = \frac{n_{CaC_2}\Delta\hat{U}_r^o}{\nu_{CaC_2}} = \frac{150\text{ g CaC}_2}{} \left| \frac{1\text{ mol}}{64.10\text{ g}} \right| \frac{52.0\text{ kJ}}{1\text{ mol CaC}_2} = \underline{\underline{121.7\text{ kJ}}}$$

Heat must be transferred to the reactor.

9.5

a. $\underline{\text{Given reaction} = (1) - (2)} \overset{\text{Hess's law}}{\Rightarrow} \Delta\hat{H}_r^o = \Delta\hat{H}_{r1}^o - \Delta\hat{H}_{r2}^o = (1226 - 18{,}935)$ Btu/lb-mole

$= \underline{\underline{-17{,}709\ \text{Btu/lb-mole}}}$

b. $\underline{\text{Given reaction} = (1) - (2)} \overset{\text{Hess's law}}{\Rightarrow} \Delta\hat{H}_r^o = \Delta\hat{H}_{r1}^o - \Delta\hat{H}_{r2}^o = (-121{,}740 + 104{,}040)$ Btu/lb-mole

$= \underline{\underline{-17{,}700\ \text{Btu/lb-mole}}}$

9.6

a. $$\text{Reaction }(3) = 0.5\times(1) - (2) \overset{\text{Hess's law}}{\Rightarrow} \Delta\hat{H}_r^o = 0.5\left(-326.2\ \frac{\text{kJ}}{\text{mol}}\right) - \left(-285.8\ \frac{\text{kJ}}{\text{mol}}\right) = \underline{\underline{122.7\ \frac{\text{kJ}}{\text{mol}}}}$$

b. Reactions (1) and (2) are easy to carry out experimentally, but it would be very hard to decompose methanol with only reaction (3) occurring.

9.7

a. $$N_2(g) + O_2(g) \rightarrow 2NO(g),\ \Delta\hat{H}_r^o = 2\left(\Delta\hat{H}_f^o\right)_{NO(g)} \overset{\text{Table B.1}}{=} 2\left(90.37\ \text{kJ/mol}\right) = \underline{\underline{180.74\ \text{kJ/mol}}}$$

b. $$n-C_5H_{12}(g) + \frac{11}{2}O_2(g) \rightarrow 5CO(g) + 6H_2O(l)$$

$$\Delta\hat{H}_r^o = 5\left(\Delta\hat{H}_f^o\right)_{CO(g)} + 6\left(\Delta\hat{H}_f^o\right)_{H_2O(l)} - \left(\Delta\hat{H}_f^o\right)_{n-C_5H_{12}(g)}$$

$$= \left[(5)(-110.52) + (6)(-285.84) - (-146.4)\right]\ \text{kJ/mol} = \underline{\underline{-2121.2\ \text{kJ/mol}}}$$

c. $$C_6H_{14}(l) + \frac{19}{2}O_2(g) \rightarrow 6CO_2(g) + 7H_2O(g)$$

$$\Delta\hat{H}_r^o = 6\left(\Delta\hat{H}_f^o\right)_{CO_2} + 7\left(\Delta\hat{H}_f^o\right)_{H_2O(g)} - \left(\Delta\hat{H}_f^o\right)_{C_6H_{14}(l)}$$

$$= \left[(6)(-393.5) + 7(-241.83) - (-198.8)\right]\ \text{kJ/mol} = \underline{\underline{-3855\ \text{kJ/mol}}}$$

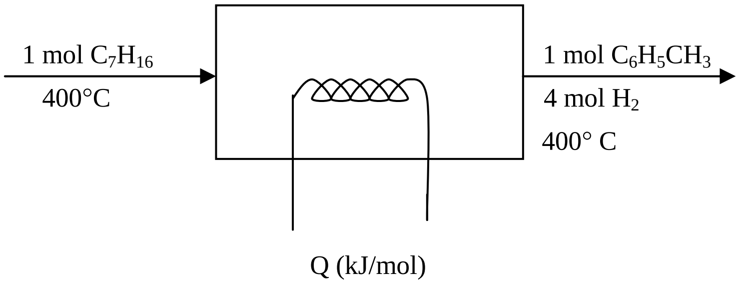
d. $$Na_2SO_4(l) + 4CO(g) \rightarrow Na_2S(l) + 4CO_2(g)$$

$$\Delta\hat{H}_r^o = \left(\Delta\hat{H}_f^o\right)_{Na_2S(l)} + 4\left(\Delta\hat{H}_f^o\right)_{CO_2(g)} - \left(\Delta\hat{H}_f^o\right)_{Na_2SO_4(l)} - 4\left(\Delta\hat{H}_f^o\right)_{CO(g)}$$

$$= \left[(-373.2 + 6.7) + (4)(-393.5) - (-1384.5 + 24.3) - 4(-110.52\right]\ \text{kJ/mol} = \underline{\underline{-138.2\ \text{kJ/mol}}}$$

9.14 **a.** $C_7H_{16}(g) \rightarrow C_6H_5CH_3(g) + 4H_2(g)$

Basis: 1 mol C_7H_{16}



b. References: $C(s), H_2(g)$ at 25°C

substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
C_7H_{16}	1	$\hat{H}_1$	–	–
C_7H_8	–	–	1	$\hat{H}_2$
H_2	–	–	4	$\hat{H}_3$

$$C_7H_{16}(g,400°C): \hat{H}_1 = (\Delta\hat{H}_f^\circ)_{C_7H_{16}(g)} + \left[\int_{25}^{400} \overset{\overset{0.2427}{\downarrow}}{C_p}\, dT\right]$$

$$= (-187.8 + 91.0)\text{ kJ/mol} = \underline{\underline{-96.8\text{ kJ/mol}}}$$

$$C_6H_5CH_3(g,400°C): \hat{H}_2 = (\Delta\hat{H}_f^\circ)_{C_6H_5CH_3(g)} + \left[\int_{25}^{400} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p}\, dT\right]$$

$$= (+50 + 60.2)\text{ kJ / mol} = \underline{\underline{110.2\text{ kJ / mol}}}$$

$$H_2(g,400°C): \hat{H}_3 = \hat{H}_{H_2}(400^\circ C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{10.89\text{ kJ/mol}}}$$

c.

$$Q = \Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i$$

$$= \left[(1)(110.2) + (4)(10.89) - (1)(-96.8)\right]\text{kJ} = 251\text{ kJ (transferred to reactor)}$$

d.

$$\Delta\hat{H}_r(400^\circ C) = \frac{251\text{ kJ}}{1\text{ mol } C_7H_{16}\text{ react}} = \underline{\underline{251\text{ kJ/mol}}}$$

9.19 (cont'd)

$$\underline{\text{Makeup water required}}: 495{,}000\text{ gal} - \frac{46{,}360\text{ gal C}_2\text{H}_5\text{OH}}{\,}\left|\frac{25\text{ gal mash}}{2.6\text{ gal C}_2\text{H}_5\text{OH}}\right. = \underline{\underline{4.9\times10^4\text{ gal}}}$$

b.

$$\underline{\text{Acres reqd.}}: \frac{46{,}360\text{ gal C}_2\text{H}_5\text{OH}}{1\text{ batch}}\left|\frac{1\text{ bu}}{2.6\text{ gal C}_2\text{H}_5\text{OH}}\right|\frac{1\text{ acre}}{101\text{ bu}}\left|\frac{1\text{ batch}}{8\text{ h}}\right|\frac{24\text{ h}}{1\text{ day}}\left|\frac{330\text{ days}}{1\text{ year}}\right. = \underline{\underline{1.75\times10^5\ \frac{\text{acres}}{\text{year}}}}$$

$$\text{C}_{12}\text{H}_{22}\text{O}_{11}(\text{s}) + 12\text{O}_2(\text{g}) \rightarrow 12\text{CO}_2(\text{g}) + 11\text{H}_2\text{O}(\text{l}) \qquad \Delta\hat{H}_\text{c}^\text{o} = -5649.1\text{ kJ / mol}$$

$$\Delta\hat{H}_\text{c}^\text{o} = 12\,\Delta\hat{H}_\text{f}^\text{o}(\text{CO}_2) + 11\Delta\hat{H}_\text{f}^\text{o}(\text{H}_2\text{O}) - \Delta\hat{H}_\text{f}^\text{o}(\text{C}_{12}\text{H}_{22}\text{O}_{11})$$

$$\Rightarrow \Delta\hat{H}_\text{f}^\text{o}(\text{C}_{12}\text{H}_{22}\text{O}_{11}) = -2217.14\text{ kJ / mol}$$

$$\text{C}_{12}\text{H}_{22}\text{O}_{11}(\text{s}) + \text{H}_2\text{O}(\text{l}) \rightarrow 4\text{C}_2\text{H}_5\text{OH}(\text{l}) + 4\text{CO}_2(\text{g})$$

$$\Delta\hat{H}_\text{r}^\text{o} = 4\,\Delta\hat{H}_\text{f}^\text{o}(\text{C}_2\text{H}_5\text{OH}) + 4\,\Delta\hat{H}_\text{f}^\text{o}(\text{CO}_2) - \Delta\hat{H}_\text{f}^\text{o}(\text{C}_{12}\text{H}_{22}\text{O}_{11}) - \Delta\hat{H}_\text{f}^\text{o}(\text{H}_2\text{O}) = -184.5\text{kJ / mol}$$

c.

$$\Rightarrow \Delta\hat{H}_\text{r}^\text{o} = \frac{-181.5\text{ kJ}}{1\text{ mol}}\left|\frac{453.6\text{ mol}}{1\text{ lb - mole}}\right|\frac{0.9486\text{ Btu}}{1\text{ kJ}} = \underline{\underline{-7.811\times10^4\text{ Btu / lb - mole}}}$$

Moles of maltose :

$$\frac{4.336\times10^6\text{ lb}_\text{m}\text{ solution}}{\,}\left|\frac{0.071\text{ lb C}_2\text{H}_5\text{OH}}{1\text{ lb}_\text{m}\text{ solution}}\right|\frac{1\text{ lb - mole C}_2\text{H}_5\text{OH}}{46.1\text{ lb C}_2\text{H}_5\text{OH}}\left|\frac{1\text{ lb - mole C}_{12}\text{H}_{22}\text{O}_{11}}{4\text{ lb - mole C}_2\text{H}_5\text{OH}}\right.$$

$$= 1669\text{ lb - moles C}_{12}\text{H}_{22}\text{O}_{11} \Rightarrow \xi = n_{\text{C}_{12}\text{H}_{22}\text{O}_{11}} = 1669\text{ lb - moles}$$

$$Q = \xi\Delta\hat{H}_r + mC_p(95^\circ\text{F - }85^\circ\text{F})$$

$$= (1669\text{ lb - moles})(-7.811\times10^4\frac{\text{Btu}}{\text{lb - mole}}) + (4.336\times10^6\text{ lb}_\text{m})(0.95\frac{\text{Btu}}{\text{lb - }^\circ\text{F}})(10^\circ\text{F})$$

$$= \underline{\underline{-8.9\times10^7\text{ Btu}}} \quad \text{(heat transferred from reactor)}$$

d. Brazil has a shortage of natural reserves of petroleum, unlike Venezuela.

9.20 **a.** $4\text{NH}_3 + 5\text{O}_2 \rightarrow 4\text{NO} + 6\text{H}_2\text{O},$

$$2\text{NH}_3 + \frac{3}{2}\text{O}_2 \rightarrow \text{N}_2 + 3\text{H}_2\text{O}$$

References: $\text{N}_2(\text{g}),\ \text{H}_2(\text{g}),\ \text{O}_2(\text{g}),$ at 25°C

Substance	$\dot{n}_\text{in}$ (mol/min)	$\hat{H}_\text{in}$ (kJ/mol)	$\dot{n}_\text{out}$ (mol/min)	$\hat{H}_\text{out}$ (kJ/mol)
NH_3	100	$\hat{H}_1$	–	–
Air	900	$\hat{H}_2$	–	–
NO	–	–	90	$\hat{H}_3$
H_2O	–	–	150	$\hat{H}_4$
N_2	–	–	716	$\hat{H}_5$
O_2	–	–	69	$\hat{H}_6$

$$\hat{H}_i = \Delta\hat{H}_{\text{f}i}^\text{o} + \int_{25}^{T} C_{pi}\,dT$$

$$\text{NH}_3(\text{g, }25^\circ\text{C}):\ \hat{H}_1 = (\Delta\hat{H}_\text{f}^\text{o})_{\text{NH}_3} \overset{\overset{\text{Table B.1}}{\downarrow}}{=} \underline{\underline{-46.19\text{ kJ/mol}}}$$

9.20 (cont'd)

$$\text{Air}(\text{g, }150^\circ\text{C}):\ \hat{H}_2 \overset{\substack{\text{Table B.8}\\ \downarrow}}{=} \underline{\underline{3.67\ \text{kJ/mol}}}$$

$$\text{NO}(\text{g, }700^\circ\text{C}):\ \hat{H}_3 = 90.37 + \int_{25}^{700} C_p\,dT \overset{\substack{\text{Table B.1, Table B.2}\\ \downarrow}}{=} \underline{\underline{111.97\ \text{kJ/mol}}}$$

$$\text{H}_2\text{O}(\text{g, }700^\circ\text{C}):\ \hat{H}_4 \overset{\substack{\text{Table B.1,}\\ \text{Table B.8}\\ \downarrow}}{=} \underline{\underline{-216.91\ \text{kJ/mol}}}$$

$$\text{N}_2(\text{g, }700^\circ\text{C}):\ \hat{H}_5 \overset{\substack{\text{Table B.8}\\ \downarrow}}{=} \underline{\underline{20.59\ \text{kJ/mol}}}$$

$$\text{O}_2(\text{g, }700^\circ\text{C}):\ \hat{H}_6 \overset{\substack{\text{Table B.8}\\ \downarrow}}{=} \underline{\underline{21.86\ \text{kJ/mol}}}$$

b. $$\dot{Q} = \Delta\dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = -4890\ \text{kJ/min} \times (1\ \text{min}/60\text{s}) = \underline{\underline{-81.5\ \text{kW}}}$$

(heat transferred from the reactor)

c. If molecular species had been chosen as references for enthalpy calculations, the extents of each reaction would have to be calculated and Equation 9.5-1b used to determine $\Delta\dot{H}$. The value of $\dot{Q}$ would remain unchanged.

9.21 **a.** Basis: 1 mol feed

$$\text{C}_2\text{H}_4(\text{v}) + \text{H}_2\text{O}(\text{v}) \Leftrightarrow \text{C}_2\text{H}_5\text{OH}(\text{v})$$

$$2\text{C}_2\text{H}_5\text{OH}(\text{v}) \Leftrightarrow (\text{C}_2\text{H}_5)_2\text{O}(\text{v}) + \text{H}_2\text{O}(\text{v})$$

5% ethylene conversion: $(0.537)(0.05) = 0.02685\ \text{mol C}_2\text{H}_4\ \text{consumed}$

$$\Rightarrow n_1 = (0.95)(0.537) = 0.510\ \text{mol C}_2\text{H}_4$$

90% ethanol yield:

$$n_3 = \frac{0.02685\ \text{mol C}_2\text{H}_4\ \text{consumed}}{} \left| \frac{0.9\ \text{mol C}_2\text{H}_5\text{OH}}{1\ \text{mol C}_2\text{H}_4} \right. = 0.02417\ \text{mol C}_2\text{H}_5\text{OH}$$

C balance : $(2)(0.537) = (2)(0.510) + (2)(0.02417) + 4n_4 \Rightarrow n_4 = 1.415 \times 10^{-3}\ \text{mol}\ (\text{C}_2\text{H}_5)_2\text{O}$

O balance : $0.367 = n_2 + 0.02417 + 1.415 \times 10^{-3} \Rightarrow n_2 = 0.3414\ \text{mol H}_2\text{O}$

9.22 (cont'd)

Plan of attack:

$\%$ excess air $\Rightarrow n_0$

$13\%\ C_6H_5CHO$ formation $\Rightarrow n_3$

$0.5\%\ CO_2$ formation $\Rightarrow n_4$

C balance $\Rightarrow n_1$

H balance $\Rightarrow n_5$

O balance $\Rightarrow n_2$

Ideal gas equation of state $\Rightarrow V_0$

Ideal gas equation of state $\Rightarrow V_p$

E.B. on reactor $\Rightarrow Q$

E.B. on jacket $\Rightarrow m_w$

Scale $V_0,\ V_p,\ Q,\ m_w$ by $(\dot{n}_5)\text{actual} / (n_5)\text{basis}$

100% excess air:

$$n_0 = \frac{100 \text{ lb-moles } C_6H_5CH_3}{} \left| \frac{1 \text{ mol } O_2 \text{ reqd}}{1 \text{ mole } C_6H_5CH_3} \right| \frac{(1+1)\text{mole } O_2 \text{ fed}}{1 \text{ mol } O_2 \text{ reqd}} = 200 \text{ lb-moles } O_2$$

$$\underline{N_2 \text{ feed } (\&\ \text{output})} = 3.76(200)\text{lb-moles } N_2 = 752 \text{ lb-moles } N_2$$

$$\underline{13\% \rightarrow C_6H_5CHO} \Rightarrow n_3 = \frac{100 \text{ lb-moles } C_6H_5CH_3}{} \left| \frac{0.13 \text{ mole } C_6H_5CH_3 \text{ react}}{1 \text{ mole } C_6H_5CH_3 \text{ fed}} \right| \frac{1 \text{ mole } C_6H_5CHO \text{ formed}}{1 \text{ mole } C_6H_5CH_3 \text{ react}}$$

$$= 13 \text{ lb-moles } C_6H_5CHO$$

$$\underline{0.5\% \rightarrow CO_2} \Rightarrow n_4 = \frac{(100)(0.005)\text{lb-moles } C_6H_5CH_3 \text{ react}}{} \left| \frac{7 \text{ moles } CO_2}{1 \text{ mole } C_6H_5CH_3} \right. = 3.5 \text{ lb-moles } CO_2$$

$$\underline{\text{C balance:}} \quad (100)(\overset{\substack{\text{mol C/mole } C_7H_8 \\ \downarrow}}{7})\text{ lb-moles C} = 7n_1 + (13)(7) + (3.5)(1) \Rightarrow n_1 = 86.5 \text{ lb-moles } C_6H_5CH_3$$

$$\underline{\text{H balance:}} \quad (100)(8)\text{lb-moles H} = (86.5)(8) + (13)(6) + 2n_5 \Rightarrow n_5 = 15.0 \text{ lb-moles } H_2O(v)$$

$$\underline{\text{O balance:}} \quad (200)(2)\text{lb-moles O} = 2n_2 + (13)(1) + (3.5)(2) + (15)(1) \Rightarrow n_2 = 182.5 \text{ lb-moles } O_2$$

Ideal gas law – inlet:

$$V_0 = \frac{(100 + 200 + 752)\text{lb-moles}}{} \left| \frac{359 \text{ ft}^3(\text{STP})}{1 \text{ lb-moles}} \right| \frac{(350 + 460)^\circ \text{R}}{492^\circ \text{R}} = 6.218 \times 10^5 \text{ ft}^3$$

Ideal gas law – outlet:

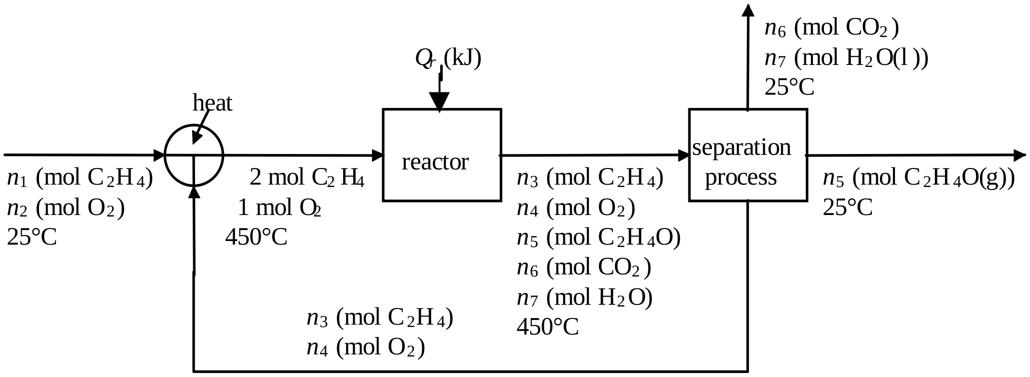
$$V_p = \frac{\left(\overset{C_7H_8}{86.5} + \overset{O_2}{182.5} + \overset{C_7H_8O}{13} + \overset{CO_2}{3.5} + \overset{H_2O}{15} + \overset{N_2}{752} \right)\text{lb-moles}}{} \left| \frac{359 \text{ ft}^3}{1 \text{ lb-mole}} \right| \frac{(379 + 460)^\circ \text{R}}{492^\circ \text{R}} = 6.443 \times 10^5 \text{ ft}^3$$

9.26 **a.**

Basis: 2 mol C_2H_4 fed to reactor

$$C_2H_4(g) + \frac{1}{2}O_2(g) \rightarrow C_2H_4O(g)$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$$



25% conversion $\Rightarrow$ 0.500 mol C_2H_4 consumed $\Rightarrow n_3 = \underline{\underline{1.50 \text{ mol } C_2H_4}}$

70% yield $\Rightarrow n_5 = \dfrac{0.500 \text{ mol } C_2H_4 \text{ consumed}}{} \left| \dfrac{0.700 \text{ mol } C_2H_4O}{1 \text{ mol } C_2H_4} \right. = \underline{\underline{0.350 \text{ mol } C_2H_4O}}$

C balance on reactor: $(2)(2) = (2)(1.50) + (2)(0.350) + n_6 \Rightarrow n_6 = \underline{\underline{0.300 \text{ mol } CO_2}}$

Water formed: $n_7 = \dfrac{0.300 \text{ mol } CO_2}{} \left| \dfrac{1 \text{ mol } H_2O}{1 \text{ mol } CO_2} \right. = \underline{\underline{0.300 \text{ mol } H_2O}}$

O balance on reactor: $(2)(1) = 2n_4 + 0.350 + (2)(0.300) + 0.300 \Rightarrow n_4 = \underline{\underline{0.375 \text{ mol } O_2}}$

Overall C balance: $2n_1 = n_6 + 2n_5 = 0.300 + (2)(0.350) \Rightarrow n_1 = \underline{\underline{0.500 \text{ mol } C_2H_4}}$

Overall O balance: $2n_2 = 2n_6 + n_7 + n_5 = (2)(0.300) + (0.300) + (0.350) \Rightarrow n_2 = \underline{\underline{0.625 \text{ mol } O_2}}$

Feed stream: 44.4% C_2H_4, 55.6% O_2 Reactor inlet: 66.7% C_2H_4, 33.3% O_2

Recycle stream: 80.0% C_2H_4, 20.0% O_2

Reactor outlet: 53.1% C_2H_4, 13.3% O_2, 12.4% C_2H_4O, 10.6% CO_2, 10.6% H_2O

Mass of ethylene oxide $= \dfrac{0.350 \text{ mol } C_2H_4O}{} \left| \dfrac{44.05 \text{ g}}{1 \text{ mol}} \right| \dfrac{1 \text{ kg}}{10^3 \text{ g}} = 0.0154 \text{ kg}$

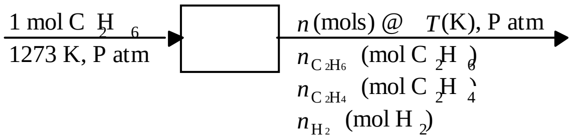
b. References for enthalpy calculations: C(s), $H_2(g)$, $O_2(g)$ at 25° C

$$\hat{H}_i(T) = \Delta\hat{H}_{fi}^o + \int_{25}^{T} C_p dT \quad \text{for } C_2H_4$$

$$= \Delta\hat{H}_f^0 + \int_{298}^{T+273} C_p dT \quad \text{for } C_2H_4O$$

$$\left.\begin{aligned} &= \Delta\hat{H}_{fi}^o + \hat{H}_i(\text{table B.8}) \\ &= \Delta\hat{H}_f^o \quad \text{for } H_2O(l) \end{aligned}\right. \quad \text{for } O_2,\ CO_2,\ H_2O(g)$$

9.35 Basis: 1 mol C_2H_6 fed to reactor



a. $$C_2H_6 \Leftrightarrow C_2H_4 + H_2\ ,\quad K_p = \frac{x_{C_2H_4}x_{H_2}}{x_{C_2H_6}}P = 7.28\times10^6 \exp[-17{,}000/T(K)] \qquad (1)$$

Fractional conversion = f (mols C_2H_6 react/mol fed)

$$\left.\begin{aligned}&\xi(\text{mol}) = f\\ &n_{C_2H_6} = (1-f)(\text{mol } C_2H_6)\\ &n_{C_2H_4} = f(\text{mol } C_2H_4)\\ &n_{H_2} = f(\text{mol } H_2)\\ \hline &n = 1+f(\text{mols})\end{aligned}\right\} \Rightarrow \begin{aligned}x_{C_2H_6} &= \frac{1-f}{1+f}\frac{\text{mol } C_2H_6}{\text{mol}}\\ x_{C_2H_4} &= \frac{f}{1+f}\frac{\text{mol } C_2H_4}{\text{mol}}\\ x_{H_2} &= \frac{f}{1+f}\frac{\text{mol } H_2}{\text{mol}}\end{aligned}$$

$$K_p = \frac{x_{C_2H_4}x_{H_2}}{x_{C_2H_4}}P \Rightarrow K_p = \frac{\frac{f^2}{(1+f)^2}P}{\frac{(1-f)}{(1+f)}} = \frac{f^2\,P}{(1-f)(1+f)} = \frac{f^2}{1-f^2}P$$

$$(1-f^2)K_p = f^2P \Rightarrow \underline{\underline{f = \left(\frac{K_p}{P+K_p}\right)^{1/2}}} \qquad (2)$$

b. References: $C_2H_6(g)$, $C_2H_4(g)$, $H_2(g)$ at 1273 K

Energy balance:

$$\Delta H = 0 \Rightarrow \xi\Delta\hat{H}_r(1273\text{ K}) + \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i$$

$$\left(\hat{H}_i\right)_{\text{in}} = 0 \text{ (inlet temperature = reference temperature)}$$

$$\left(\hat{H}_i\right)_{\text{out}} = \int_{1273}^{T} C_{pi}\,dT$$

$$\Downarrow \text{energy balance}$$

$$f\Delta\hat{H}_r(1273\text{ K})\text{kJ} + (1-f)\int_{1273}^{T}\left(C_p\right)_{C_2H_6}dT + f\int_{1273}^{T}\left(C_p\right)_{C_2H_4}dT + f\int_{1273}^{T}\left(C_p\right)_{H_2}dT = 0$$

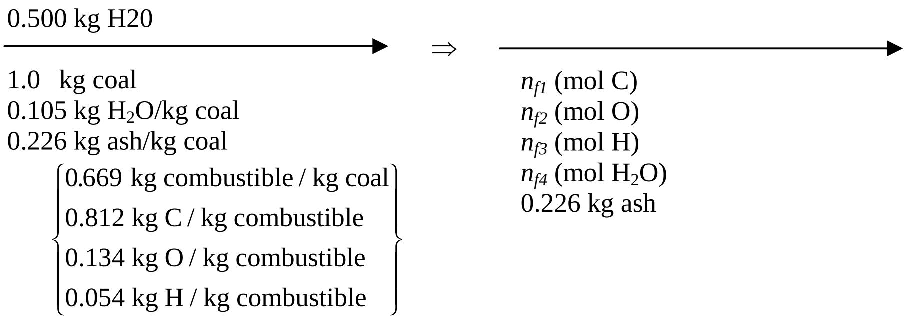
$$\Big\Downarrow \text{ rearrange, reverse limits and change signs of integrals}$$

$$\frac{1-f}{f} = \underbrace{\frac{\Delta\hat{H}_r(1273K) - \int_T^{1273}\left(C_p\right)_{C_2H_4}dT - \int_T^{1273}\left(C_p\right)_{H_2}dT}{\int_T^{1273}\left(C_p\right)_{C_2H_6}dT}}_{\phi(T)} \qquad (3)$$

$$\frac{1-f}{f} = \phi(T) \Rightarrow 1-f = f\phi(T) \Rightarrow f = \frac{1}{1+\phi(T)} \qquad (4)$$

9.38 **a.** Any C consumed in reaction (2) is lost to reaction (1). Without the energy released by reaction (2) to compensate for the energy consumed by reaction (1), the temperature in the adiabatic reactor and hence the reaction rate would drop.

b. Basis : 1.00 kg coal fed (+0.500 kg $H_2$0)

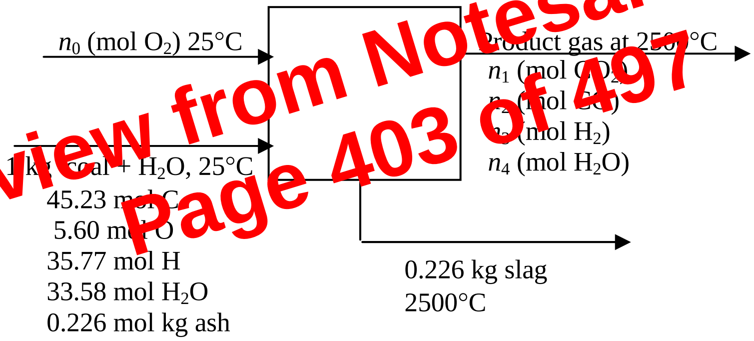


$$n_{f1} = [\,(1.00)(0.669)(0.812)\text{ kg C}][1\text{ mol C}/12.01\times10^{-3}\text{ kg}] = 45.23\text{ mol C}$$

$$n_{f2} = (1.00)(0.669)(0.134)\ /16.0\times10^{-3} = 5.6\text{ mol O}$$

$$n_{f3} = (1.00)(0.669)(0.054)\ /1.01\times10^{-3} = 35.77\text{ mol H}$$

$$n_{f4} = [\,(0.500+0.105)\text{ kg}][1\text{ mol }H_2O/18.016\times10^{-3}\text{ kg}] = 33.58\text{ mol }H_2O$$



$$\underline{\text{Reactive oxygen (O) available}} = (2n_0+5.60)\text{ mol O}$$

$$\underline{\text{Oxygen consumed by H}}\ \ (2H+O\rightarrow H_2O):\ \frac{35.77\text{ mol H}}{}\left|\frac{1\text{ mol O}}{2\text{ mol H}}\right. = 17.88\text{ mol O}$$

$$\Rightarrow\ \text{Reactive O remaining} = (2n_0+5.60)-17.88 = (2n_0-12.28)\text{ mol O}$$

$$\underline{CO_2\ \text{formed}}\ \ (C+2O\rightarrow CO_2):n_1 = \frac{(2n_0-12.28)\text{ mol O}}{}\left|\frac{1\text{ mol }CO_2}{2\text{ mol O}}\right. = \underline{\underline{(n_0-6.14)\text{ mol }CO_2}}$$

$$\underline{\text{C balance}}: 45.23 = n_1+n_2 \overset{n_1=n_0-6.14}{\Longrightarrow} n_2 = \underline{\underline{(51.37-n_0)\text{ mol CO}}}$$

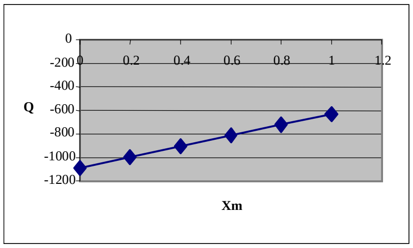
$$\underline{\text{O balance}}: 2n_0+5.60+33.58 = 2n_1+n_2+n_4 \underset{n_2=51.37-n_0}{\overset{n_1=n_0-6.14}{\Longrightarrow}} n_4 = \underline{\underline{(n_0+0.06)\text{ mol }H_2O}}$$

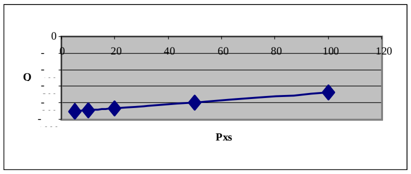
$$\underline{\text{H balance}}: 35.77+2(33.58) = 2n_3+2n_4 \overset{n_4=n_0+0.06}{\Longrightarrow} n_3 = \underline{\underline{(51.37-n_0)\text{ mol }H_2}}$$

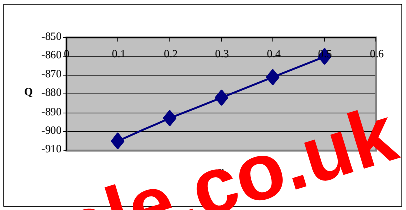
9.58 (cont'd)

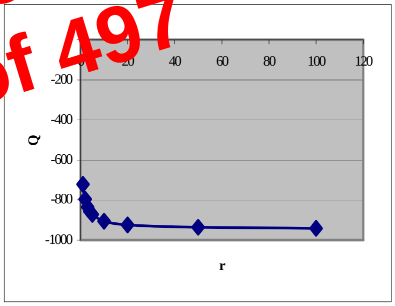
d.

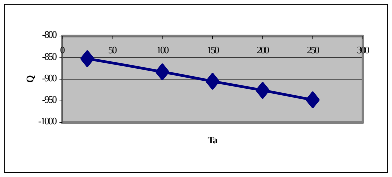
Xa	Pxs	r	Ta	Ts	Q
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.1	5	10	150	700	-
0.1	10	10	150	700	-
0.1	20	10	150	700	-
0.1	50	10	150	700	-
0.1	100	10	150	700	-
0.1	5	10	150	700	-
0.2	5	10	150	700	-
0.3	5	10	150	700	-
0.4	5	10	150	700	-
0.5	5	10	150	700	-
0.1	5	1	150	700	-722
0.1	5	2	150	700	-796
0.1	5	3	150	700	-834
0.1	5	4	150	700	-856
0.1	5	5	150	700	-871
0.1	5	10	150	700	-905
0.1	5	20	150	700	-924
0.1	5	50	150	700	-936
0.1	5	100	150	700	-941
0.1	5	10	25	700	-852
0.1	5	10	100	700	-883
0.1	5	10	150	700	-905
0.1	5	10	200	700	-926
0.1	5	10	250	700	-948
0.1	5	10	150	500	-1014
0.1	5	10	150	600	-960
0.1	5	10	150	700	-905
0.1	5	10	150	800	-848
0.1	5	10	150	900	-790
0.1	5	10	150	1000	-731

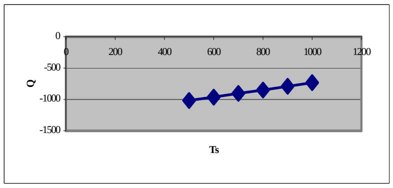












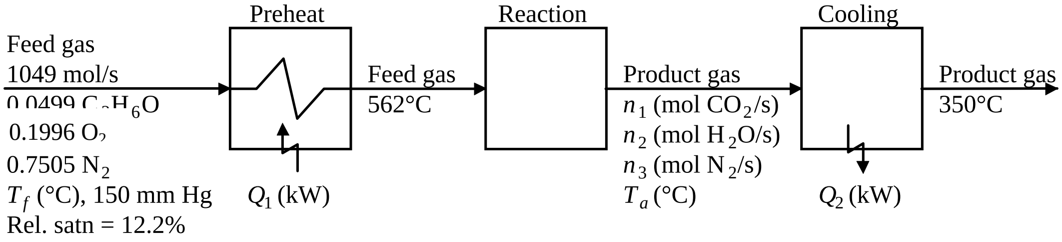
9.64 $C_3H_6O(g) + 4O_2(g) \rightarrow 3CO_2(g) + 3H_2O(l),\ \Delta\hat{H}_i^o = -1821.4\ \text{kJ/mol}$

$$\underline{\text{Basis}}: \frac{1410\ \text{m}^3(\text{STP})\ \text{feed gas}}{\text{min}}\left|\frac{10^3\ \text{mol}}{22.4\ \text{m}^3(\text{STP})}\right|\frac{1\ \text{min}}{60\ \text{s}} = 1049\ \text{mol/s feed gas}$$

<u>Stochiometric proportion:</u>

$$1\ \text{mol}\ C_3H_6O \Rightarrow 4\ \text{mol}\ O_2 \Rightarrow 4\times 3.76 = 15.04\ \text{mol}\ N_2 \Rightarrow (1+4+15.04) = 20.04\ \text{mol}$$

$$y_{C_3H_6O} = \frac{1\ \text{mol}\ C_3H_6O}{20.04\ \text{mol}} = 0.0499\frac{\text{mol}\ C_3H_6O}{\text{mol}},\ y_{O_2} = \frac{4}{20.04} = 0.1996\ \text{mol}\ O_2/\text{mol}$$



a. Relative saturation $= 12.2\% \Rightarrow y_{C_3H_6O}P = 0.122\,p^*_{C_3H_6O}(T_f)$

$$\Rightarrow p^* = \frac{(0.0499)(1500\ \text{mm Hg})}{0.122} = 613.52\ \text{mm Hg} \xRightarrow{\text{Table B.4}} \underline{\underline{T_f = 50.0^\circ C}}$$

b. Feed contains $(1049\ \text{mol/s})(0.0499\ C_3H_6O/\text{mol}) = 52.34\ \text{mol}\ C_3H_6O/\text{s}$

$(1049)(0.1996) = 209.4\ \text{mol}\ O_2/\text{s}$

$(1049)(0.7505) = 787.3\ \text{mol}\ N_2/\text{s}$

$$\Rightarrow \text{Product contains}\left.\begin{array}{l} n_1 = (52.34)(3) = 157.0\ \text{mol}\ CO_2/\text{s} \\ n_2 = (52.34)(3) = 157.0\ \text{mol}\ H_2O/\text{s} \\ n_3 = 787.3\ \text{mol}\ N_2/\text{s}\end{array}\right\} \Rightarrow \begin{array}{l}\underline{\underline{14.25\ \text{mole\%}\ CO_2}} \\ \underline{\underline{14.25\%\ H_2O}} \\ \underline{\underline{71.5\%\ N_2}}\end{array}$$

<u>References</u>: $C_3H_6O(g),\ O_2,\ N_2,\ H_2O(l),\ CO_2$ at $25^\circ C$

Substance	$\dot{n}_{in}$ (mols)	$\hat{H}_{in}$ (kJ/mol) ($562^\circ C$)	$\dot{n}_{out}$ (mols)	$\hat{H}_{out}$ (kJ/mol) T_a
C_3H_6O	52.34	67.66	–	–
O_2	209.4	17.72	–	–
N_2	787.3	17.18	787.3	$0.032(T_a - 25)$
CO_2	–	–	157.0	$0.052(T_a - 25)$
H_2O	–	–	157.0	$44.013 + 0.040(T_a - 25)$

<u>Energy balance on reactor:</u>

$$\Delta H = n_{C_3H_6O}\Delta\hat{H}_c^o + \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = 0\ (\text{kJ/s})$$

$$\Rightarrow (5234\ \text{mol/s})\left(-1821.1\frac{\text{kJ}}{\text{mol}}\right) + 39.638(T_a - 25) + 157.0(44.013) - 2.078\times 10^4 = 0 \Rightarrow \underline{\underline{T_a = 2780^\circ C}}$$

9.70 (cont'd)

Solids balance on dryer:

$$0.35 \times 24{,}000\ \text{kg/d} = 0.75\dot{n}_2 \Rightarrow \dot{n}_2 = 11200\ \text{kg/d} \Rightarrow \underline{\underline{\ \text{F}\quad 11.2\ \text{tonnes/d}}}\ \text{(conc. sludge)}$$

Mass Balance on dryer: $24{,}000 = \dot{n}_1 + 11200 \Rightarrow \dot{n}_1 = 12{,}800\ \text{kg/d}$

Energy balance on sludge side of dryer:

References: $H_2O(l, 22^\circ C)$, Solids$(22^\circ C)$

Substance	$\dot{n}_{in}$ (kg/d)	$\hat{H}_{in}$ (kJ/kg)	$\dot{n}_{out}$ (kg/d)	$\hat{H}_{out}$ (kJ/kg)
Solids	8400	0	8400	$\hat{H}_1$
$H_2O(l)$	15600	0	2800	$\hat{H}_2$
$H_2O(v)$	–	–	12800	$\hat{H}_3$

$$\hat{H}_1 = 2.5(100-22) = 195.0\ \text{kJ/kg}$$

$$\hat{H}_2 = (419.1-92.2) = 326.9\ \text{kJ/kg}$$

$$\hat{H}_3 = (2676-92.2) = 2584\ \text{kJ/kg}$$

$(\hat{H}_{water}$ from Table B.5)

$$\dot{Q}_2 = \sum_{out}\dot{m}_i\hat{H}_i - \sum_{in}\dot{m}_i\hat{H}_i \Rightarrow \underline{\underline{\dot{Q}_2 = 3.56\times10^7\ \text{kJ/day}}}$$

$$\dot{Q}_{steam} = \frac{3.56\times10^7}{0.55} = 6.47\times10^7\ \text{kJ/d} \Rightarrow \underline{\underline{\dot{Q}_3 = 2.91\times10^7\ \text{kJ/d}}}$$

Energy balance on steam side of dryer:

$$6.47\times10^7\ \frac{\text{kJ}}{\text{d}} = \dot{n}_3\left(\frac{\text{kg}}{\text{d}}\right)\times \overset{\substack{\Delta\hat{H}_v\ \text{for} \\ H_2O(\text{sat'd},\ ) \\ \downarrow}}{2133}\left(\frac{\text{kJ}}{\text{kg}}\right)\left(\frac{1\ \text{tonne}}{10^3\ \text{kg}}\right) \Rightarrow \underline{\underline{\dot{n}_3 = 30.3\ \text{tonnes/d}}}\ \text{(boiler feedwater)}$$

Energy balance on steam side of boiler:

$$Q_1 = (30300\frac{\text{kg}}{\text{d}})(2737.6-83.9)\frac{\text{kJ}}{\text{kg}} = \underline{\underline{8.04\times10^7\ \text{kJ/d}}}$$

62% efficiency $\Rightarrow$ Fuel heating value needed $= \dfrac{8.04\times10^7}{0.62} = 1.3\times10^8\ \text{kJ/d}$

$$\Rightarrow \dot{n}_4 = \frac{1.30\times10^8\ \text{kJ/d}}{3.75\times10^4\ \text{kJ/kg}} = \underline{\underline{3458\ \text{kg/d}}} \Rightarrow \underline{\underline{\text{D} = 3.5\ \text{tonnes/day}}}\ \text{(fuel oil)}$$

Air feed to boiler furnace: $C + O_2 \rightarrow CO_2$, $4H + O_2 \rightarrow 2H_2O$, $S + O_2 \rightarrow SO_2$

$$(n_{O_2})_{theo} = 3458\frac{\text{kg}}{\text{d}}\left[(0.87\frac{\text{kgC}}{\text{kg}})(\frac{1\ \text{kmol C}}{12\ \text{kg}})(\frac{1\ \text{kmol } O_2}{1\ \text{kmol C}}) + (0.10)(\frac{1}{1})(\frac{1}{4}) + (0.0084)(\frac{1}{32})(\frac{1}{1})\right]$$

$$= 338\ \text{kmol } O_2/\text{d}$$

10.2 10 variables $(n_1, n_2, n_3, n_4, x_1, x_2, x_3, x_4, T, P)$

-2 material balances

-2 equilibrium relations: $[x_3 P = x_4 P_B^*(T),\ (1-x_3)P = (1-x_4)P_C^*(T)]$

6 degrees of freedom

a. <u>A straightforward set</u>: $\underline{\underline{\{n_1,\ n_3,\ n_4,\ x_1,\ x_4,\ T\}}}$

Calculate n_2 from total material balance, P from sum of Raoult's laws:

$$P = x_4 p_B^*(T) + (1-x_4)P_c^*(T)$$

x_3 from Raoult's law, x_2 from B balance

b. <u>An iterative set</u>: $\underline{\underline{\{n_1,\ n_2,\ n_3,\ x_1,\ x_2,\ x_3\}}}$

Calculate n_4 from total mole balance, x_4 from B balance.

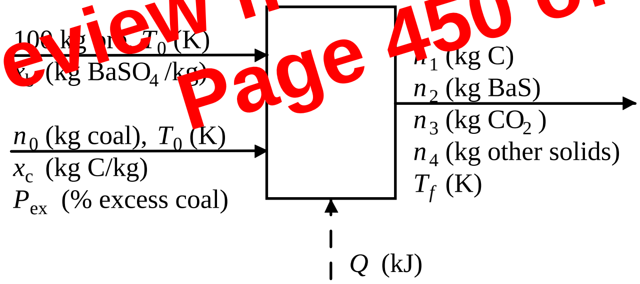
Guess P, calculate T from Raoult's law for B, P from Raoult's law for C, iterate until pressure checks.

c. <u>An impossible set</u>: $\underline{\underline{\{n_1,\ n_2,\ n_3,\ n_4,\ T,\ P\}}}$

Once n_1, n_2, and n_3 are specified, a total mole balance determines n_4.

10.3 $2\mathrm{BaSO_4(s)} + 4\mathrm{C(s)} \rightarrow 2\mathrm{BaS(s)} + 4\mathrm{CO_2(g)}$

a.



11 variables $(n_0, n_1, n_2, n_3, n_4, x_b, x_c, T_0, T_f, Q, P_{ex})$

-5 material balances$(\mathrm{C},\ \mathrm{BaS},\ \mathrm{CO_2},\ \mathrm{BaSO_4},\ \text{other solids})$

-1 energy balance

$+1$ reaction

-1 relation defining P_{ex} in terms of n_0, x_b, and x_c

$\underline{\underline{5}}$ degrees of freedom

b. <u>Design set</u>: $\underline{\underline{\{x_b,\ x_c,\ T_0,\ T_f,\ P_{ex}\}}}$

Calculate n_0 from x_b, x_c, and P_{ex}; n_1 through n_4 from material balances, Q from energy balance

10.8

a. Let Bz = benzene, Tl = toluene

Antoine equations: $p_{Bz}^* = 10^{6.89272-1211.033/(T+220.790)}$ (=1350.491)

$p_{Tl}^* = 10^{6.95805-1346.773/(T+219.693)}$ (=556.3212)

Raoult's law: $x_{Bz} = (P - p_{Tl}^*)/(p_{Bz}^* - p_{Tl}^*)$ (=0.307) , $y_{Bz} = x_{Bz} p_{Bz}^* / P$ (= 0.518)

$$\left.\begin{array}{ll}\text{Total mole balance: } & 100 = n_v + n_l \\ \text{Benzene balance: } & 40 = y_{Bz} n_v + x_{Bz} n_l\end{array}\right\}$$

$$\Rightarrow n_v = \frac{40 - 100x_{Bz}}{y_{Bz} - x_{Bz}} \ (=44.13),\ n_l = 100 - n_v \ (=55.87)$$

Fractional benzene vaporization : $f_B = n_v y_{Bz} / 40$ (=0.571)

Fractional toluene vaporization : $f_T = n_v (1 - y_{Bz}) / 60$ (=0.354)

The specific enthalpies are calculated by integrating heat capacities and (for vapors) adding the heat of vaporization.

$Q = \sum n_{out} \hat{H}_{out} - \sum n_{in} \hat{H}_{in}$ (= 1097.9)

b. Once the spreadsheet has been prepared, the goalseek tool can be used to determine the bubble-point temperature (find the temperature for which n_v=0) and the dew-point temperature (find the temperature for which n_l=0). The solutions are

$T_{bp} = 96.9^\circ$ C, $T_{dp} = 103.2^\circ$ C

c.

```
    C  **CHAPTER 10 PROBLEM B
          DIMENSION SF(3), SL(3), SV(3)
          DATA A1, B1, C1/6.90565, 1211.033, 220.790/
          DATA A2, B2, C2/6.95334, 1343.943, 219.377/
          DATA CP1, CP2, HV1, HV2/ 0.160, 0.190, 30.765, 33.47/
          COMMON A1, B1, C1, A2, B2, C2, CP1, CP2, NV1, NV2
          FLOW = 1.0
          SF(1) = 0.30*FLOW
          SF(2) = 0.70*FLOW
          T = 363.0
          P = 512.0
          CALL FLASH2 (SF, SL, SV, T, P, Q)
          WRITE (6, 900) 'Liquid Stream', SL(1), SL(2), SL(3)
          WRITE (6, 900) 'Vapor Stream', SV(1), SV(2), SV(3)
    900   FORMAT (A15, F7.4,' mol/s Benzene',/,
          * 15X, F7.4, mol/s Toluene',/,
          * 15X, F7.2, 'K')
          WRITE (6, 901) Q
```

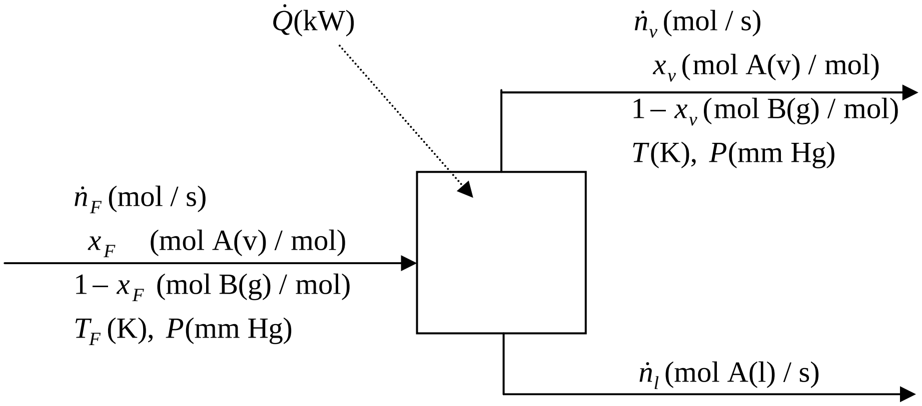
10.9 (cont'd)

```
600     NL = NF – NVP
        DO 700 I = 1, N
        XL(I) = XF(I)*NF/(NF + NV**(PV(I)/P – 1))
        SL(I) = XL(I)*NL
        XV(I) = XL(I)*PV(I)/P
700     SV(I) = SF(I) – SL(I)
        Q1 = 0.
        Q2 = 0.
        DO 800 I = 1, N
        Q1 = Q1 + CP(I)*SF(I)
800     Q2 = Q2 + HV(I)*XV(I)
        Q = Q1*(T – TF) + Q2*NVP
        RETURN
        END
```

```
Program Output:  Liquid Stream   0.0563  mols/s  n-pentane
                                 0.1000  mols/s  n-hexane
                                 0.2011  mols/s  n-heptane
                                 338.00 K
                 Vapor Stream    0.2944  mols/s  n-pentane
                                 0.2000  mols/s  n-hexane
                                 0.1509  mols/s  n-heptane
                                 338.00 K
                 Heat Required   13.01 kW
```

10.10

a.

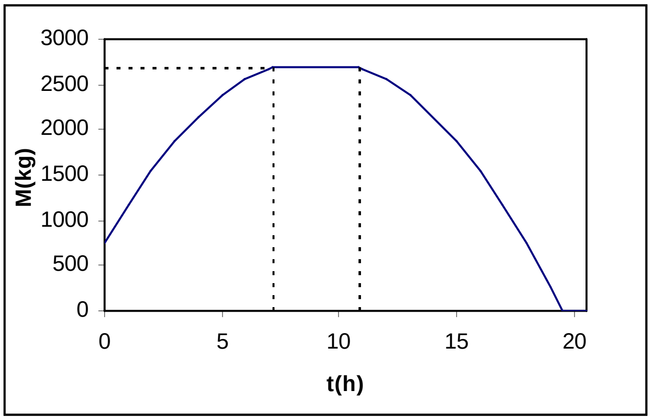


10.10 (cont’d)

e.

```
      C  **CHAPTER 10 -- PROBLEM 10
         DIMENSION SF(3), SV(3), SL(2)
         COMMON A, B, C, CPL, HV, CPV, CPG
         DATA A, B, C / 7.87863, 1473.11, 230.0/
         DATA CPL, HV, CPV, CPG,/ 0.078, 35.27, 0.050, 0.029/
         FLOW = 1.0
         SF(1) = 0.704*FLOW
         SF(2) = FLOW – SF(1)
         YC = 0.90
         P = 1.
         SF(3) = 333.
         CALL CNDNS (SF, SV, SL, P, YC, Q)
         WRITE (6, 900) SV(3)
         WRITE (6, 401) 'Vapor Stream', SV(1), SV(2)
         WRITE (6, 401) 'Liquid Stream', SL(1)
         WRITE (6, 902)Q
  900    FORMAT ('Condenser Temperature', F7.2,' K')
  901    FORMAT (A15, F7.3,' 'mols/s Methyl Alcohol', /,
        *15X, F7.3, 'mols/s air')
  902    FORMAT ('Heat Removal Rate', F7.2,' kW')
         END
      C  SUBROUTINE CNDNS (SF, SV, SL, P, YC, Q)
         REAL NF, NL, NV
         DIMENSION SF(3), SV(3), SL(2)
         COMMON A, B, C, CPL, HV, CPV, CPG
      C  Inlet Stream Variables
         NF = SF(1) + SF(2)
         TF = SF(3)
         XF = SF(1)/NF
      C  Solve Equations
         NL = YC * XF * NF
         NV = NF - NL
         XV = (XF*NF - NL)/NV
         PV = P * XV * 760.
         T = B/(A - LOG(N)/LOG (10.)) - C
         T = T + 273.15
         Q = ((CPV * XV + CPG * (1 - XY)) * NV + CPL * NL) * (T - TF) - NL * HV
      C  Output Variables
         SL(1) = NL
         S2(2) = T
         SV(1) = XV*NV
         SV(2) = NV - SV(1)
         SV(3) = T
         RETURN
         END
```

11.3 (cont'd)



11.4 **a.** Air initially in tank: $N_0 = \dfrac{10.0\ \text{ft}^3}{} \left| \dfrac{492°\text{R}}{532°\text{R}} \right| \dfrac{1\ \text{lb-mole}}{359\ \text{ft}^3(\text{STP})} = 0.0258\ \text{lb-mole}$

Air in tank after 15 s:

$$\frac{P_f V}{P_0 V} = \frac{N_f RT}{N_0 RT} \Rightarrow N_f = N_0 \frac{P_f}{P_0} = \frac{0.0258\ \text{lb-mole}}{} \left| \frac{114.7\ \text{psia}}{14.7\ \text{psia}} \right. = 0.2013\ \text{lb-mole}$$

Rate of addition: $\dot{n} = \dfrac{(0.2013 - 0.0258)\ \text{lb-mole air}}{15\ \text{s}} = \underline{\underline{0.0117\ \text{lb-mole air/s}}}$

b. Balance on air in tank: Accumulation = input

$$\underline{\underline{\frac{dN}{dt}}} = 0.0117(\text{lb-moles/s});\ \underline{\underline{t = 0,\ N = 0.0258\ \text{lb-mole}}}$$

c. Integrate balance: $\displaystyle\int_{0.0258}^{N} dN = \int_0^t \dot{n}\, dt \Rightarrow \underline{\underline{N = 0.0258 + 0.0117t}}\ (\text{lb-mole air})$

Check the solution in two ways:

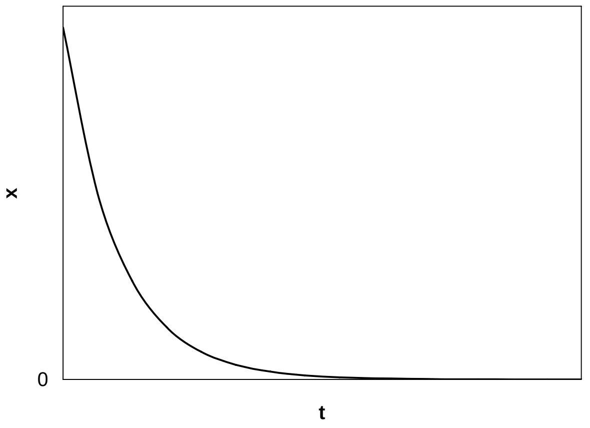
(1) $t = 0, N = 0.0258$ lb-mole $\Rightarrow$ satisfies the initial condition

(2) $\dfrac{dN}{dt} = 0.0117$ lb-mole air / s $\Rightarrow$ reproduces the mass balance

d. $t = 120\ \text{s} \Rightarrow N = 0.0258 + (0.0117)(120) = 1.43\ \text{lb-moles air}$

O$_2$ in tank $= 0.21(1.43) = \underline{\underline{0.30\ \text{lb-mole O}_2}}$

11.8 (cont'd)



c. Separate variables and integrate the balance equation:

$$\int_{3.30\times10^{-5}}^{x}\frac{dx}{x}=\int_{0}^{t}-0.6364dt \Rightarrow \ln\frac{x}{3.30\times10^{-5}}=-0.6364t \Rightarrow \underline{\underline{x=3.30\times10^{-5}e^{-0.6364t}}}$$

Check the solution in two ways:

(1) $t = 0,\ x = 3.30\times10^{-5}$ mol SO_2 / mol ⇒ satisfies the initial condition;

(2) $\frac{dx}{dt}=-0.6364\times3.30\times10^{-5}e^{-0.6364t}=-0.6364x \Rightarrow$ reproduces the mass balance.

d. $C_{SO_2}=\frac{45,440\text{ moles}}{1100\text{ m}^3}\left|\frac{x\text{ mol SO}_2}{\text{mol}}\right|\frac{1\text{ m}^3}{10^3\text{ L}}=4.131\times10^{-2}x=\underline{\underline{1.3632\times10^{-6}e^{-0.6364t}\text{ mol SO}_2/\text{L}}}$

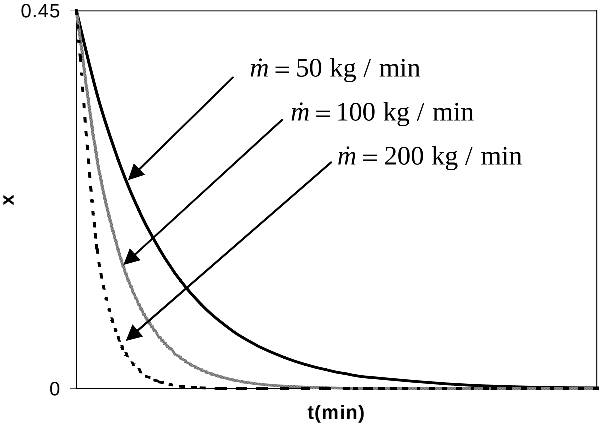
i) $t=2\text{ min}\Rightarrow C_{SO_2}=\underline{\underline{3.82\times10^{-7}\ \frac{\text{mol SO}_2}{\text{liter}}}}$

ii) $x=10^{-6}\Rightarrow t=\frac{\ln\left(10^{-6}/3.30\times10^{-5}\right)}{-0.6364}=\underline{\underline{5.5\text{ min}}}$

e. The room air composition may not be uniform, so the actual concentration of the SO_2 in parts of the room may still be higher than the safe level. Also, "safe" is on the average; someone would be particularly sensitive to SO_2.

11.10 (cont'd)

c.



$$\frac{\mathrm{dx}}{\mathrm{dt}} = -\frac{\dot{m}}{200}x < 0$$, x decreases when t increases

$\frac{\mathrm{dx}}{\mathrm{dt}}$ becomes less negative until x reaches 0;

Each curve is concave up and approaches x = 0 as t $\rightarrow \infty$;

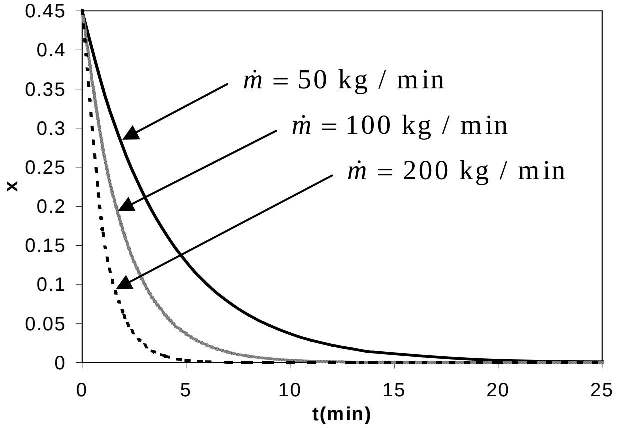
$\dot{m}$ increases $\Rightarrow$ $\frac{\mathrm{dx}}{\mathrm{dt}}$ becomes more negative $\Rightarrow$ x decreases faster.

d. $$\int_{0.45}^{x} \frac{dx}{x} = -\int_{0}^{t} \frac{\dot{m}}{M} dt \Rightarrow \ln\frac{x}{0.45} = -\frac{\dot{m}}{200}t \Rightarrow \underline{\underline{x = 0.45\exp\left(-\frac{\dot{m}t}{200}\right)}}$$

Check the solution:

(1) t = 0, x = 0.45 $\Rightarrow$ satisfies the initial condition;

(2) $\frac{\mathrm{dx}}{\mathrm{dt}} = -0.45 \times \frac{\dot{m}}{200}\exp(-\frac{\dot{m}t}{200}) = -\frac{\dot{m}}{200}x \Rightarrow$ satisfies the mass balance.



e. $\dot{m} = 100$ kg/min $\Rightarrow t = -2\ln\left(x_f/0.45\right)$

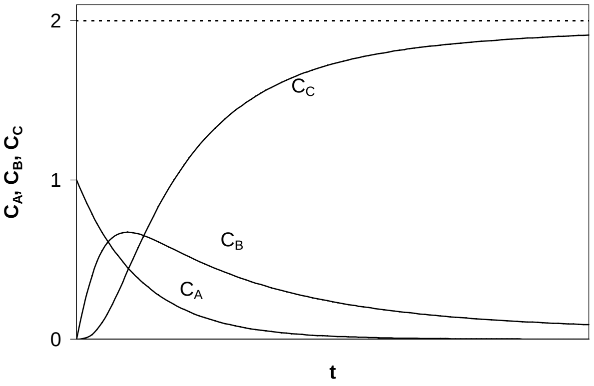
90% $\Rightarrow x_f = 0.045 \Rightarrow \underline{\underline{t = 4.6 \text{ min}}}$

99% $\Rightarrow x_f = 0.0045 \Rightarrow \underline{\underline{t = 9.2 \text{ min}}}$

99.9% $\Rightarrow x_f = 0.00045 \Rightarrow \underline{\underline{t = 13.8 \text{ min}}}$

11.29 (cont'd)

c.

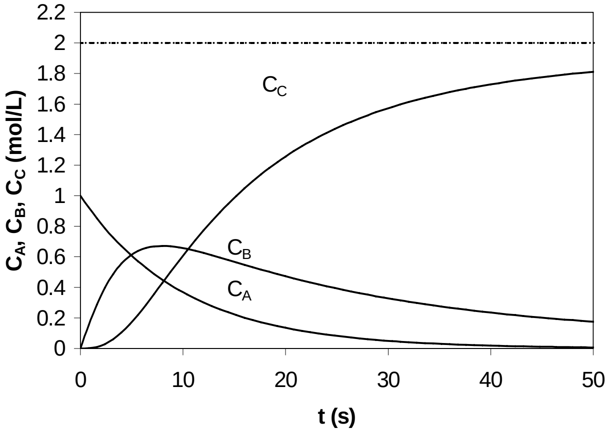


The plot of C_A vs. t begins at (t=0, C_A=1). When t=0, the slope (=dC_A/dt) is $-0.1 \times 1 = -0.1$. As t increases, C_A decreases ⇒ $dC_A/dt=-0.1C_A$ becomes less negative, approaches zero as t→∞. C_A→0 as t→∞. The curve is therefore <u>concave up.</u>

The plot of C_B vs. t begins at (t=0, C_B=0). When t=0, the slope (=dC_B/dt) is $0.2(1-0) = 0.2$. As t increases, C_B increases, C_A decreases ($C_B^2 < C_A$)⇒ $dC_B/dt = 0.2(C_A - C_B^2)$ becomes less positive until dC_B/dt changes to negative ($C_B^2 > C_A$). Then C_B decreases with increasing t as well as C_A. Finally dC_B/dt approaches zero as t→∞. Therefore C_B increases first until it reaches a maximum value, then it decreases. C_B→0 as t→∞.

The plot of C_C vs. t begins at (t=0, C_C=0). When t=0, the slope (=dC_C/dt) is $0.2(0) = 0$. As t increases, C_B increases ⇒ $dC_c/dt = 0.2\, C_B^2$ becomes positive also increases with increasing t ⇒ C_C increases faster until C_B decreases with increasing t ⇒ $dC_c/dt = 0.2\, C_B^2$ becomes less positive, approaches zero as t→∞ so C_C increases more slowly. Finally C_C→2 as t→∞. The curve is therefore S-<u>shaped.</u>

d.

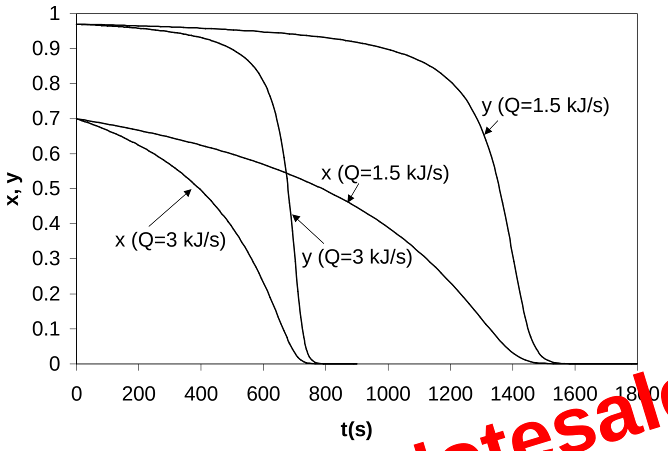


11.30 (cont'd)

$$\frac{dx}{dt} = -\frac{\dot{n}_V}{N_L}\left(\frac{ax}{x+b} - x\right) = -\frac{\dot{Q}/27.0}{100 - \dfrac{\dot{Q}t}{27.0}}\left(\frac{ax}{x+b} - x\right)$$

$$x(0) = 0.70$$

e.



f. The mole fractions of pentane in the vapor product and residual liquid continuously decrease over a run. The initial and final mole fraction of pentane in the vapor are 0.970 and 0, respectively. The higher the heating rate, the faster *x* and *y* decrease.